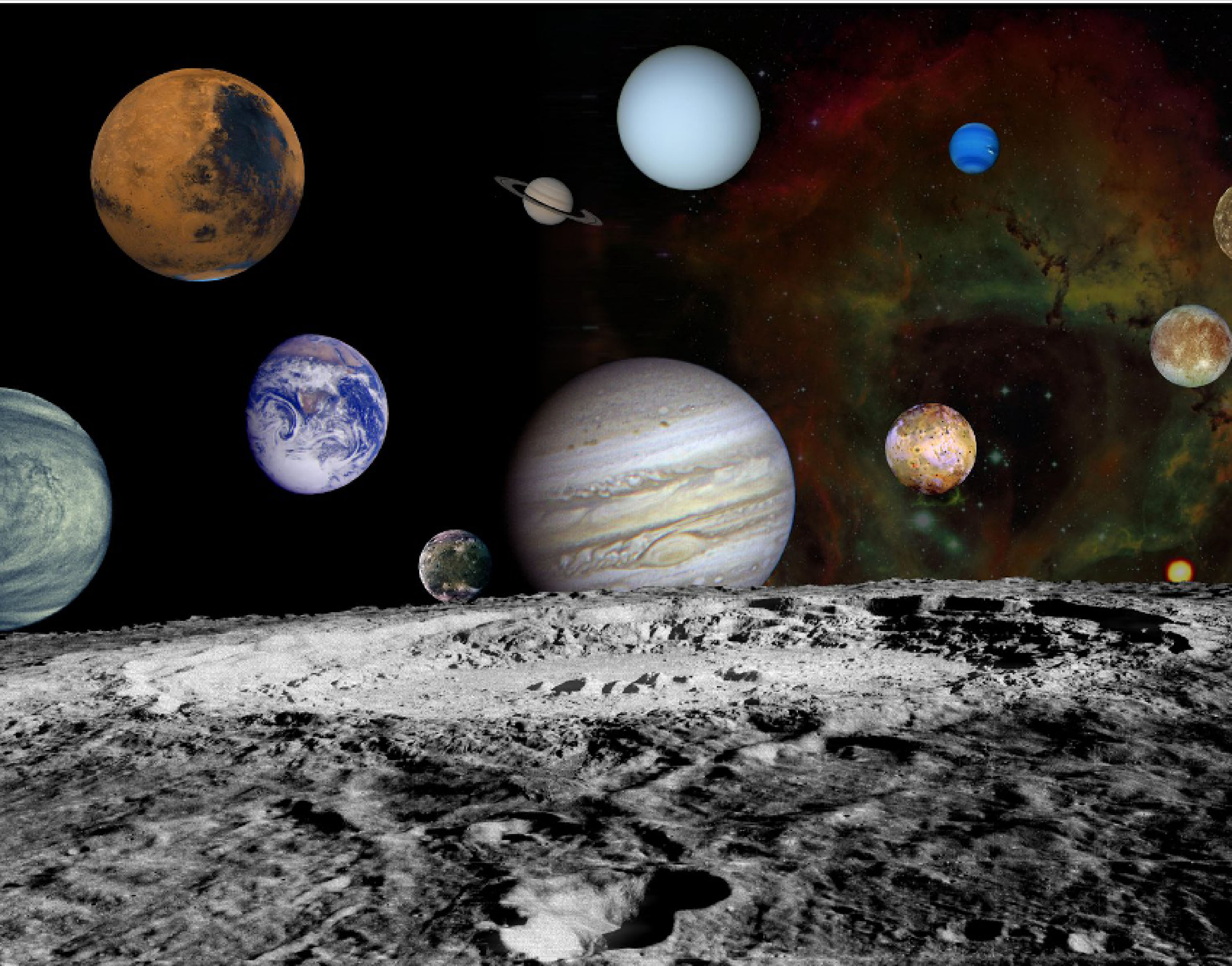
Earth Science



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Chapter 1

What is Earth Science?

1.1 Nature of Science

Lesson Objectives

- Explain the importance of asking questions.
- State the steps of the scientific method.
- Describe the three major types of scientific models.
- Use appropriate safety precautions inside and outside the science laboratory.

Introduction

Think of your favorite science fiction movie. What is it about? Maybe it's about spaceships going to distant planets, or people being cloned in laboratories, or undersea civilizations, or robots that walk among us. These entertaining imaginings are make-believe fantasies, that's why they're called science "fiction." They are not real. But why are they called "science" fiction?

The answer is that science uses a disciplined process to answer questions. In science, "disciplined" does not mean well-behaved. It means following orderly steps in order to come up with the best answers. Science involves observing, wondering, categorizing, communicating, calculating, analyzing, and much more. In order to convert creativity into reality, we need science. In order to travel beyond where anyone has gone before, we need science. In order to understand the world, make sense of it, and conserve it, we need science. In order to confirm our best guesses about the universe and the things in it, we need science. Science fiction stories extend and expand on all the ideas of science and technology in creative ways.

Asking Questions

Why is the sky blue?

How tall will this tree grow?

Why does the wind blow so hard?

Will it be cold tonight?

How many stars are out there?

Are there planets like Earth that orbit about some of those stars?

How did this rock get holes in it?

Why are some rocks sharp and jagged, while others are round?

You probably ask yourself a thousand questions a day, many of which you never ask anyone else. For many of the questions you do ask, you never even get an answer. But your brain keeps churning with questions and curiosity. We can't help but want to know.

The list of questions above are some of the same questions that scientists ask. Science has developed over centuries and centuries, and our ability to measure the tiniest trait has increased immensely. So although there is no wrong question, there are questions that lend themselves more to the scientific process than others. In other words, some questions can be investigated using the scientific method while others rely on pure faith or opinion.

Scientific Methods

The scientific method is not a list of instructions but a series of steps that help to investigate a question. By using the scientific method, we can have greater confidence in how we evaluate that question. Sometimes, the order of the steps in the scientific method can change, because more questions arise from observations or data that we collect. The basic sequence followed in the scientific method is illustrated in **Figure** 1.1.

Question

The scientific method almost always begins with a question that helps to focus the investigation. What are we studying? What do we want to know? What is the problem we want to solve? The best questions for scientific investigation are specific as opposed to general, they imply what factors may be observed or manipulated.

Example: A farmer has heard of a farming method called "no-till farming." In this method, certain techniques in planting and fertilizing eliminate the need for tilling (or plowing) the land. Will no-till farming reduce the erosion of the farmland (**Figure** 1.2)?

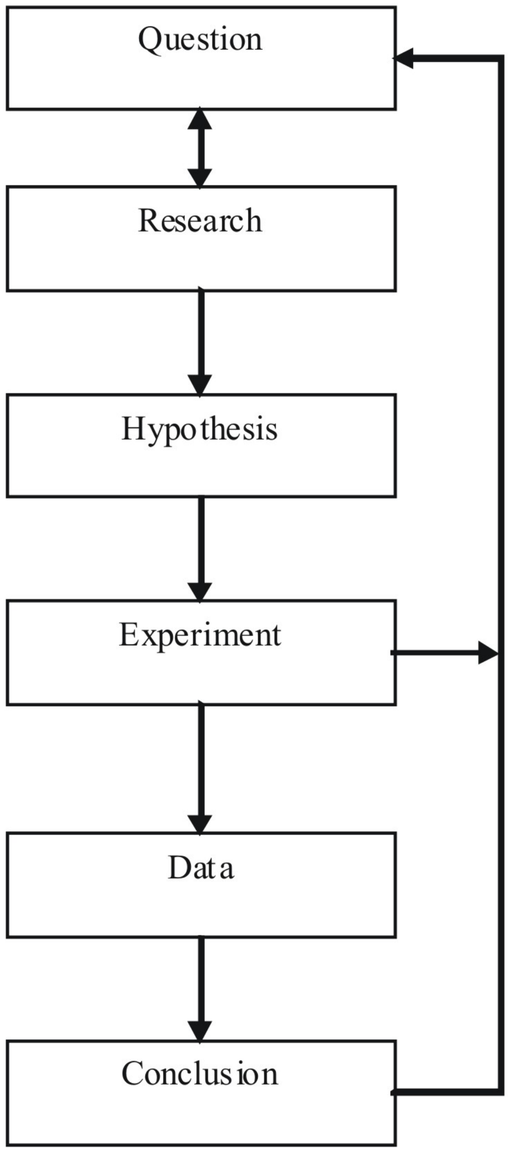

Figure 1.1: The Scientific Method. (2)

Figure 1.2: Soil Erosion (7)

Research

Before we go any further, it is important to find out what is already known about the topic. You can research a topic by looking up books and magazines in the library, searching on the Internet, and even talking to people who are experts in the area. By learning about your topic, you'll be able to make thoughtful predictions. Your experimental design might be influenced by what you have researched. Or you might even find that your question has been researched thoroughly. Although repeating experiments is valid and important in science, you may choose to introduce new ideas into your investigation, or you may change your initial question.

Example: The farmer decides to research the topic of no-till farming (**Figure** 1.3). She finds sources on the Internet, at the library, and at the local farming supply store that discuss what type of fertilizer might be used and what the best spacing for her crop would be. She even finds out that no-till farming can be a way to reduce carbon dioxide emissions into the atmosphere, which helps in the fight against global warming.

Figure 1.3: The farmer would need to research no-till farming methods. (8)

Hypothesis

Now that you have researched the topic, you can make an educated guess or explanation to the question. This is your **hypothesis.** The best hypothesis is directly related to the question and is testable, so that you can do experiments to determine whether your hypothesis is correct.

Example: The farmer has researched her question and developed the following hypothesis:

No-till farming will decrease the soil loss on hills of similar steepness as compared to the traditional farming technique because there will be less disturbance to the soil.

A hypothesis can be either proved or disproved by testing. If a hypothesis is repeatedly tested and proven to be true, then scientists will no longer call it a hypothesis.

Experiment

Not all questions can be tested by experimentation. However, many questions present us with ways to test them that give us the clearest conclusions. When we design experiments, we select the factor that will be manipulated or changed. This is the **independent variable.** We will also choose all of the factors that must remain the same. These are the experimental **controls.** Finally, we will choose the factor that we are measuring, as we change the independent variable. This is the **dependent variable.** We might say that the dependent variable "depends" on the independent variable. How much soil is eroded depends on the type of farming technique that we choose.

Figure 1.4: A farmer takes careful measurements in the field. (13)

Example: The farmer will conduct an experiment on two separate hills with similar slopes or steepnesses (**Figure** 1.4). On one hill, he will use a traditional farming technique which includes plowing to stir up the nutrients in the soil. On the other hill, he will use a no-till technique by spacing plants further apart and using specialized equipment that plants the plants without tilling. He will give both sets of plants identical amounts of water and fertilizer.

In this case, the independent variable is the farming technique—either traditional or no-till—because that is what is being manipulated. In order to be able to compare the two hills, they must have the same slope and the same amount of fertilizer and water. If one had a different slope, then it could be the angle that affects the erosion, not the farming technique, for example. These are the controls. Finally, the dependent variable is the amount of erosion because the farmer will measure the erosion to analyze its relatedness to the farming technique.

Data and Experimental Error

Data can be collected in many different ways depending on what we are interested in finding out. Scientists use electron microscopes to explore the universe of tiny objects and telescopes to venture into the universe itself. Scientists routinely travel to the bottom of the ocean in research submersibles to make observations and collect samples. Probes are used to make observations in places that are too dangerous or too impractical for scientists to venture. Probes have explored the Titanic as it lay on the bottom of the ocean and to other planets in our solar system. Data from the probes travels through cables or through space to a computer where it can be manipulated by scientists. Of course, many scientists work in a laboratory and perform experiments and analyses on a bench top.

During an experiment, we may make many measurements. These measurements are our observations that will be carefully recorded in an organized manner. This data is often computerized and kept in a spreadsheet that can be in the form of charts or tables that are clearly labeled, so that we won't forget what each number represents. "Data" refers to the list of measurements that we have collected. We may make written descriptions of our observations but often, the most useful data is numerical. Even data that is difficult to measure with a number is sometimes represented numerically. For example, we may make observations about cleanliness on a scale from one to ten, where ten is very clean and one is very dirty. Statistical analyses also allow us to make more effective use of the data by allowing us to show relationships between different categories of data. Statistics can make sense of the variability (spread) in a data set. By graphing data, we can visually understand the relationships between data. Besides graphs, data can be displayed as charts or drawings so that other people who are interested can see the relationships easily.

As in just about every human endeavor, errors are unavoidable. In an experiment, systematic errors are inherent in the experimental setup so that the numbers are always skewed in one direction or another. For example, a scale may always measure one-half ounce high. Like many systematic errors, the scale can be recalibrated or the error can be easily corrected. Random errors occur because no measurement can be made exactly precisely. For example, a stopwatch may be stopped too soon or too late. This type of error is reduced if many measurements are taken and then averaged. Sometimes a result is inconsistent with the results from other samples. If enough tests have been done, the inconsistent data point can be thrown out since likely a mistake was made in that experiment. The remaining results can be averaged.

Not all data is quantified, however. Our written descriptions are qualitative data, data that describes the situation observed. In any case, data is used to help us draw logical conclusions.

Conclusions

After you have summarized the results of the experiments and presented the data as graphs, tables and diagrams, you can try to draw a conclusion from the experiments. You must gather all your evidence and background information. Then using logic you need to try formulate an explanation for your data. What is the answer to the question based on the results of the experiment? A conclusion should include comments about the hypothesis. Was the hypothesis supported or not? Some experiments have clear, undeniable results that completely support the hypothesis. Others do not support the hypothesis. However, all experiments contribute to our wealth of knowledge. Even experiments that do not support the hypothesis may teach us new information that we can learn from. In the world of science, hypotheses are rarely proved to one hundred percent certainty. More often than not, experiments lead to even more questions and more possible ways of considering the same idea.

Example: After a full year of running her experiment, the farmer finds 2.2 times as much erosion on the traditionally farmed hill as on the no-till hill. She intends to use no-till methods of farming from now on and to continue researching other factors that may affect erosion. The farmer also notices that plants in the no-till plots are taller and the soil moisture seems higher. She decides to repeat the experiment and measure soil moisture, plant growth, and total water needed to irrigate in each kind of farming.

Theory

If a topic is of interest to scientists, many scientists will conduct experiments and make observations, which they will publish in scientific journals. Over time the evidence will mount in, for, or against the hypothesis being tested. If a hypothesis explains all the data and no data contradicts the hypothesis, the hypothesis becomes a theory. A theory is supported by many observations and there are no major inconsistencies. A theory is also used to predict behavior. Although a theory can be overthrown if conflicting data is discovered, the longer a theory has been in existence the more data it probably has to back it up and the less likely it will be proven wrong. A theory is a model of reality that is simpler than the phenomenon itself.

The common usage of the word theory is very different from the scientific usage; e.g. I have a theory as to why Joe likes Sue more than Kay. The word hypothesis would be more correct in most cases.

Scientific Models

Many scientists use models to understand and explain ideas. Models are representations of objects or systems. Simpler than the real life system, models may be manipulated and adjusted far more easily. Models can help scientists to understand, analyze and make predictions about systems that would be impossible without them.

Models are extremely useful but they have many limitations. Simple models often look at only a single characteristic and not at the myriad conditions other aspects of a system. Since the scientists who construct a model often do not entirely understand the system they are modeling, the model may not accurately represent reality. Models are very difficult to test. One way to test a model is to use as its starting point a time in the past and then have the model predict the present. A model that can successfully predict the present is more likely to be accurate when predicting the future.

Many models are created on computers because only computers can handle and manipulate such enormous amounts of data. For example, climate models are very useful for trying to determine what types of changes we can expect as the composition of the atmosphere changes. A reasonably accurate climate model would be impossible on anything other than the most powerful computers.

There are three types of models and each type is useful in certain ways.

Physical Models

Physical models are physical representations of whatever subject is being studied. These models may be simplified by leaving out certain real components, but will contain the important elements. Model cars and toy dinosaurs are examples of physical models. Drawings and maps are also physical models. They allow us to see and feel and move them, so that we can compare them to one another and illustrate certain features.

We can use a drawing to model the layers of the Earth (**Figure** 8.13). This type of model is useful in understanding the composition of the Earth, the relative temperatures within the Earth, and the changing densities of the Earth beneath the surface. Yet there are many differences between a cut-away model of the Earth and the real thing. First of all, the size is much different. It is difficult to understand the size of the Earth by looking at a simple drawing. You can't get a good idea of the movement of substances beneath the surface by looking at a drawing that does not move. The model is very useful but has its shortcomings.

Conceptual Models

A conceptual model is not a physical model, but rather a mental explanation that ties together many ideas to attempt to explain something. A conceptual model tries to combine

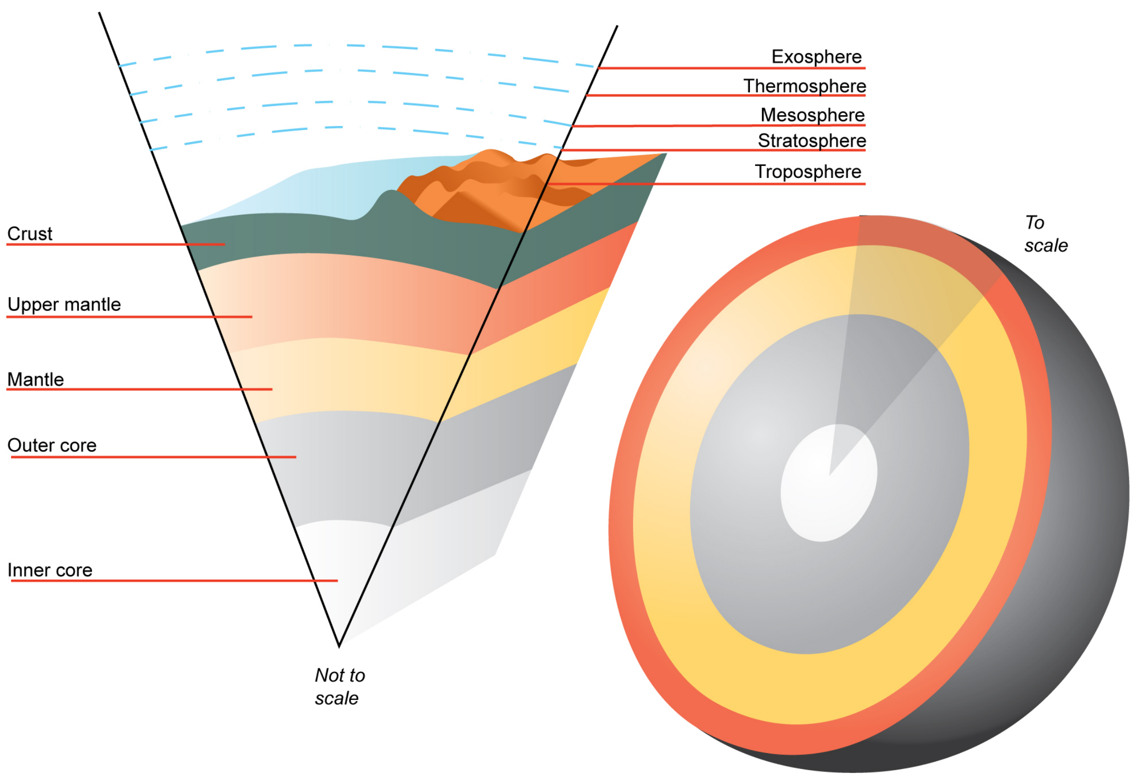

Figure 1.5: The Earth's Center. (9)

knowledge and must incorporate new knowledge that may change it as knowledge is acquired. The origin of the moon, for example, is explained by some as a Mars sized planet that hit the Earth and formed a great cloud of debris and gas (Figure 1.6). This debris and gas eventually formed a single spherical body called the Moon. This is a useful model of an event that probably occurred billions of years ago. It incorporates many ideas about the craters and volcanoes on the Moon, and the similarity of some elements on both the moon and the Earth. Not all data may fit this model, however, and there may be much information that we simply don't know. Some people think that the Moon was initially an asteroid out in space which was captured in orbit by the gravity of the Earth. This may be a competing conceptual model which has its own arguments and weaknesses. As with physical models, all conceptual models have limitations.

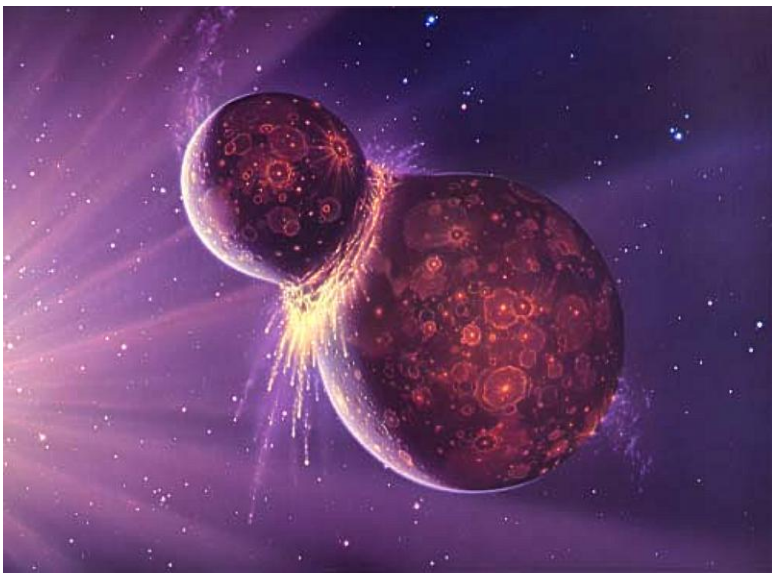

Figure 1.6: A collision showing a meteor striking the Earth. (14)

Mathematical Models

A third type of model is the mathematical model. These models are created through a great deal of consideration and analysis of data. A mathematical model is an equation or formula that takes many factors or variables into account. These models may help predict complex events like tornadoes and climate change. In order to predict climate change, for example, a mathematical model may take into account factors such as temperature readings, ice density, snow fall, and humidity. These data may be plugged into equations to give a prediction. As with other models, not all factors can be accounted for, so that the mathematical model may not work perfectly. This may yield false alarms or prediction failures. No model is without its limitations.

Models are a useful tool in science. They allow us to efficiently demonstrate ideas and create hypotheses. They give us visual or conceptual manners for thinking about things. They allow us to make predictions and conduct experiments without all of the difficulties of real-life objects. Could you imagine trying to explain a plant cell by only using a real plant cell or trying to predict the next alignment of planets by only looking at them? In general, models have limitations that should be taken into consideration before any prediction is believed or any conclusion seen as fact.

Safety in Science

Accidents happen from time to time in everyday life. Since science involves an adventure into the unknown, it is natural that accidents can happen. Therefore, we must be careful and use proper equipment to prevent as many accidents as possible (**Figure** 1.7). We must also be sure to treat any injury or accident appropriately.

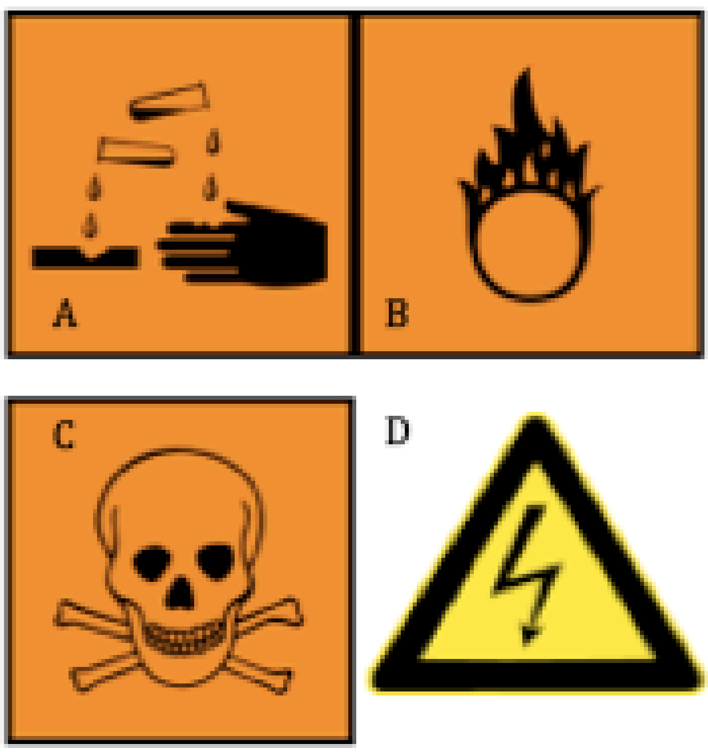

Figure 1.7: Safety Symbols: A. Corrosive , B. Oxidizing Agent, C. Toxic, D. High Voltage. (12)

Inside the Science Laboratory

If you work in the science lab, you may come across dangerous materials or situations. Sharp objects, chemicals, heat, and electricity are all used at times in earth science laboratories. With proper protection and precautions, almost all accidents can be prevented and suffering minimized (**Figure** 1.8). Below is a list of safety guidelines that you should follow when doing labs:

- Follow directions at all times.
- Although working in the science lab can be fun, it is not a play area. Be sure to obey any safety guidelines given in lab instructions or by the lab supervisor.
- Use only the quantities of materials directed. Check with your teacher before you do something different than what's described on the lab procedure.
- Tie back long hair. Wear closed shoes with flat heels and shirts with no hanging sleeves, hoods, or drawstrings.
- Use gloves, goggles, or safety aprons when instructed to do so.
- Use extreme care with any sharp or pointed objects like scalpels, knives, or broken glass.
- Never eat or drink anything in the science lab, even if you brought it there yourself. Table tops and counters could have dangerous substances on them.
- Keep your work area neat and clean. Be sure to properly clean and maintain materials like test tubes and beakers. Leftover substances could interact with other substances in future experiments. A messy work area leaves more opportunities for spills and breakage.
- Be careful when you reach. Flames or heat plates could be beneath your arms or long hair could get burned.
- Use electrical appliances and burners as instructed.
- Know how to use an eye wash station, fire blanket, fire extinguisher, or first aid kit.
- Alert the lab supervisor in the case that anything out of the ordinary occurs. An accident report may be required if someone is hurt and the lab supervisor must know if any materials are damaged or discarded.

Outside the Laboratory

Many earth science investigations are conducted outside of the science laboratory (**Figure** 1.9). Of course, the same precautions must be taken with lab-like materials but we must take additional considerations into mind. For any scientific endeavor outside or at home:

- Be sure to wear appropriate clothing. Hiking into a canyon requires boots, long pants, and protection from the sun, for example.

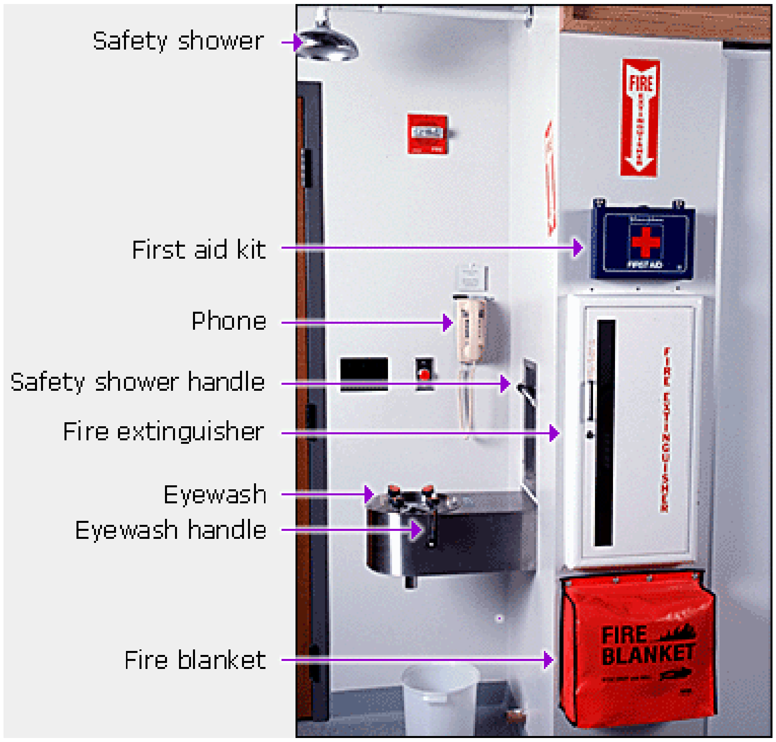

Figure 1.8: Safety Equipment in the Laboratory. (6)

- Bring sufficient supplies like food and water, even for a short trip. Dehydration can occur rapidly.
- Have appropriate first aid available.
- Be sure to let others know where you are going, what you will be doing, and when you will be returning. Be sure to take a map with you if you don't know the area and you may leave a copy of the map with someone at home.
- Be sure you have access to emergency services and some way to communicate. Keep in mind that not all places have coverage for cellular phones.
- Finally, be sure that you are accompanied by a person familiar with the area to which you are traveling or familiar with the type of investigation that you are going to do.

Review Questions

1. Write a list of five questions about the world around you that you find interesting.
2. A scientist was studying the effects of oil contamination on ocean seaweed. He believed that oil runoff from storm drains would keep seaweed from growing normally. He had two large aquarium tanks of equal size. He monitored the dissolved oxygen in the water to keep it equal as well as the water's temperature. He introduced some motor oil into one tank but not in the other. He then measured the growth of seaweed plants in each

Figure 1.9: Outdoor Excursions. (15)

tank. In the tank with no oil, the average growth was 2.57cm. The average growth of the seaweed in the tank with oil was 2.37cm. Based on this experiment, answer the following questions:

(a) What was the question that the scientist started with?
(b) What was his hypothesis?
(c) Identify the independent variable, the dependent variable, and the experimental control(s).
(d) What did the data show?

3. Explain three types of scientific models. What is one benefit of each and one disadvantage of each?
4. Identify or design five of your own safety symbols, based on your knowledge of safety procedures in a science laboratory.
5. Design your own experiment based on one of your questions from question 1 above. Include the question, hypothesis, independent and dependent variables, and safety precautions. You may want to work with your teacher or a group.

Vocabulary

conceptual model An abstract, mental representation of something using thoughts and ideas instead of physical objects.

control Factors that are kept the same in an experiment, in order to focus just on the independent and dependent variables.

dependent variable The variable in an experiment that you are measuring as you change the independent variable. It "depends" on the independent variable.

hypothesis A good working explanation for a problem that can be tested.

independent variable The variable (or thing) in an experiment that is controlled and changed by the researcher.

mathematical model A set of mathematical equations and numbers that simulates a natural system being modeled.

physical model A representation of something using objects.

theory A hypothesis that has been repeatedly tested and proven to be true.

Points to Consider

- What parts of the Earth do you think are most important and should be better studied?
- What type of model have you had experience with? What did you learn from it?
- What situations are both necessary and dangerous for scientists to study? What precautions do you think they should use when they study them?
- If you could go anywhere, where would it be? What safety equipment or precautions would you take?

1.2 Earth Science and Its Branches

Lesson Objectives

- Define and describe Earth Science as a general field with many branches.
- Identify the field of geology as a branch of Earth Science that deals with the solid part of the Earth.

- Describe the field of oceanography as a branch of Earth Science that has several subdivisions that deal with the various aspects of the ocean.
- Define the field of meteorology as a branch of Earth Science that deals with the atmosphere.
- Understand that astronomy is an extension of Earth Science that examines other parts of the solar system and universe.
- List some of the other branches of Earth Science, and how they relate to the study of the Earth.

Overview of Earth Science

Earth is the mighty planet upon which we all live. Only recently have humans begun to understand the complexity of this planet. In fact, it was only a few hundred years ago that we discovered that Earth was just a tiny part of an enormous galaxy, which in turn is a small part of an even greater universe. Earth Science deals with any and all aspects of the Earth. Our Earth has molten lava, icy mountain peaks, steep canyons and towering waterfalls. Earth scientists study the atmosphere high above us as well as the planet's core far beneath us. Earth scientists study parts of the Earth as big as continents and as small as the tiniest atom. In all its wonder, Earth scientists seek to understand the beautiful sphere on which we thrive (**Figure** 1.10).

Because the Earth is so large and science is so complex, Earth scientists specialize in studying just a small aspect of our Earth. Since all of the branches are connected together, specialists work together to answer complicated questions. Let's look at some important branches of Earth Science.

Geology

Geology is the study of the solid matter that makes up Earth. Anything that is solid, like rocks, minerals, mountains, and canyons is part of geology. Geologists study the way that these objects formed, their composition, how they interact with one another, how they erode, and how humans can use them. Geology has so many branches that most geologists become specialists in one area. For example, a mineralogist studies the composition and structure of minerals such as halite (rock salt), quartz, calcite, and magnetite (**Figure** 1.11).

A volcanologist braves the high temperatures and molten lava of volcanoes. Seismologists study earthquakes and the forces of the Earth that create them. Seismologists monitor earthquakes worldwide to help protect people and property from harm (**Figure** 1.12). Scientists interested in fossils are paleontologists, while scientists who compare other planets' geologies to that of the Earth are called planetary geologists. There are geologists who only study the Moon. Some geologists look for petroleum, others are specialists on soil. Geochronologists study how old rocks are and determine how different rock layers formed. There are so many

Figure 1.10: Earth as seen from Apollo 17. (5)

Figure 1.11: Mineralogists focus on all kinds of minerals. (16)

Figure 1.12: Seismographs are used to measure earthquakes and pinpoint their origins. (19)

specialties in geology that there is probably an expert in almost anything you can think of related to the Earth (**Figure** 1.13).

Figure 1.13: Geology is the study of the solid Earth and its processes. (10)

Oceanology

Oceanology is the study of everything in the ocean environment. More than 70% of the Earth's surface is covered with water. Most of that water is found in the oceans. Recent technology has allowed us to go to the deepest parts of the ocean, yet much of the ocean remains truly unexplored. Some people call the ocean the last frontier. But it is a frontier already deeply influence by human activity. As the human population gets ever bigger, we are affecting the ocean in many ways. Populations of fish and other marine species have plummeted because of overfishing; contaminants are polluting the waters, and global warming caused by greenhouse gases is melting the thick ice caps. As ocean waters warm, the water expands and, along with the melting ice caps, causes sea levels to rise.

Climatologists help us understand the climate and how it will change in the future in response to global warming. Oceanographers study the vast seas and help us to understand all that happens in the water world. As with geology, there are many branches of oceanography. Physical oceanography is the study of the processes in the ocean itself, like waves and ocean currents (**Figure** 1.14). Marine geology uses geology to study ocean earthquakes, mountains, and trenches. Chemical oceanography studies the natural elements in ocean water and pollutants.

Figure 1.14: Physical oceanography studies things like currents and waves. (17)

Climatology and Meteorology

Meteorologists don't study meteors — they study the atmosphere! Perhaps this branch of Earth Science is strangely named but it is very important to living creatures like humans. **Meteorology** includes the study of weather patterns, clouds, hurricanes, and tornadoes. Using modern technology like radars and satellites, meteorologists work to predict or forecast the weather. Because of more accurate forecasting techniques, meteorologists can help us to prepare for major storms, as well as help us know when we should go on picnics.

Climatologists and other atmospheric scientists study the whole atmosphere, which is a thin layer of gas that surrounds the Earth. Most of it is within about 10 - 11 kilometers of the Earth's surface. Earth's atmosphere is denser than Mars's thin atmosphere, where the average temperature is -63°C, and not as thick as the dense atmosphere on Venus, where carbon dioxide in the atmosphere makes it hot and sulfuric acid rains in the upper atmosphere. The atmosphere on Earth is just dense enough to even out differences in temperature from the equator to the poles, and contains enough oxygen for animals to breathe.

Over the last several decades, climatologists studying the gases in our atmosphere have found that humans are putting a dangerous amount of carbon dioxide into the air by burning fossil fuels (**Figure** 1.15). Normally, the atmosphere contains only small amounts of carbon dioxide, and too much of it makes it trap heat from the sun, causing the Earth to heat up, an effect we call global warming. Climatologists can help us better understand the climate and how it may change in the future in response to different amounts of greenhouse gases and other factors (**Figure** 1.16).

Figure 1.15: Carbon dioxide released into the atmosphere is causing global warming. (3)

Figure 1.16: When hurricanes are accurately forecast by meteorologists, many lives can be saved. (4)

Astronomy

Astronomers have proven that our Earth and solar system are not the only set of planets in the universe. By 2007, over a hundred planets outside our solar system had been discovered. Although no one can be sure how many there are, astronomers estimate that there are billions of other planets. In addition, the universe contains black holes, other galaxies, asteroids, comets, and nebula. As big as Earth seems to us, the entire universe is vastly greater. Our Earth is an infinitesimally small part of our universe.

Astronomers use resources on the Earth to study physical things beyond the Earth. They use a variety of instruments like optical telescopes and radio telescopes to see things far beyond what the human eye can see. Spacecraft travel great distances in space to send us information on faraway places, while telescopes in orbit observe astronomical bodies from the darkness of space (**Figure** 1.17).

Figure 1.17: The Hubble Space Telescope. (1)

Astronomers ask a wide variety of questions. Astronomers could study how an object or energy outside of Earth could affect us. An impact from an asteroid could have terrible effects for life on Earth. Strong bursts of energy from the sun, called solar flares, can knock out a power grid or disturb radio, television or cell phone communications. But astronomers ask bigger questions too. How was the universe created? Are there other planets on which we might live? Are there resources that we could use? Is there other life out there? Astronomy also relies on Earth Science, when scientists compare what we know about life on Earth to the chances of finding life beyond this planet.

Other Branches of Earth Science

Geology, oceanography, and meteorology represent a large part of Earth science, while astronomy represents science beyond Earth. However, there are still many smaller branches of science that deal with the Earth or interact greatly with Earth sciences. Most branches of science are connected with other branches of science in some way or another. A biologist who studies monkeys in rainforests must be concerned with the water cycle that brings the rain to the rainforests. She must understand the organic chemistry of the food the monkeys eat, as well as the behavior between the monkeys. She might examine the soil in which the trees of the rainforest grow. She must even understand the economy of the rainforest to understand reasons for its destruction. This is just one example of how all branches of science are connected.

Below are examples of a few branches of science that are directly related to Earth science. Environmental scientists study the ways that humans interact with the Earth and the effects of that interaction. We hope to find better ways of sustaining the environment. Biogeography is a branch of science that investigates changes in populations of organisms in relation to place over time. These scientists attempt to explain the causes of species' movement in history. Ecologists focus on ecosystems, the complex relationship of all life forms and the environment in a given place (**Figure** 1.18). They try to predict the chain reactions that could occur when one part of the ecosystem is disrupted.

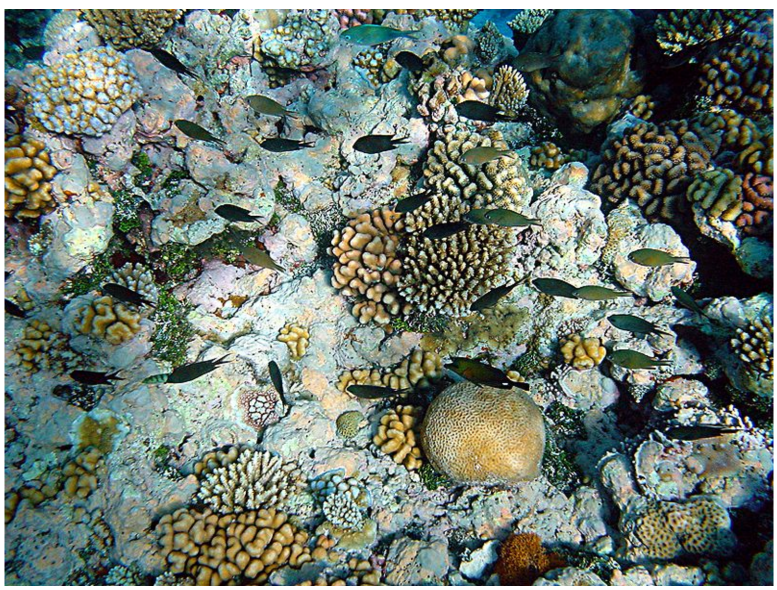

Figure 1.18: In a marine ecosystem, coral, fish, and other sea life depend on each other for survival. (11)

As opposed to an oceanographer, a limnologist studies inland waters like rivers and lakes. A hydrogeologist focuses on underground water found between soil and rock particles, while glaciologists study glaciers and ice.

None of these scientific endeavors would be possible without geographers who explore the features of the surface and work with cartographers, who make maps. Stratigraphy is another area of Earth science which examines layers of rock beneath the surface (**Figure** 1.19). This helps us to understand the geological history of the Earth. There is a branch of science for every interest and each is related to the others.

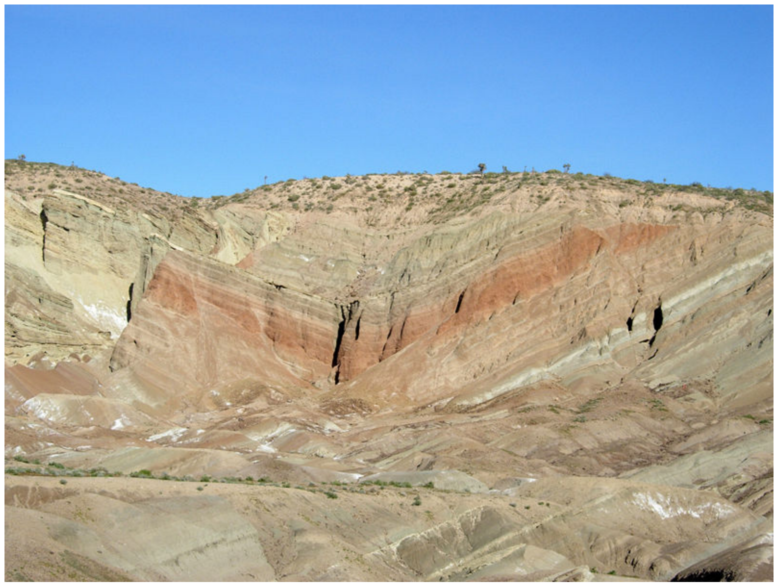

Figure 1.19: Folded strata are layers in the rock that have bent over time. Stratigraphy attempts to explain these layers and the geologic history of the area. (18)

Review Questions

1. What are three major branches of Earth science?
2. What branch of science deals with stars & galaxies beyond the Earth?
3. List important functions of Earth scientists.
4. What do you think is the focus of a meteorologist?
5. A meteorologist studies the atmosphere. This includes weather and climate changes as well as global warming
6. An ecologist notices that an important coral reef is dying off. She believes that it has to do with some pollution from a local electric plant. What type of scientist might help her analyze the water for contamination?
7. Design an experiment that you could conduct in any branch of Earth science. Identify the independent variable and dependent variable. What safety precautions would you have to take?

Vocabulary

astronomers Scientists who study the universe, galaxies and stars.

geology The study of the rocks, processes and history of Earth.

meteorology Study of the atmosphere, weather and storms.

oceanology Study of the ocean realm in all its aspects.

Points to Consider

- Why is Earth science so important?
- Which branch of Earth science would you most like to explore?
- What is the biggest problem that we face today? Which Earth scientists may help us to solve the problem?
- What other branches of science or society are related to and necessary for Earth science?

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Chapter 2

Studying Earth's Surface

2.1 Introduction to Earth's Surface

Lesson Objectives

- Distinguish between location and direction.
- Describe topography.
- Identify various landforms and briefly describe how they came about.

Location

Wherever you are on Earth's surface, in order to describe your location, you need some point of reference. Right now you are probably reading this chapter at your computer. But where is your computer? It may set up in a certain place or you may be on a laptop computer, which means you can change where you are. In order to describe your location, you could name other items around you to give a more exact position of your computer. Or you could measure the distance and direction that you are from a reference point. For example, you may be sitting in a chair that is one meter to the right of the door. This statement provides more precise information for someone to locate your position within the room.

Similarly, when studying the Earth's surface, Earth scientists must be able to pinpoint any feature that they observe and be able to tell other scientists where this feature is on the Earth's surface. Earth scientists have a system to describe the location of any feature. To describe your location to a friend when you are trying to get together, you could do what we did with describing the location of the computer in the room. You would give her a reference point, a distance from the reference point, and a direction, such as, "I am at the corner of Maple Street and Main Street, about two blocks north of your apartment." Another way is to locate the feature on a coordinate system, using latitude and longitude. Lines of latitude and longitude form a grid that measures distance from a reference point. You will learn about this type of grid when we discuss maps later in this chapter.

Direction

If you are at a laptop, you can change your location. When an object is moving, it is not enough to describe its location; we also need to know direction. Direction is important for describing moving objects. For example, a wind blows a storm over your school. Where is that storm coming from? Where is it going? The most common way to describe direction in relation to the Earth's surface is by using a **compass**. The compass is a device with a floating needle that is a small magnet (**Figure** 2.1). The needle aligns itself with the Earth's magnetic field, so that the compass needle points to magnetic north. Once you find north, you can then describe any other direction, such as east, south, west, etc., on a **compass rose** (**Figure** 2.2).

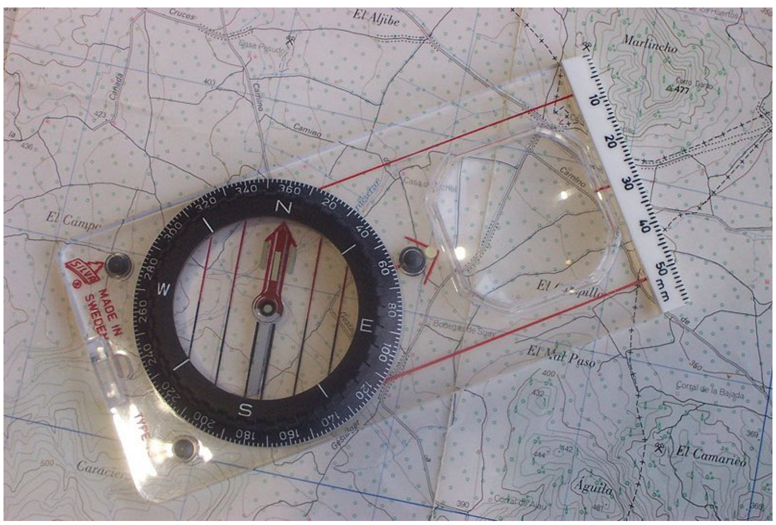


Figure 2.1: A compass is a device that is used to determine direction. The needle points to the Earth's magnetic north pole. (41)

A compass needle aligns to the Earth's magnetic North Pole, not the Earth's geographic North Pole or true north. The geographic North Pole is the top of the imaginary axis upon which the Earth's rotates, much like the spindle of a spinning top. The magnetic North Pole shifts in location over time. Depending on where you live, you can correct for this difference when you use a map and a compass (**Figure** 2.3).

When you study maps later, you will see that certain types of maps have a double compass rose to make the corrections between magnetic north and true north. An example of this type is a nautical chart that sailors and boaters use to chart their positions at sea or offshore (**Figure** 2.4).

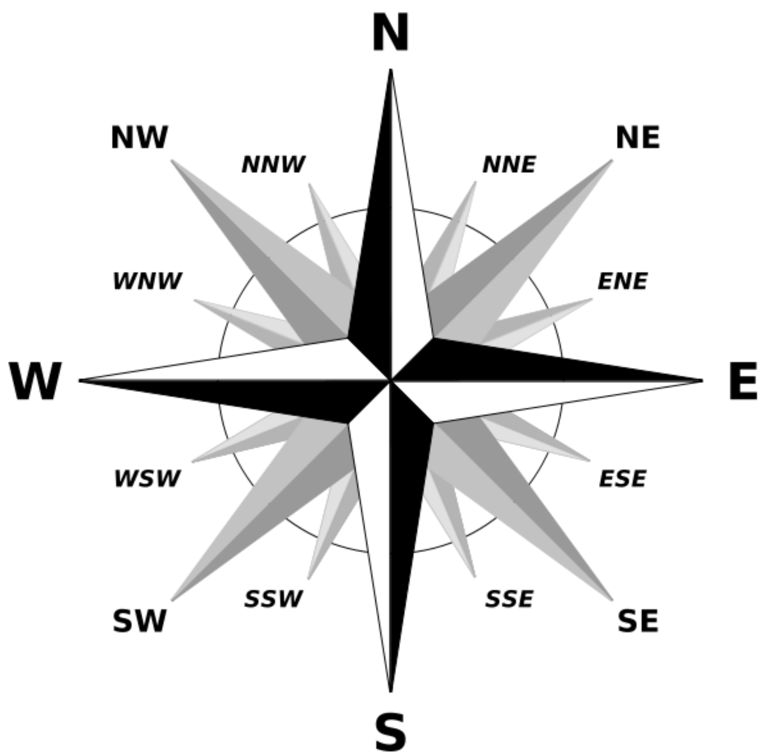


Figure 2.2: A compass rose shows the various directions, such as North (N), East (E), South (S), West (W) and various combinations. (7)

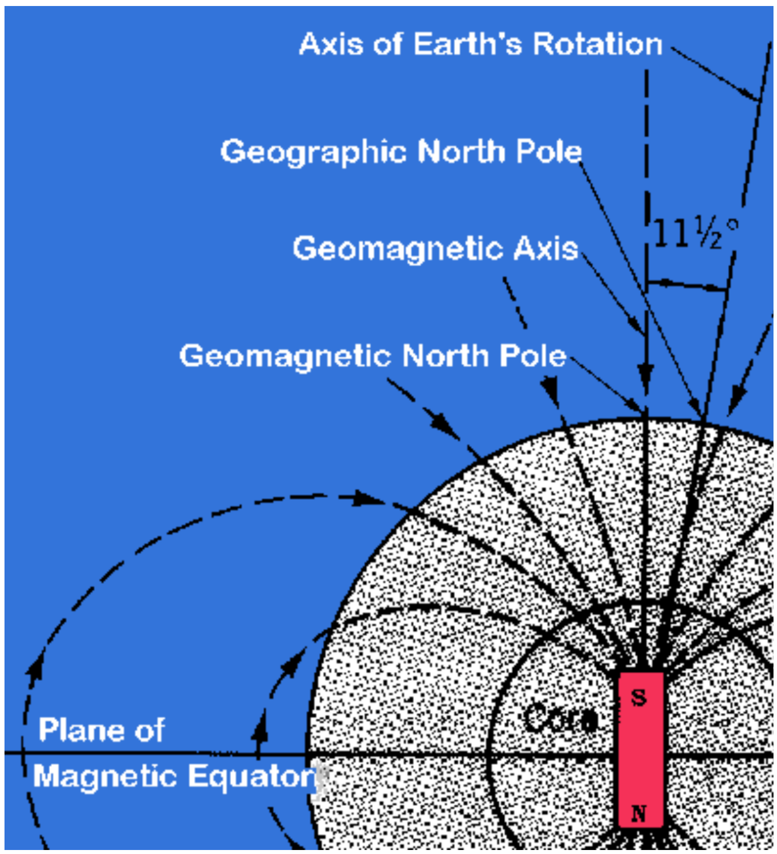


Figure 2.3: Earth's magnetic north pole is about 11 degrees offset from its geographic north pole on the axis of rotation. (5)

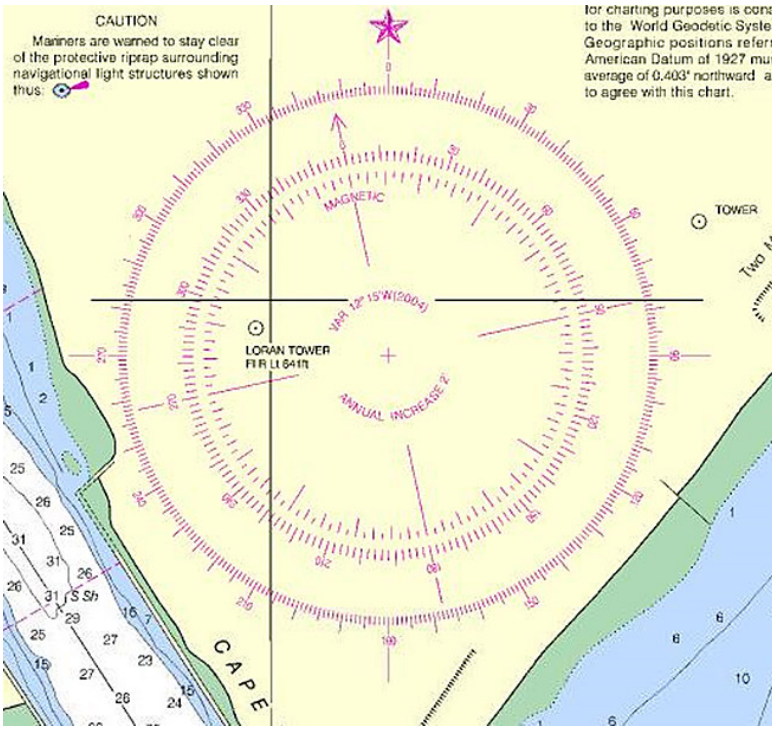


Figure 2.4: Nautical maps include a double compass rose that shows both magnetic directions (inner circle) and geographic compass directions (outer circle). (37)

Topography

As you know, the surface of the Earth is not flat. Some places are high and some places are low. For example, mountain ranges like the Sierra Nevada in California or the Andes mountains in South America are high above the surrounding areas. We can describe the **topography** of a region by measuring the height or depth of that feature relative to sea level (**Figure** 2.5). You might measure your height relative to your best friend or classmate. When your class lines up, some kids make high "mountains" and others are more like small hills!

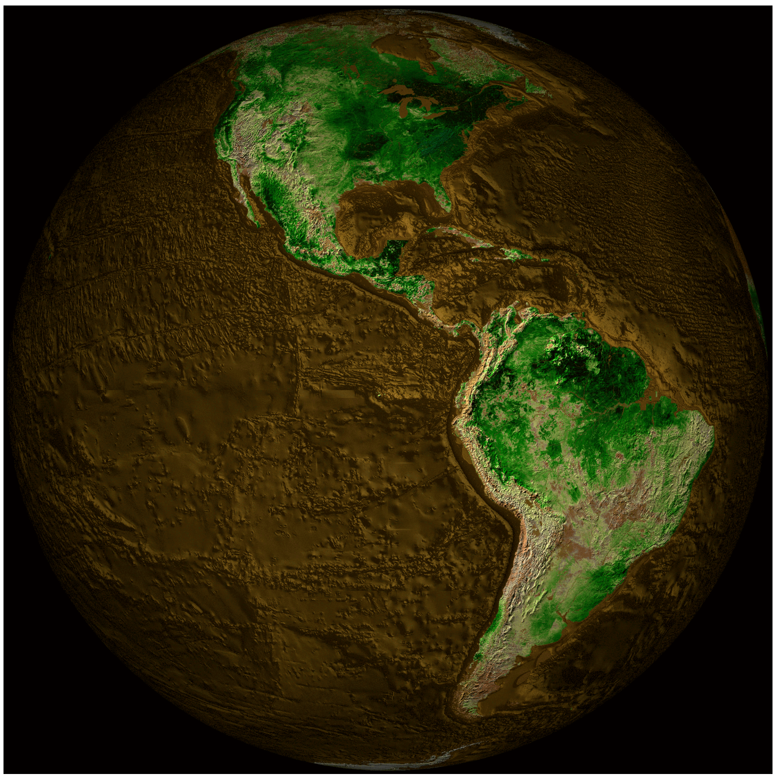


Figure 2.5: Topographical map of the Earth showing North America and South America. (1)

What scientists call **relief** or terrain includes all the major features or landforms of a region. A topographic map of an area shows the differences in height or **elevation** for mountains, craters, valleys, and rivers. For example, **Figure** 2.6 shows the San Francisco Mountain area in northern Arizona as well as some nearby lava flows and craters. We will talk about some different landforms in the next section.

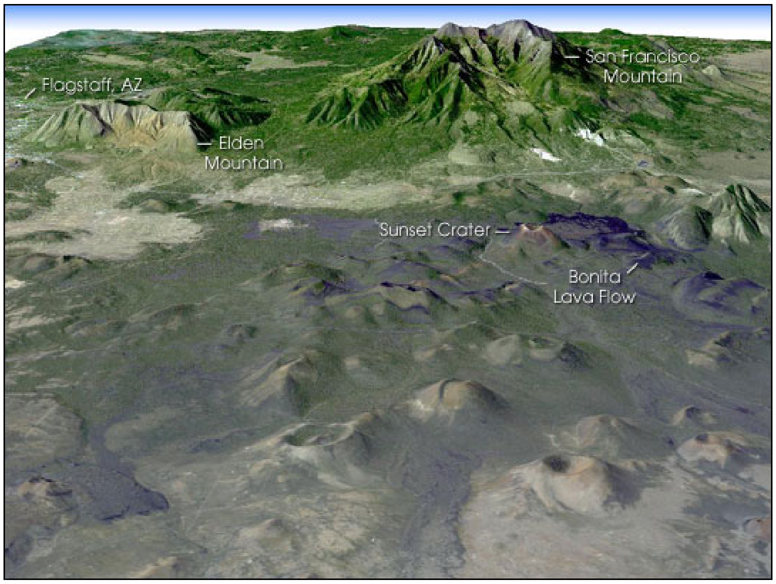


Figure 2.6: This image was made from data of the Landsat satellite and shows the topography of the San Francisco Mountain and surrounding areas in northern Arizona. You can see the differences in elevation of the mountain and surrounding lava flows. (25)

Landforms

If you look at the Earth's surface and take away the water in the oceans (**Figure** 2.7), you will see that the surface has two distinctive features, continents and the ocean basins. The **continents** are large land areas extending from high elevations to sea level. The **ocean basins** extend from the edges of the continents down steep slopes to the ocean floor and into deep trenches.

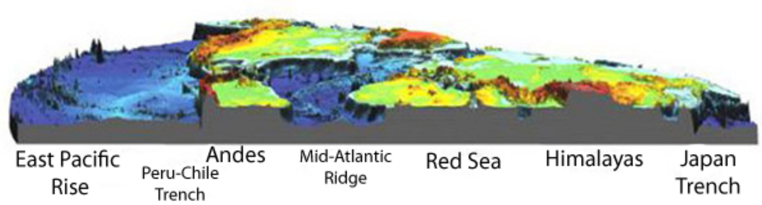


Figure 2.7: This image shows examples of some of the main features found on the ocean floor, as well as their above-water continuations. The red areas are high elevations (mountains). Yellow and green areas are lower elevations and blue areas are the lowest on the ocean floor. (i.e., the image below is a slice through a relief map of world. (32)

Both the continents and the ocean floor have many features with different elevations. Some areas of the continents are high. These are the mountains we have already talked about.

Even on the ocean floor there are mountains! Let's discuss each.

Continents

Continents are relatively old (billions of years) compared to the ocean basins (millions of years). Because the continents have been around for billions of years, a lot has happened to them! As continents move over the Earth's surface, mountains are formed when continents collide. Once a mountain has formed, it gradually wears down by weathering and erosion. Every continent has mountain ranges with high elevations (**Figure** 2.8). Some mountains formed a very long time ago and others are still forming today:

- *Young mountains* (< 100 million years) – Mountains of the Western United States (Rocky Mountains, Sierra Nevada, Cascades), Mountains around the edge of the Pacific Ocean, Andes Mountains (South America), Alps (Europe), Himalayan Mountains (Asia)
- *Old mountains* (> 100 million years) – Appalachian Mountains (Eastern United States), Ural Mountains (Russia).

Mountains can be formed when the Earth's crust pushes up, as two continents collide, like the Appalachian Mountains in the eastern United States and the Himalayas in Asia. Mountains can also be formed by a long chain of volcanoes at the edge of a continent, like the Andes Mountains in South America.

Figure 2.8: Features of continents include mountain ranges, plateaus, and plains. (27)

Over millions of years, mountains are worn down by rivers and streams to form high flat areas called **plateaus** or lower lying **plains**. Interior plains are in the middle of continents while coastal plains are on the edge of a continent, where it meets the ocean.

Figure 2.9: Summary of major landforms on continents and features of coastlines. (11)

As rivers and streams flow across continents, they cut away at rock, forming **river valleys** (**Figure** 2.9). The bits and pieces of rock carried by rivers are deposited where rivers meet the oceans. These can form **deltas**, like the Mississippi River delta and **barrier islands**, like Padre Island in Texas. Our rivers bring sand to the shore which forms our **beaches**.

Ocean Basins

The ocean basins begin where the ocean meets the land. The names for the parts of the ocean nearest to the shore still have the word "continental" attached to them because the continents form the edge of the ocean. The **continental margin** is the part of the ocean basin that begins at the coastline and goes down to the ocean floor. It starts with the **continental shelf**, which is a part of the continent that is underwater today. The continental shelf usually goes out about 100 – 200 kilometers and is about 100-200 meters deep, which is a very shallow area of the ocean (**Figure** 2.10).

From the edge of the continental shelf, the **continental slope** is the hill that forms the edge of the continent. As we travel down the continental slope, before we get all the way to the ocean floor, there is often a large pile of sediments brought from rivers, which forms the **continental rise**. The continental rise ends at the ocean floor, which is called the **abyssal plain**.

The ocean floor itself is not totally flat. Small hills rise above the thick layers of mud that cover the ocean floor. In many areas, small undersea volcanoes, called **seamounts** (**Figure** 2.11) rise more than 1000 m above the seafloor. Besides seamounts, there are long, very tall (about 2 km) mountain ranges that form along the middle parts of all the oceans. They are connected in huge ridge systems called **mid-ocean ridges** (**Figure** 2.12). The mid-ocean ridges are formed from volcanic eruptions, when molten rock from inside the Earth breaks through the crust, flows out as lava and forms the mountains.

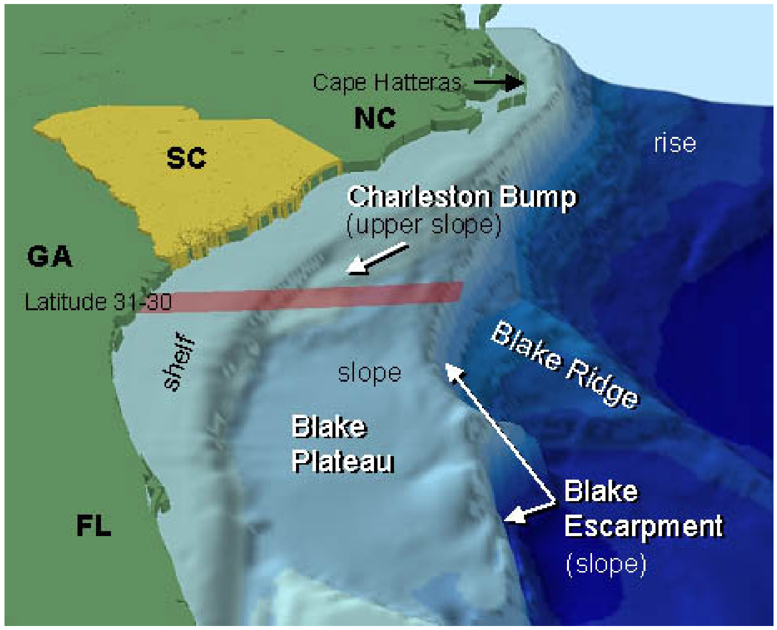


Figure 2.10: Diagram of the continental shelf and slope of the southeastern United States leading down to the ocean floor. (12)

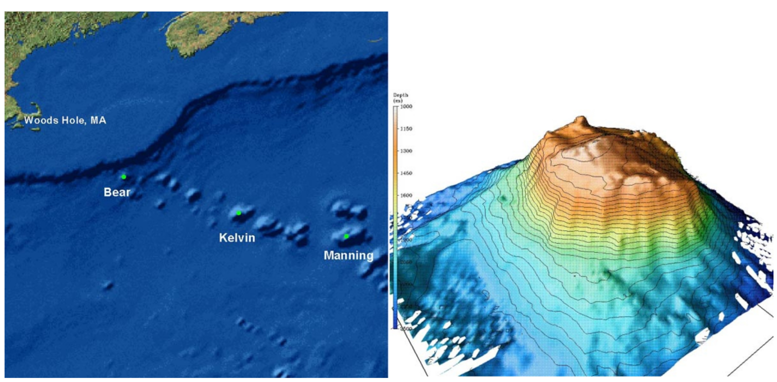


Figure 2.11: A chain of seamounts is located off the coast of New England (left) and oceanographers mapped one of these seamounts called Bear Seamount in great detail (right). (16)

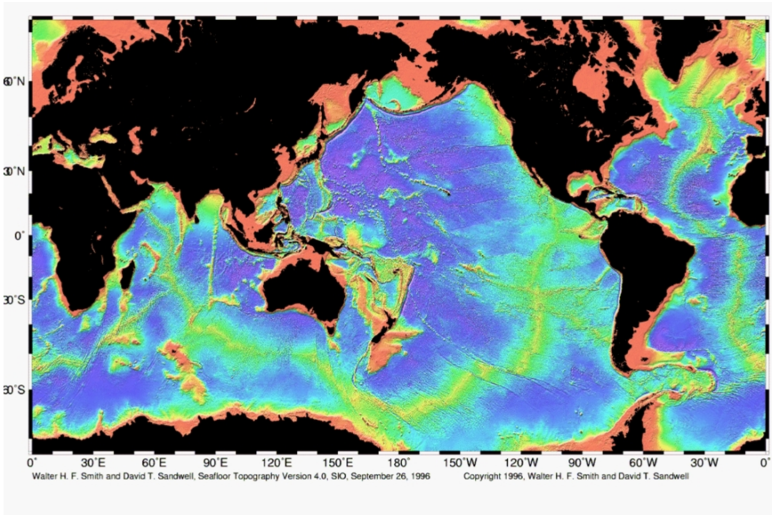


Figure 2.12: Map of the mid-ocean ridge system (yellow-green) in the Earth's oceans. (23)

The deepest places of the ocean are the **ocean trenches**. There are many trenches in the world's oceans, especially around the edge of the Pacific Ocean. The Mariana Trench, which is located east of Guam in the Pacific Ocean, is the deepest place in the ocean, about 11 kilometers deep (**Figure** 2.13). To compare the deepest place in the ocean with the highest place on land, Mount Everest is less than 9 kilometers tall. In these trenches, the ocean floor sinks deep inside the Earth. The ocean floor gets constantly recycled. New ocean floor is made at the mid-ocean ridges and older parts are destroyed at the trenches. This recycling is why the ocean basins are so much younger than the continents.

The Earth's surface is constantly changing over long periods of time. For example, new mountains get formed by volcanic activity or uplift of the crust. Existing mountains and continental landforms get worn away by erosion. Rivers and streams cut into the continents and create valleys, plains, and deltas. Underneath the oceans, new crust forms at the mid-ocean ridges, while old crust gets destroyed at the trenches. Wave activity erodes the tops of some seamounts and volcanic activity creates new ones. You will explore the ways that the Earth's surface changes as you proceed through this book.

Lesson Summary

- Earth scientists must be able to describe the exact positions or locations of features on the Earth's surface.
- Positions often include distances and directions. To determine direction, you can use a compass, which has a tiny magnetic needle that points toward the Earth's magnetic North Pole. Once you have found north, you can find east, west and south, using your compass for reference.

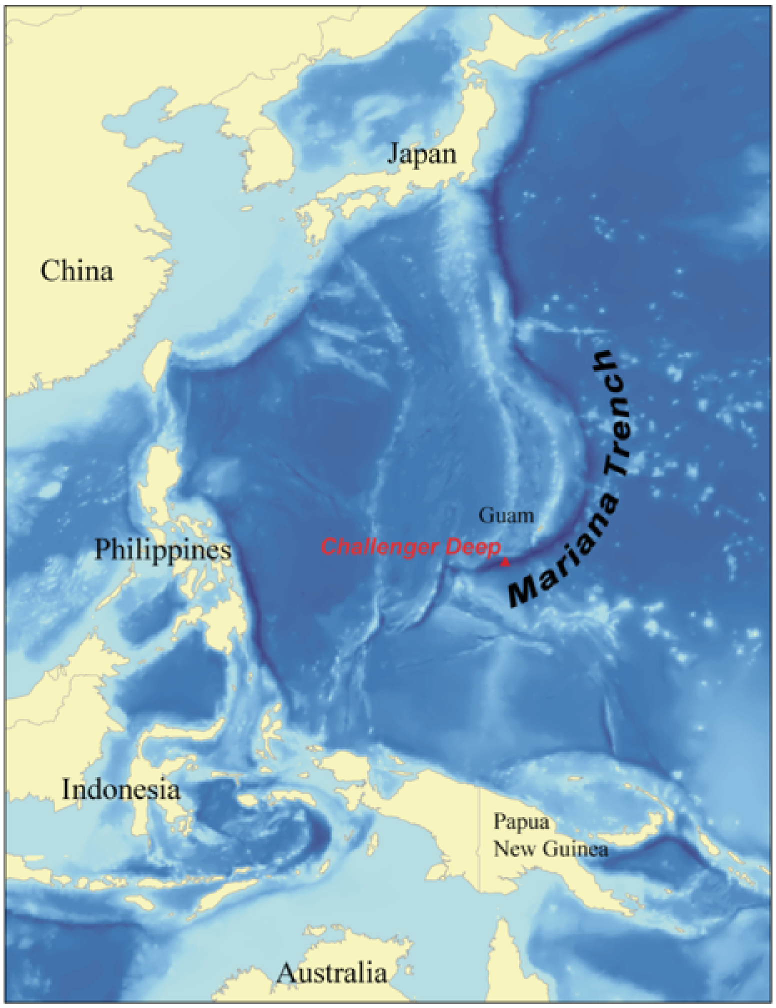


Figure 2.13: This map shows the location of the Mariana Trench in the Pacific Ocean. (26)

- Topography describes how the Earth's surface varies in elevation. Mountains form the highest areas. Valleys and trenches form the lowest areas. Both continents and ocean basins have mountains and mountain ranges. They each also have plateaus, plains, and valleys or trenches.
- Mountains form as continents collide and as volcanoes erupt. Mountains are worn away by wind and water. The earth's surface is constantly changing due to these creative and destructive processes.

Review Questions

1. What information might you need to describe the location of a feature on the Earth's surface?
2. Why would you need to know direction if an object is moving?
3. Explain how new ocean floor is created and also how ocean crust is destroyed. Why are the ocean basins younger than the continents?
4. Why do nautical charts have two compass roses on them
5. What landforms are the highest on the continents?
6. Explain what landforms on the continents are created by erosion from wind and water. How does erosion create a landform?
7. What is topography?

Further Reading/Supplemental Links

- http://www.cerritos.edu/earth-science/tutor/landform_identification.htm
- http://www.enotes.com/earth-science/landforms
- http://oceanexplorer.noaa.gov/explorations/04etta/welcome

Vocabulary

abyssal plain The very flat, deep ocean floor.

barrier island A long, narrow island parallel to the shore.

beaches Areas along the shore where sand or gravel accumulates.

compass Hand-held device with a magnetic needle used to find magnetic north.

compass rose Figure on a map or nautical chart for displaying locations of north, south, east and west.

continent Land mass above sea level.

continental margin Submerged, outer edge of the continent.

continental rise Gently sloping accumulation of sediments that forms where the continental slope meets the ocean floor.

continental shelf Very gently sloping portion of the continent covered by the ocean.

continental slope Sloping, underwater edge of the continent.

delta Often triangular shaped deposit of sediment at the mouth of a river.

elevation Height of a feature measured relative to sea level.

mid-ocean ridge A large, continuous mountain range found in the middle of an ocean basin; marks a divergent plate boundary.

ocean basins Areas covered by ocean water.

plains Low lying continental areas, can be inland or coastal.

plateaus Flat lying, level elevated areas.

relief Difference in height of landforms in a region.

river valleys Areas formed as water erodes the landscape, often 'V' shaped.

seamount Underwater, volcanic mountain more than 1000 meters tall.

topography Changes in elevation for a given region.

Points to Consider

- A volcano creates a new landform in Mexico. As the earth scientist assigned to study this feature, explain how you would describe its position in a report or scientific communication?
- Suppose you wanted to draw a map to show all the changes in elevation around the area where you live. How might you show low areas and high areas? What would you do if you wanted this map to show these changes as if you were flying above your home?
- Why do you think continents are higher areas on Earth than our ocean basins?

2.2 Modeling Earth's Surface

Lesson Objectives

- Describe what information a map can convey.
- Identify some major types of map projections and discuss the advantages and disadvantages of each.
- Discuss the advantages and disadvantages of using a globe.

Maps as Models

Imagine you are going on a road trip. Perhaps you are going on vacation. How do you know where to go? Most likely, you will use a **map**. Maps are pictures of specific parts of the Earth's surface. There are many types of maps. Each map gives us different information. Let's look at a road map, which is the probably the most common map that you use (**Figure** 2.14).

Figure 2.14: shows a road map of the state of Florida. What information can you get from this map? (31)

Look for the legend on the top left side of the map. It explains how this map records different features. You can see the following:

- The boundaries of the state show its shape.
- Black dots represent the cities. Each city is named. The size of the dot represents the population of the city.

- Red and brown lines show major roads that connect the cities.
- Blue lines show rivers. Their names are written in blue.
- Blue areas show lakes and other waterways - the Gulf of Mexico, Biscayne Bay, and Lake Okeechobee. Names for bodies of water are also written in blue.
- A line or scale of miles shows the distance represented on the map – an inch or centimeter on the map represents a certain amount of distance (miles or kilometers).
- The legend explains other features and symbols on the map.
- Although this map does not have a compass rose, north is at the top of the map.

You can use this map to find your way around Florida and get from one place to another along roadways.

There are many other types of maps besides road maps. Some examples include:

- Topographic maps show detailed elevations of landscapes on the map.
- Relief maps show elevations of areas, but usually on a larger scale. Relief maps might show landforms on a global scale rather than a local area.
- Satellite view maps show terrains and vegetation – forests, deserts, and mountains.
- Climate maps show average temperatures and rainfall.
- Precipitation maps show the amount of rainfall in different areas.
- Weather maps show storms, air masses, and fronts.
- Radar maps also show storms and rainfall.
- Geologic maps detail the types and locations of rocks found in an area.
- Political or geographic maps show the outlines and borders of states and/or countries.

These are but a few types of maps that various earth scientists might use. You can easily carry a map around in your pocket or bag. Maps are easy to use because they are flat or two-dimensional. However, the world is three-dimensional. So, how do map makers represent a three-dimensional world on flat paper? Let's see.

Map Projections

The Earth is a three-dimensional ball or sphere. In a small area, the Earth looks flat, so it is not hard to make accurate maps of a small place. When map makers want to map the Earth on flat paper, they use projections. Have you ever tried to flatten out the skin of a peeled orange? Or have you ever tried to gift wrap a soccer ball to give to a friend as a present? Wrapping a round object with flat paper is difficult. A **projection** is a way to represent the Earth's curved surface on flat paper (**Figure** 2.15).

There are many types of projections. Each uses a different way to change three-dimensions into two-dimensions.

There are two basic methods that the map maker uses in projections:

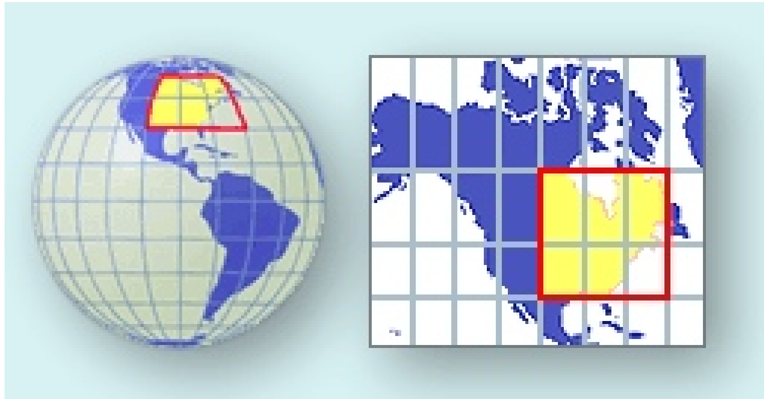


Figure 2.15: A map projection translates Earth's curved surface onto two dimensions. (20)

- The map maker "slices" the sphere in some way and unfolds it to make a flat map, like flattening out an orange peel.
- The map maker can look at the sphere from a certain point and then translate this view onto a flat paper.

Let's look at a few commonly used projections.

Mercator Projection

In 1569, Gerardus Mercator (1512-1594) (**Figure** 2.16) figured out a way to make a flat map of our round world, called a **Mercator projection** (**Figure** 2.17). Imagine wrapping our round, ball shaped Earth with a big, flat piece of paper to make a tube or a cylinder. The cylinder will touch the Earth at the equator, the imaginary line running horizontally around the middle of the Earth, but the poles will be further away from the cylinder. If you could shine a light from the inside of your model Earth out to the cylinder, the image you would project onto the paper would be a Mercator projection. Your map would be just right at the equator, but the shapes and sizes of continents would get more stretched out for areas near the poles. Early sailors and navigators found the Mercator map useful because most explorers at that time traveled to settlements that were located near the equator. Many world maps still use Mercator projection today.

The Mercator projection best describes the shapes and sizes of countries within 15 degrees north or south of the equator. For example, if you look at Greenland on a globe, you see it is a relatively small country near the North Pole. Yet on a Mercator projection, Greenland looks almost as big the United States. Greenland's shape and size are greatly increased, while the United States is represented closer to its true dimensions. In a Mercator projection, all compass directions are straight lines, which makes it a good type of map for navigation. The top of the map is north, the bottom is south, the left side is west and the right side is east.

Figure 2.16: Gerardus Mercator developed a map projection used often today, known as the Mercator projection. (17)

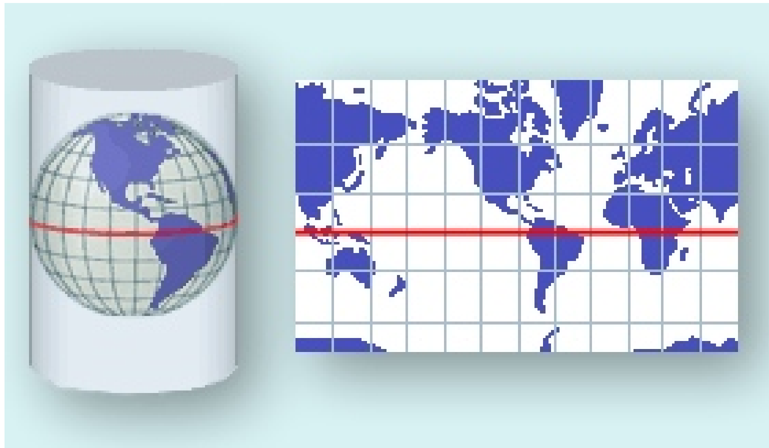


Figure 2.17: A Mercator projection translates the curved surface of Earth onto a cylinder. (24)

However, because it is a flat map of a curved surface, a straight line on the map is not the shortest distance between the two points it connects.

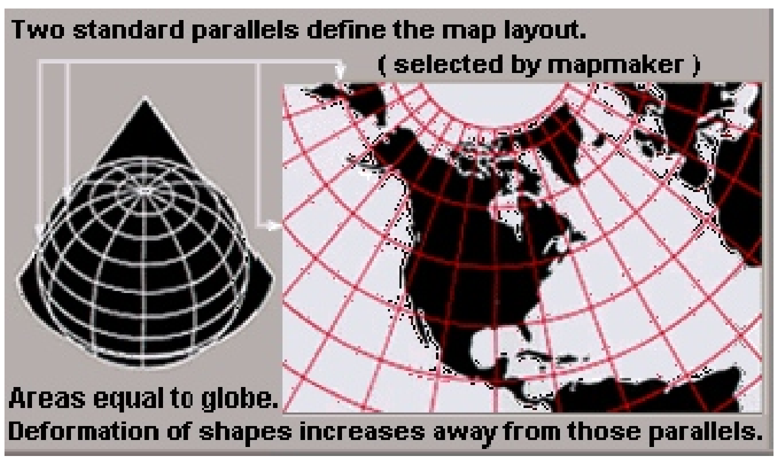


Figure 2.18: A conic map projection wraps the Earth with a cone shape rather than a cylinder. (40)

Instead of a cylinder, you might try wrapping the flat paper into a cone. **Conic** map projections use a cone shape to better represent regions equally (**Figure** 2.18). This type of map does best at showing the area where the cone shape touches the globe, which would be along a line of latitude, like the equator. Maybe you don't like trying to wrap a flat piece of paper around a round object at all. In this case, you could put a flat piece of paper right on the area that you want to map. This type of map is called a **gnomonic** map projection (**Figure** 2.19). The paper only touches the Earth at one point, but it will do a good job showing sizes and shapes of countries near that point. The poles are often mapped this way, but it works for any area that you chose.

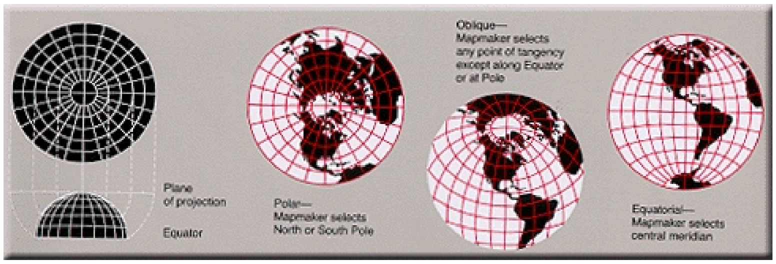


Figure 2.19: A gnomonic projection places a flat piece of paper on a point somewhere on Earth and projects an image from that point. (36)

Robinson Projection

In 1963, Arthur Robinson made a map that looks better in terms of shapes and sizes. He translated coordinates onto the map instead of using mathematical formulas. He did this so that regions on the map would look right. This map is shaped like an ellipse (oval shape) rather than a rectangle (**Figure** 2.20).

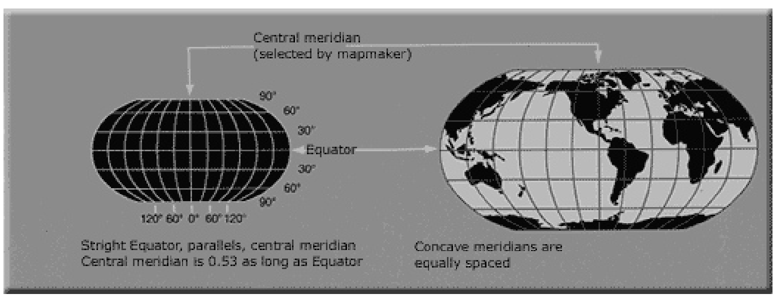


Figure 2.20: A Robinson projection uses mathematical formulas to best represent the true shapes and sizes of areas on Earth. (13)

Robinson's map shows less distortion near the poles and keeps shapes and sizes of continents close to their true dimensions, especially within 45 degrees of the equator. The distances along the equator and lines parallel to it are true, but the scales along each line of latitude are different. In 1988, the National Geographic Society adopted Robinson's projection for all of its world maps. Whatever map projection is used, maps are designed to help us find places and to be able to get from one place to another. So how do you find your location on a map? Let's look.

Map Coordinates

Most maps use a grid or **coordinate system** to find your location. This grid system is sometimes called a geographic coordinate system. The system defines your location by two numbers, latitude and longitude. Both numbers are angles that you make between your location, the center of the Earth, and a reference line (**Figure** 2.21).

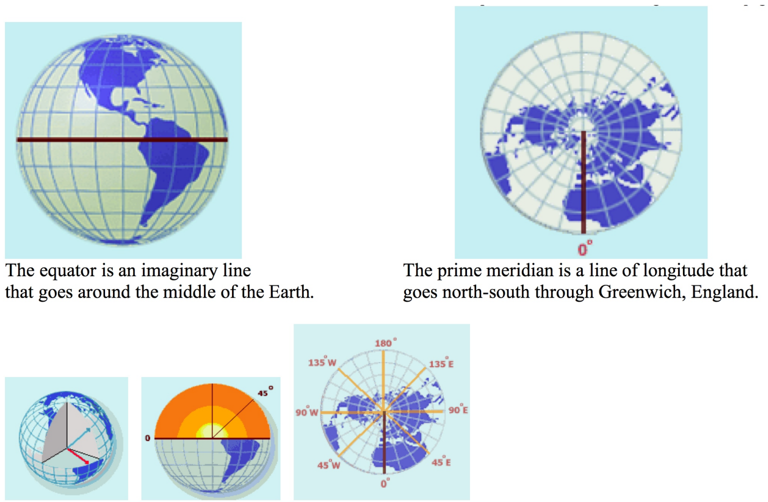


Figure 2.21: Lines of latitude start with the equator. Lines of longitude begin at the prime meridian. (19)

Lines of **latitude** circle around the Earth. The equator is a line of latitude right in the middle of the Earth, which is the same distance from both the North and South Pole. In a grid, your latitude tells you how far you are north or south of the equator. Lines of **longitude** are circles that go around the Earth from pole to pole, like the sections of an orange. Lines of longitude start at the Prime Meridian, which is a circle that runs north to south and passes through Greenwich, England. Longitude tells you how far east or west you are from the Prime Meridian. You can remember latitude and longitude by doing jumping jacks. When your hands are above your head and your feet are together, say longitude (your body is long!), then when you put your arms out to the side horizontally, say latitude (your head and arms make a cross, like the "t" is latitude). While you are jumping, your arms are going the same way as each of these grid lines; horizontal for latitude and vertical for longitude.

If you know the latitude and longitude for a particular place, you can find it on a map. Simply place one finger on the latitude on the vertical axis of the map. Place your other finger on the longitude along the horizontal axis of the map. Move your fingers along the latitude and longitude lines until they meet. For example, if the place you want to find is at 30°N and 90°W, place your right finger along 30°N at the right of the map (**Figure** 2.22). Place your left finger along the bottom at 90°W. Move them along the lines until they meet.

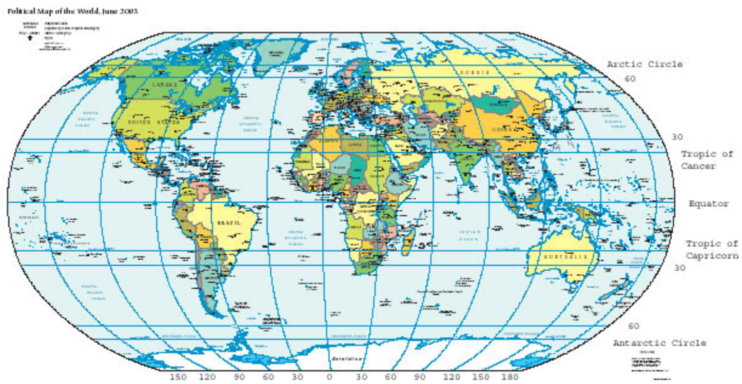


Figure 2.22: Lines of latitude and longitude form convenient reference points on a map. (39)

Your location should be near New Orleans, Louisiana along the Gulf coast of the United States. Also, if you know where you are on a map, you can reverse the process to find your latitude and longitude.

One other type of coordinate system that you can use to go from one place to another is a polar coordinate system. Here your location is marked by an angle and distance from some reference point. The angle is usually the angle between your location, the reference point, and a line pointing north. The other number is a distance in meters or kilometers. To find your location or move from place to place, you need a map, a compass, and some way to measure your distance, such as a range finder. Suppose you need to go from your location to a marker that is 20°E and 500 m from your current position. You must do the following:

- Use the compass and compass rose on the map to orient your map with North.
- Use the compass to find which direction is 20°E.
- Walk 500 meters in that direction to reach your destination.

Polar coordinates are used most often in a sport called orienteering. Here, you use a compass and a map to find your way through a course across wilderness terrain (**Figure** 2.23). You move across the terrain to various checkpoints along the course. You win by completing the course to the finish line in the fastest time.

Globe

A globe is the best way to make a map of the whole Earth, because the Earth is a sphere and so is a globe. Because both the Earth and a globe have curved surfaces, sizes and shapes of countries are not distorted and distances are true to scale. (**Figure** 2.24).

Globes usually have a geographic coordinate system and a scale on them. The shortest distance between two points on a globe is the length of the arc (portion of a circle) that

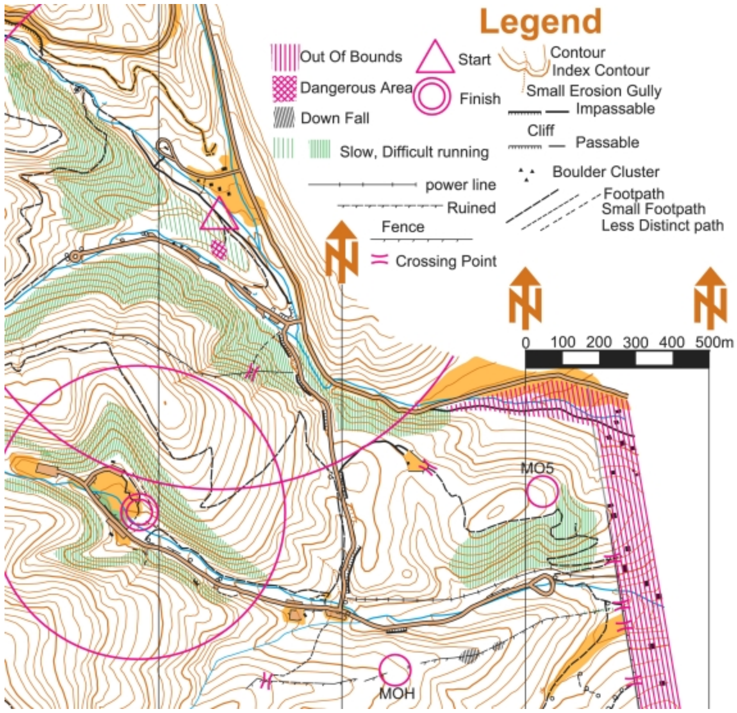


Figure 2.23: A topographic map like one that you might use for the sport of orienteering. (34)

Figure 2.24: A globe is the most accurate way to represent Earth's curved surface. (33)

connects them. Despite their accuracy, globes are difficult to make and carry around. They also cannot be enlarged to show the details of any particular area. Google Earth is a neat site to download to your computer. This is a link that you can follow to get there: earth.google.com/download-earth.html. The maps on this site allow you to zoom in or out, look from above, tilt your image and lots more.

Lesson Summary

- Maps and globes are models of the Earth's surface. There are many ways to project the three-dimensional surface of the Earth on to a flat map. Each type of map has some advantages as well as disadvantages.
- Most maps use a geographic coordinate system to help you find your location using latitude and longitude.
- Globes are the most accurate representations, because they are round like the Earth, but they cannot be carried around easily. Globes also cannot show the details of the Earth's surface that maps can.

Review Questions

1. Which of the following gives you the most accurate representations of distances and shapes on the Earth's surface? **(Beginning)**
   (a) Mercator projection map
   (b) Robinson projection map
   (c) Globe
2. Explain the difference between latitude and longitude? **(Intermediate)**

Figure 2.25: World map with geographic coordinate system (6)

3. Use (**Figure** 2.25). In what country are you located, if your coordinates are 60°N and 120°W?

4. Which map projection is most useful for navigation, especially near the equator? Explain
5. In many cases, maps are more useful than a globe. Why?
6. Which of the following map projections gives you the least distortion around the poles? **(Intermediate)**
   (a) Mercator projection map
   (b) Robinson projection map
   (c) Conic projection

Further Reading / Supplemental Links

- http://erg.usgs.gov/isb/pubs/MapProjections/projections. html
- http://www.msnucleus.org/membership/html/jh/earth/mapstype/index.htm
- http://erg.usgs.gov/isb/pubs/booklets/usgsmaps/usgsmaps. html
- http://www.mywonderfulworld.org/toolsforadventure/usingmaps/ index.html, explorers.html
- http://maps.google.com/maps
- http://www.nationalatlas.gov/
- http://www.nationalatlas.gov/articles/mapping/a_projections. html
- http://www.nationalatlas.gov/articles/mapping/a_latlong html
- http://www.fao.org/docrep/003/T0390E/T0390E04.htm
- http://en.wikipedia.org/

Vocabulary

conic map A map projection made by projecting Earth's three dimensional surface onto a cone wrapped around an area of the Earth.

coordinate system Numbers in a grid that locate a particular point.

gnomonic map A map projection made by projecting onto a flat paper from just one spot on the Earth.

latitude An imaginary horizontal line drawn around the Earth parallel to the equator, which is 0º latitude.

longitude An imaginary vertical line drawn on the Earth, from pole to pole; the Prime Meridian is 0º longitude.

map A two dimensional representation of Earth's surface.

Mercator projection A map projection created by Mercator using a cylinder wrapped around the Earth.

projection A way to represent a three dimensional surface in two dimensions.

Points to Consider

- Imagine you are a pilot and must fly from New York to Paris. Use a globe and a world map to do the following:
  - Plot your course from New York to Paris on a globe. Make it the shortest distance possible.
  - Measure the distance by using the scale, a ruler, and a string.
  - Draw the course from the globe on a world map.
  - Draw a line on the map connecting New York and Paris.
- How does the course on the globe compare with the line on the map? Which is the shortest distance? Write a brief paragraph describing the differences and explain why they are different.
- Would you choose a map that used a Mercator projection if you were going to explore Antarctica? Explain why this would not be a good choice. What other type of map would be better?
- Maps use a scale, which means a certain distance on the map equals a larger distance on Earth. Why are maps drawn to scale? What would be some problems you would have with a map that did not use a scale?

2.3 Topographic Maps

Lesson Objectives

- Describe a topographic map.
- Explain what information a topographic map contains.
- Explain how to read and interpret a topographic map.
- Explain how various earth scientists use topographic maps to study the Earth.

What is a Topographic Map?

Mapping is a crucial part of earth science. **Topographic maps** represent the locations of major geological features. Topographic maps use a special type of line, called a **contour line**, to show different elevations on a map. Contour lines are drawn on a topographic map to show the location of hills, mountains and valleys. When you use a regular road map, you can see *where* the roads go, but a road map doesn't tell you why a road stops or bends.A topographic map will show you that the road bends to go around a hill or stops because that is the top of a mountain. Let's look at topographic maps.

Look at this view of the Swamp Canyon Trail in Bryce Canyon National Park, Utah (**Figure** 2.26). You can see the rugged canyon walls and valley below. The terrain clearly has many steep cliffs. There are high and low points between the cliffs.

Figure 2.26: View of Swamp Canyon in Bryce Canyon National Park, looking southeast from Swamp Canyon Trail overlook. (14)

Now look at the corresponding section of the Visitor's map (**Figure** 2.27). You can see a green line which is the main road. The black dotted lines are trails. You see some markers for campsites, a picnic area, and a shuttle bus stop. But nothing on the map shows the height of the terrain. Where are the hills and valleys located? How high are the canyon walls? Which way will streams or rivers flow?

You need a special type of map to represent the elevations in an area. This type of map is called a topographic map (**Figure** 2.28).

What makes a topographic map different from other maps? Contour lines help show various elevations.

Contour Lines and Intervals

Contour lines connect all the points on the map that have the same elevation. Let's take a closer look at this (**Figure** 2.28).

- Each contour line represents a specific elevation and connects all the places that are

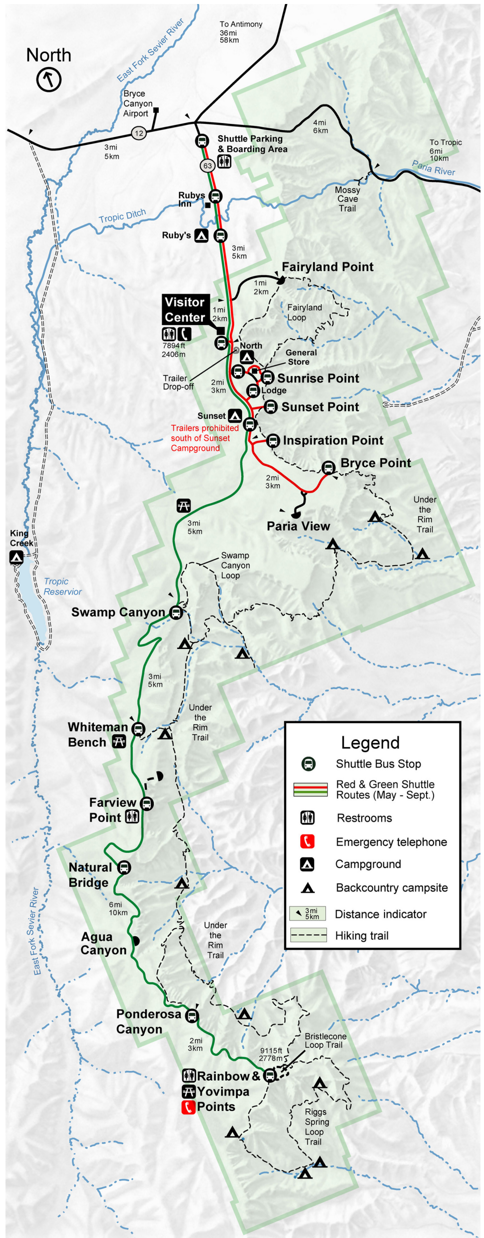


Figure 2.27: Portion of Bryce Canyon National Park road map showing Swamp Canyon Loop. (22)

Figure 2.28: Topographic map of Swamp Canyon Trail portion of Bryce Canyon National Park. (42)

at the same elevation. Every fifth contour line is bolded. The bold contour lines are labeled with numerical elevations.

- The contour lines run next to each other and NEVER cross one another. That would mean one place had two different elevations, which cannot happen.
- Two contour lines next to one another are separated by a constant difference in elevation (e.g. 20 ft or 100 ft.). This difference between contour lines is called the **contour interval**. You can calculate the contour interval. The legend on the map will also tell you the contour interval.
  - Take the difference in elevation between 2 bold lines.
  - Divide that difference by the number of contour lines between them.

If the difference between two bold lines is 100 feet and there are five lines between them, what is the contour interval? If you answered 20 feet, then you are correct (100 ft/5 = 20 ft)

Interpreting Contour Maps

How does a topographic map tell you about the terrain? Well, in reading a topographic map, consider the following principles:

1. *Contour lines can indicate the slope of the land.* Closely-spaced contour lines indicate a steep slope, because elevation changes quickly in a small area. In contrast, broadly spaced contour lines indicate a shallow slope. Contour lines that seem to touch indicate a very steep or vertical rise, like a cliff or canyon wall. So, contour lines show the three-dimensional shape

of the land. For example, on this topographic map of Stowe, Vermont (**Figure** 2.29), you will see a steep hill rising just to the right of the city of Stowe. You can tell this because the contour lines there are closely spaced. Using the contour lines, you can see that the hill has a sharp rise of about 200 ft and then the slope becomes less steep as you proceed right.

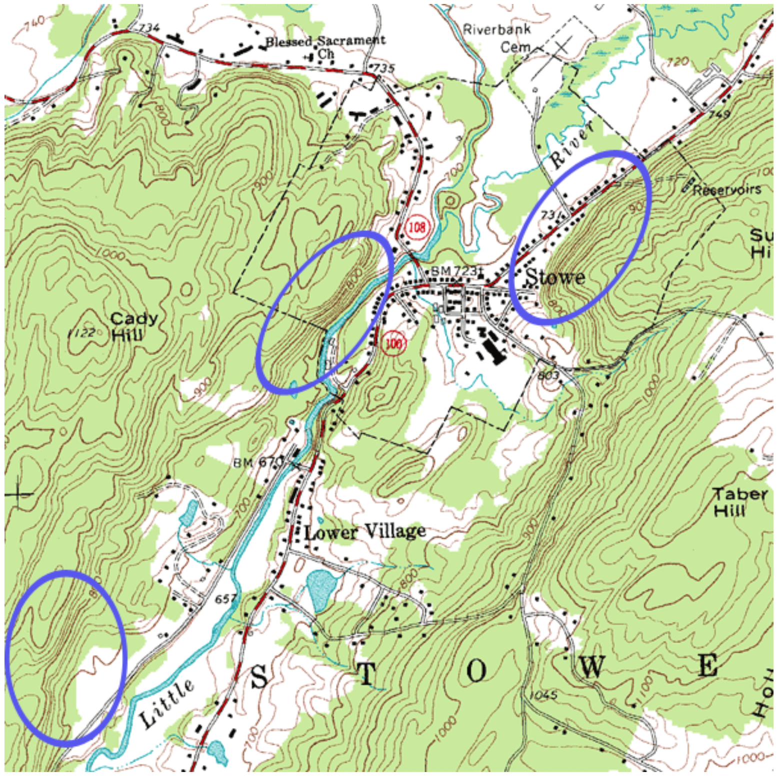


Figure 2.29: Portion of a USGS topographic map of Stowe, VT. In this map, you can see how the spacings of the contour lines indicate a steep hill just to the right of the city of Stowe in the right half. The hill becomes less steep as you proceed right. (10)

2. *Concentric circles indicate a hill.* **Figure** 2.30 shows another side of the topographic map of Stowe, Vermont. When contour lines form closed loops all together in the same area, this is a hill. The smallest loops are the higher elevations and the larger loops are downhill. If you look at the map, you can see Cady Hill in the lower left and another, and another smaller hill in the upper right.

3. *Hatched concentric circles indicate a depression.* The hatch marks are short, perpendicular lines inside the circle. The innermost hatched circle would represent the deepest part of the depression, while the outer hatched circles represent higher elevations (**Figure** 2.31).

4. *V-shaped portions of contour lines indicate stream valleys.* Here the V- shape of the contour lines "point" uphill. The channel of the stream passes through the point of the V and the open end of the V represents the downstream portion. Thus, the V points upstream. A blue line will indicate the stream if water is actually running through the valley; otherwise,

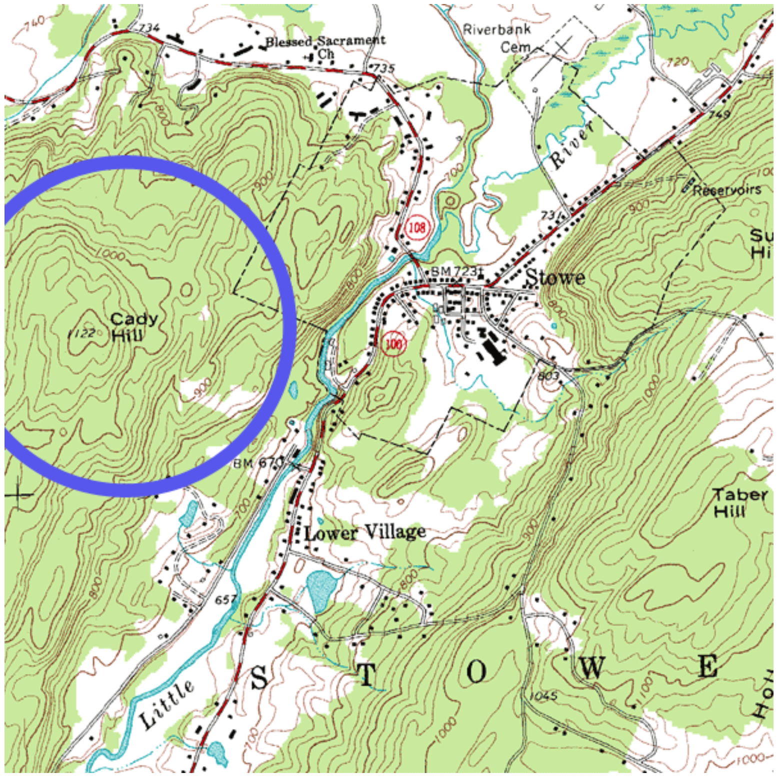


Figure 2.30: Portion of a USGS topographic map of Stowe, VT. In this map, you can see Cady Hill (elevation 1122 ft) indicated by concentric circles in the lower left portion of the map and another hill (elevation ˜ 960 ft) in the upper right portion of the map. (3)

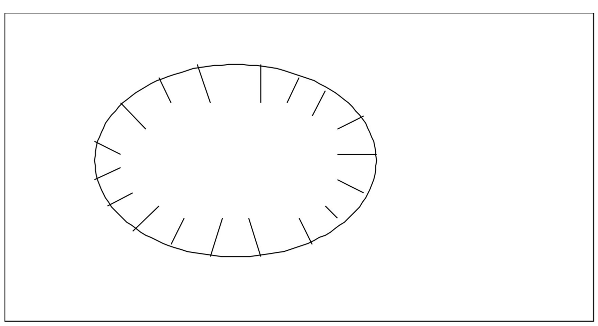


Figure 2.31: On a contour map, a circle with inward hatches indicates a depression. (38)

the V patterns will indicate which way water will flow In **Figure** 2.32, you can see examples of V-shaped markings. Try to find the direction a stream would flow.

Figure 2.32: Illustrations of 3-dimensional ground configurations (top) and corresponding topographic map (bottom). Note the V-shaped markings on the topographic maps correspond to drainage channels. Also, the closely-spaced contour lines denote the rapid rising cliff face on the left side. (43)

5. Like other maps, topographic maps have a scale on them to tell you the horizontal distance. The horizontal scale helps to calculate the slope of the land (vertical height/horizontal distance). Common scales used in United States Geological Service (USGS) maps include the following:

- 1:24,000 scale – 1 inch = 2000 ft
- 1:100,000 scale – 1 inch = 1.6 miles
- 1:250,000 scale – 1 inch = 4 miles

So, the contour lines, their spacing intervals, circles, and V-shapes allow a topographic map to convert 3-dimensional information into a 2-dimensional representation on a piece of paper. The topographic map gives us an idea of the shape of the land.

Information from a Topographic Map

As we mentioned above, topographic maps show the shape of the land. You can determine information about the slope and determine which way streams will flow. We'll examine each of these.

How Do Earth Scientists Use Topographic Maps?

Earth scientists use topographic maps for many things:

- Describing and locating surface features, especially geologic features.
- Determining the slope of the Earth's surface.
- Determining the direction of flow for surface water, ground water, and mudslides.

Hikers, campers, and even soldiers use topographic maps to locate their positions in the field. Civil engineers use topographic maps to determine where roads, tunnels, and bridges should go. Land use planners and architects also use topographic maps when planning development projects like housing projects, shopping malls, and roads.

Oceanographers use a type of topographic map called a **bathymetric map** (**Figure** 2.33). In a bathymetric map, the contour lines represent depth from the surface. Therefore, high numbers are deeper depths and low numbers are shallow depths. Bathymetric maps are made from depth soundings or sonar data. Bathymetric maps help oceanographers visualize the bottoms of lakes, bays, and the ocean. This information also helps boaters to navigate safely.

Geologic Maps

A geologic map shows the geological features of a region. Rock units are shown in a color identified in a key. On the map of Yosemite, for example, volcanic rocks are brown, the Tuolumne Intrusive Suite is peach and the metamorphosed sedimentary rocks are green. Structural features, for example folds and faults, are also shown on a geologic map. The area around Mt. Dana on the east central side of the map has fault lines.

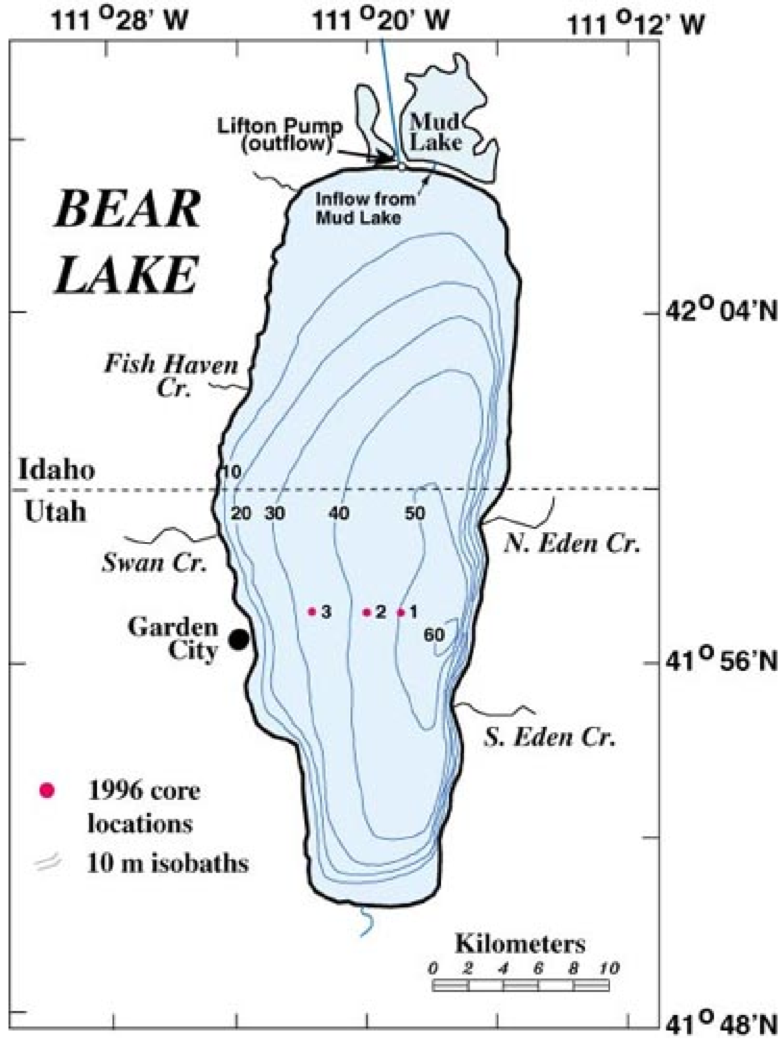
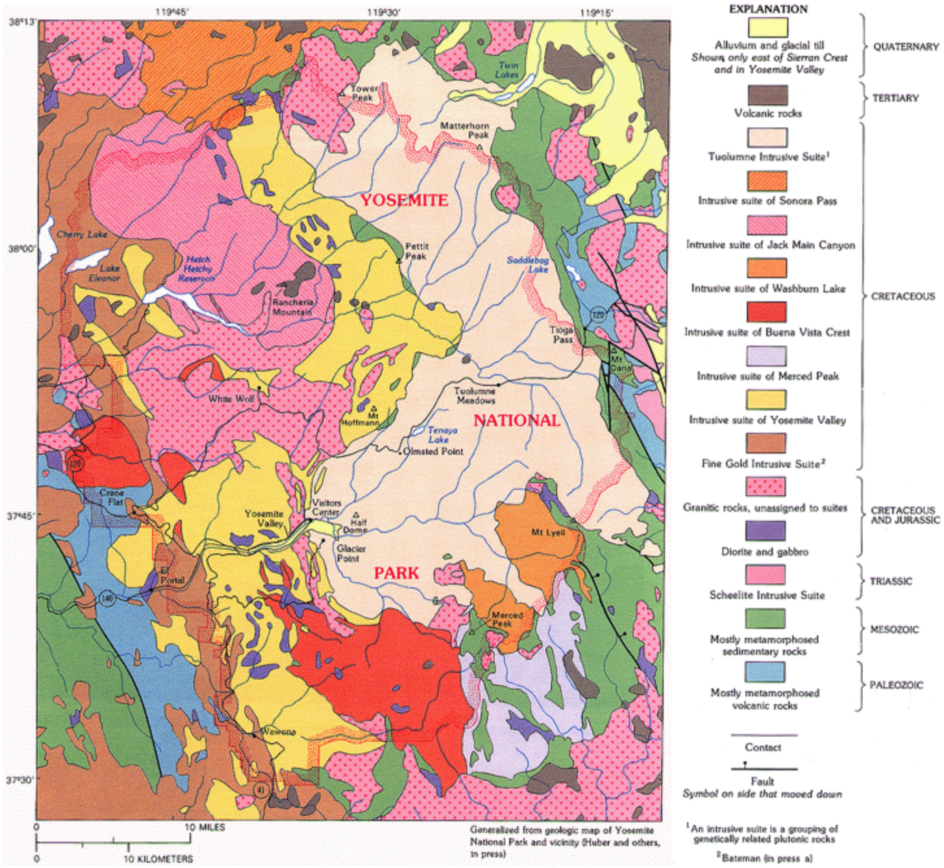
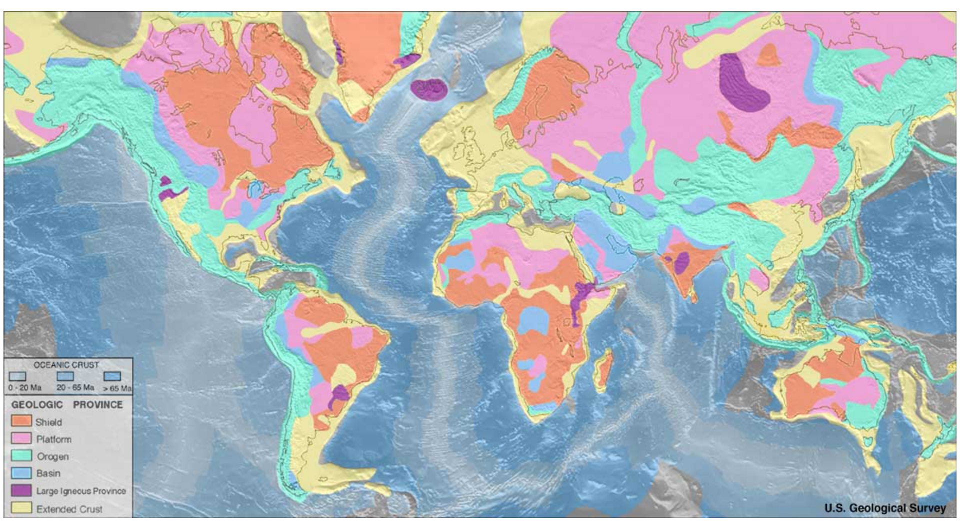


Figure 2.33: Bathymetric map of Bear lake, UT. (8)



On a large scale geologic map, colors represent geological provinces.



Lesson Summary

- Topographic maps are two-dimensional representations of the three-dimensional surface features of a given area. Topographic maps have contour lines which connect points of identical elevation above sea level.
- Contour lines run next to each other and adjacent contour lines are separated by a constant difference in elevation, usually noted on the map. Topographic maps have a horizontal scale to indicate horizontal distances. Topographic maps help users see the how the land changes in elevation.
- Many people use topographic maps to locate surface features in a given area, to find their way through a particular area, and to determine the direction of water flow in a given area.
- Oceanographers use a special type of topographic map called a bathymetric map, which shows the bottom of any given body of water.
- Geologic maps display rock units and geologic features of a region of any size. A small scale map displays individual rock units while a large scale map shows geologic provinces.

Review Questions

1. On a topographic map, you see contour lines forming closed loops that all lie in the same area. Which of the following features would this indicate? **(Beginning)**
    - a stream channel
    - a hilltop
    - depression
    - a cliff
2. Describe the pattern on a topographic map that would indicate a stream valley. How you would determine the direction of water flow?
3. On a topographic map, five contour lines are very close together in one area. The contour interval is 100 ft. What feature does that indicate? How high is this feature?
4. On a topographic map, describe how you can tell a steep slope from a shallow slope?
5. On a topographic map, a river is shown crossing from Point A in the northwest to Point B in the southeast. Point A is on a contour line of 800 ft and Point B is on a contour line of 900 ft. In which direction does the river flow? What information would help you figure this out?
6. On a topographic map, six contour lines span a horizontal distance of 0.5 inches. The horizontal scale is 1 inch equals 2000 ft. How far apart are the first and sixth lines?
7. On a geologic map of the Grand Canyon, a rock unit called the Kaibab Limestone takes up the entire surface of the region. Down some steep topographic lines is a very thin rock unit called the Toroweap Formation and just in from that is another thin unit, the Coconino sandstone. Describe how these three rock units sit relative to each

other.

Further Reading / Supplemental Links

- http://interactive2.usgs.gov/learningweb/teachers/mapsshow_lesson4.htm
- http://erg.usgs.gov/isb/pubs/booklets/symbols/topomapsymbols.pdf
- http://www.uwsp.edu/geo/faculty/ritter/geog101/textbook/manuals/instructor_manual/how_to/topographic_profile.html
- http://raider.muc.edu/~mcnaugma/Topographic%20Maps/topomapindexpage.htm
- http://www.globalsecurity.org/military/library/policy/army/fm/3-25-26/ch10.htm
- http://www.map-reading.com/intro.php

Vocabulary

bathymetric map A special type of topographic map used by oceanographers that show depth of areas underwater.

contour interval The constant difference in elevation between two contour lines on a topographic map.

contour lines Lines drawn on a topographic map to show elevation; these lines connect all the places that are the same elevation.

topographic map A special type of map that show elevations of different geologic features of a region.

Points to Consider

- Imagine that you are a civil engineer. Describe how you might use a topographic map to build a road, bridge, or tunnel through the area such as that shown in **Figure** 2.30. Would you want your road to go up and down or remain as flat as possible? What areas would need a bridge in order to cross them easily? Can you find a place where a tunnel would be helpful?

- If you wanted to participate in orienteering, would it be better to have a topographic map or a regular road map? How would a topographic map help you?

- If you were the captain of a very large boat, what type of map would you want to have to keep your boat traveling safely?

2.4 Using Satellites and Computers

Lesson Objectives

- Describe various types of satellite images and the information that each provides.
- Explain how a Global Positioning System (GPS) works.
- Explain how computers can be used to make maps.

Satellite Images

If you look at the surface of the Earth from your yard or street, you can only see a short distance. If you climb a tree or go to the top floor of your apartment building, you can see further. If you flew over your neighborhood in a plane, you could see still further. Finally, if you orbited the Earth, you would be able to see a very large area of the Earth. This is the idea behind satellites. To see things on a large scale, you need to get the highest view.

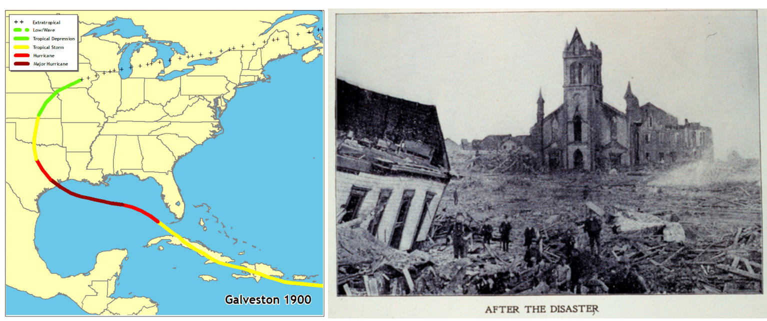


Figure 2.34: (left) Track of hurricane that hit Galveston, Texas on Sept. 8, 1900. (right) Galveston in the aftermath. (35)

Let's look at an example. One of the deadliest hurricanes in United States history hit Galveston, Texas in 1900. The storm was first spotted at sea on Monday, Aug 27, 1900. It was a tropical storm when it hit Cuba on Sept. 3^{rd}. By Sept. 8^{th}, it had intensified to a hurricane over the Gulf of Mexico. It came ashore at Galveston (**Figure** 2.34). There was not advanced warning or tracking at the time. Over 8000 people lost their lives.

Today, we have satellites with many different types of instruments that orbit the Earth. With these satellites, we can see hurricanes (**Figure** 2.35). Weather forecasters can follow hurricanes as they move from far out in the oceans to shore. Weather forecasters can warn people who live along the coasts. Their advanced warning gives people time to prepare for the storm, which helps save lives.

Satellites orbit high above the Earth in several ways. One of the most useful ways is called the **geostationary orbit** (**Figure** 2.36).

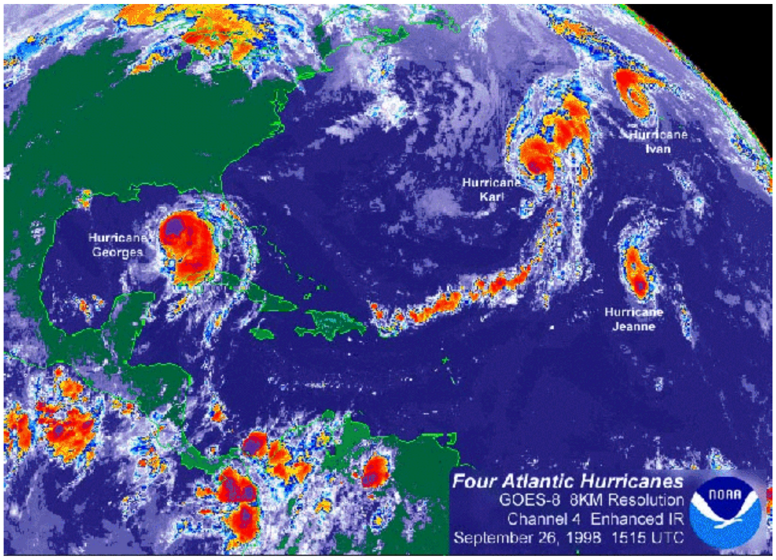


Figure 2.35: Satellite view shows four hurricanes in the Atlantic Ocean on Sept. 26, 1998. (21)

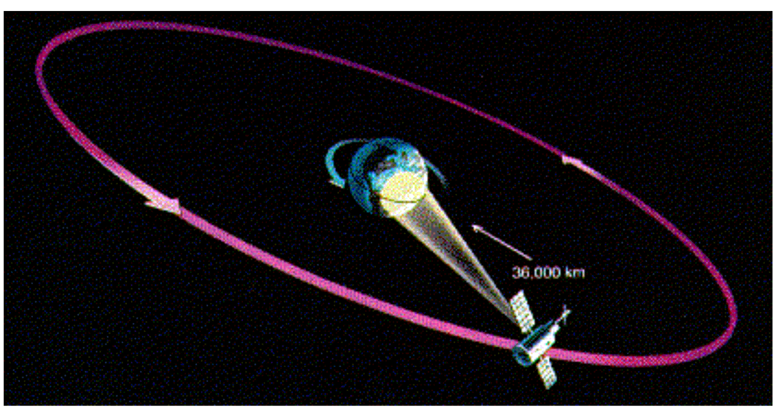


Figure 2.36: Satellite in a geostationary orbit. (30)

The satellite orbits at a distance of 36,000 km. It takes 24 hours to complete one orbit. Since the satellite and the Earth both complete one rotation in 24 hours, the satellite appears to "hang" in the sky over the same spot. In this orbit, the satellite stays over one area of the Earth's surface. Weather satellites use this type of orbit to observe changing weather conditions. Communications satellites, like satellite TV, also use this type of orbit.

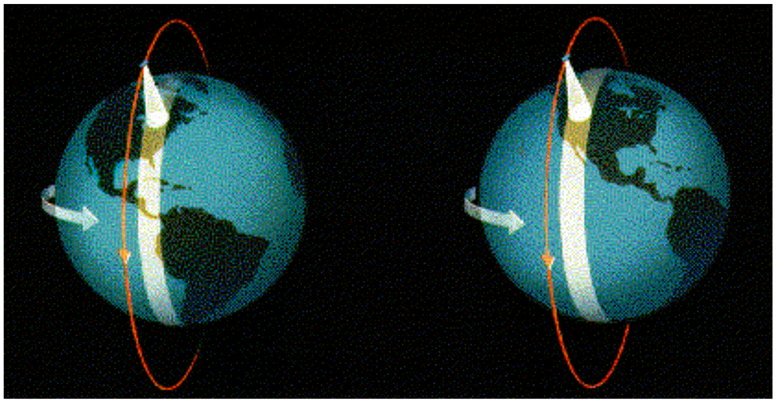


Figure 2.37: Satellite in a polar orbit. (18)

Another useful orbit is the **polar orbit** (**Figure** 2.37). The satellite orbits at a distance of several hundred kilometers. It makes one complete orbit around the Earth from the North Pole to the South Pole about every 90 minutes. In this same amount of time, the Earth rotates slightly underneath the satellite. In less than a day, the satellite can see the entire surface of the Earth. Some weather satellites use a polar orbit to get a picture of how the weather is changing globally. Also some satellites that observe the lands and oceans use a polar orbit.

The National Aeronautics and Space Administration (NASA) has launched a fleet of satellites to study the Earth (**Figure** 2.38). The satellites are operated by several government agencies, including NASA, the National Oceanographic and Atmospheric Administration (NOAA) and the United States Geological Survey (USGS). By using different types of scientific instruments, satellites make many kinds of measurements of the Earth.

- Some satellites measure the temperatures of the land and oceans.
- Some record amounts of gases in the atmosphere such as water vapor and carbon dioxide.
- Some measure their height above the oceans very precisely.

From this information, they can get an idea of the sea surface below.

- Some measure the ability of the surface to reflect various colors of light. This information tells us about plant life.

Some examples of the images from these types of satellites are shown in **Figure** 2.39).

Figure 2.38: NASA's fleet of satellites to study the Earth. (29)

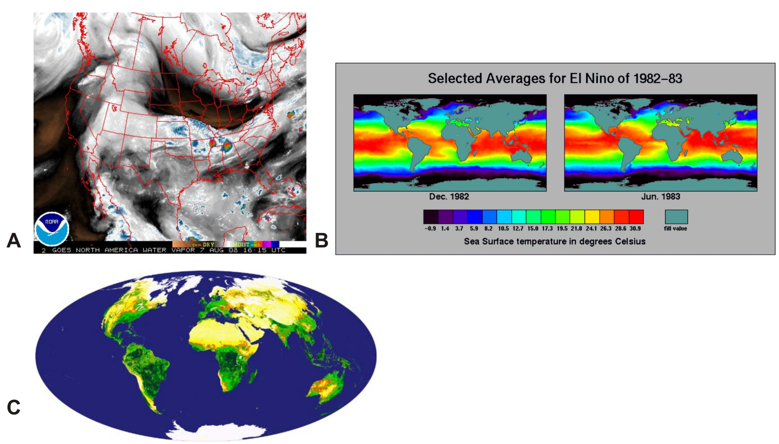


Figure 2.39: Various satellite images: A – water vapor in atmosphere, B – ocean surface temperatures, C – global vegetation. (28)

Global Positioning System

Previously, we talked about your position on Earth. In order to locate your position on a map, you must know your latitude and your longitude. But you need several instruments to measure latitude and longitude. What if you could do the same thing with only one instrument? Satellites can also help you locate your position on the Earth's surface (**Figure** 2.40).

Figure 2.40: There are 24 satellites in the US Global Positioning System. (2)

By 1993, the United States military had launched 24 satellites to help soldiers locate their positions on battlefields. This system of satellites was called the Global Positioning System (GPS). Later, the United States government allowed the public to use this system. Here's how it works.

You must have a GPS receiver to use the system (**Figure A** 2.41). You can buy many of these in stores. The GPS receiver detects radio signals from nearby GPS satellites. There are precise clocks on each satellite and in the receiver. The receiver measures the time for radio signals from satellite to reach it. The receiver uses the time and the speed of radio signals to calculate the distance between the receiver and the satellite. The receiver does this with at least four different satellites to locate its position on the Earth's surface (**Figure B** 2.41). GPS receivers are now being built into many items, such as cell phones and cars.

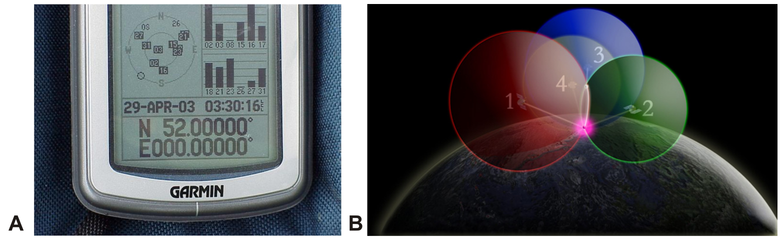


Figure 2.41: (A) You need a GPS receiver to use the GPS system. (B) It takes signals from 4 GPS satellites to find your location precisely on the surface (15)

Computer-Generated Maps

Prior to the late 20$^{\text{th}}$ and early 21$^{\text{st}}$ centuries, map-makers sent people out in the field to determine the boundaries and locations for various features for maps. State or county borders were used to mark geological features. Today, people in the field use GPS receivers to mark the locations of features. Map-makers also use various satellite images and computers to draw maps. Computers are able to break apart the fine details of a satellite image, store the pieces of information, and put them back together to make a map. In some instances, computers can make 3-D images of the map and even animate them. For example, scientists used computers and satellite images from Mars to create a 3-D image of a large Martian valley called Valles Marineris (**Figure** 2.42). The image makes you feel as if you are on the surface of Mars and looking into the valley.

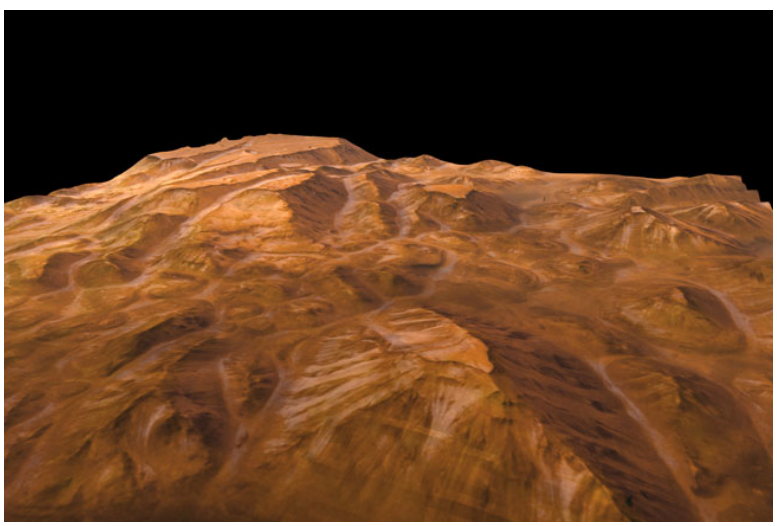


Figure 2.42: This three-dimensional image of a large valley on Mars was made from satellite images and computers. (9)

When you link any type of information to a geographical location, you can put together incredibly useful maps and images. The information could be numbers of people living in an area, types of plants or soil, locations of groundwater or levels of rainfall for an area. As long as you can link the information to a position with a GPS receiver, you can store it in a computer for later processing and map-making. This type of mapping is called a **Geographic Information System (GIS)**. Geologists can use GIS to make maps of natural resources. City leaders might link these resources to where people live and help plan the growth of cities or communities. Other types of data can be linked by GIS. For example, **Figure** 2.43 shows a map of the counties where farmers have made insurance claims for crop damage in 2008.

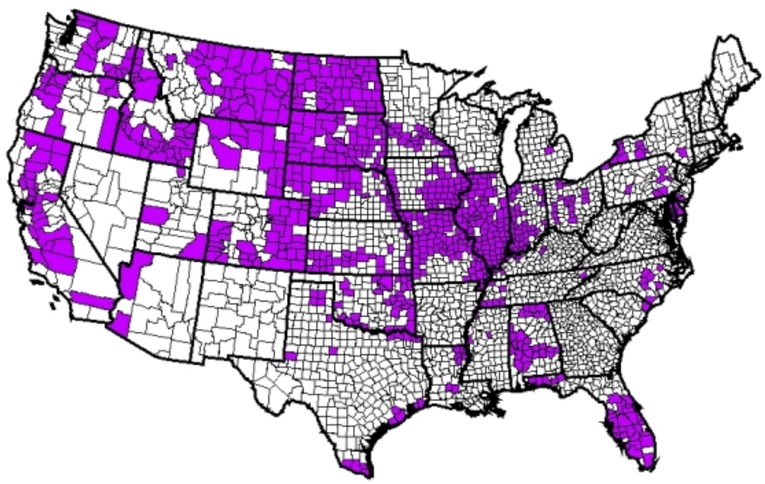


Figure 2.43: Map of insurance filings for crop damage in 2008. (4)

Computers have improved how maps are made. They have also increased the amount of information that can be displayed. During the 21st century, computers will be used more and more in mapping.

Lesson Summary

- Satellites give a larger view of the Earth's surface from high above. They make many types of measurements for earth scientists.
- A group of specialized satellites called Global Positioning Satellites help people to pinpoint their location.
- Location information, satellite views, and other information can be linked together in Geographical Information Systems (GIS).
- GIS are powerful tools that earth scientists and others can use to study the Earth and its resources.

Review Questions

1. Which type of satellite can be used to pinpoint your location on Earth? **(Beginning)**
    - weather satellite
    - communications satellite
    - global positioning satellite
    - climate satellite
2. Explain the difference between geosynchronous orbits and polar orbits?
3. Describe how GPS satellites can find your location on Earth?
4. What is a Geographical Information System or GIS?
5. If you want to map the entire Earth's surface from orbit, which type of orbit would you use?
6. Explain how weather satellites could track a tropical storm from its beginnings?

Further Reading / Supplemental Links

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- pdf. http://www3.nsta.org/main/news/pdf/tst9812_46. pdf.

"Isaac's Storm": Available on the Web at:

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USGS, Geographic Information Systems

- http://erg.usgs.gov/isb/pubs/gis_poster/

GIS.com, What is GIS?

- html http://www.gis.com/whatisgis/index. html

USGS Topographical Mapping

- http://erg.usgs.gov/isb/pubs/booklets/topo/topo.html
- http://www.ccpo.odu.edu/SEES/index.html
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- http://www.geoplane.com/gps. html
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Vocabulary

Geographic Information System (GIS) An information system that links data to a particular location.

geostationary orbit A type of orbit that allows a satellite to stay in above one location on Earth's surface.

polar orbit satellite Orbit that moves over Earth's north and south poles as Earth rotates underneath.

Points to Consider

- Imagine that you are tracking a hurricane across the Atlantic Ocean. What information would you need to follow its path? What satellite images might be most useful? Research and explain how the National Weather Service tracks and monitors hurricanes.
- If you had to do a report on the natural resources for a particular state, what type of map would help you find the most information?
- What are some ways that people use Global Positioning Systems? What problems are easier to solve using GPS?

Image Sources

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(4) *http://www.rma.usda.gov/data/GIS/maps/2008/*. GNU Free Documentation.

(5) NOAA. *http://www.ngdc.noaa.gov/geomag/faqgeom.shtml*. Public Domain.

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(25) NASA. *http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=17283 San Francisco Mountain and surrounding areas*. Public Domain.

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Chapter 3

Earth's Minerals

3.1 What are Minerals?

Lesson Objectives

- Describe the characteristics that all minerals share.
- Summarize the structure of minerals.
- Identify the groups in which minerals are classified.

What are Minerals?

You use objects that are made from minerals every day, even if you do not realize it. You are actually eating a mineral when you eat food that contains salt. You are drinking from a container made from a mineral when you drink from a glass. You might even wear silver jewelry. The shiny metal silver, the white grains of salt, and clear glass may not seem to have much in common, but they are all made from minerals (**Figure** 3.1). Silver is a mineral. Table salt is the mineral halite. Glass is produced from the mineral quartz. Scientists have identified more than 4,000 minerals in Earth's crust. Some minerals are found in very large amounts, but most minerals are found in small amounts. If minerals can be so different from each other, what makes a mineral a mineral?

A mineral is a crystalline solid formed through natural processes. A mineral can be an element or a compound, but it has a specific chemical composition and physical properties that are different from those of other minerals. Silver, tungsten, halite, and quartz are all examples of minerals. Each one has a different chemical composition, as well as different physical properties such as crystalline structure, hardness, density, flammability, and color. For example, silver is shiny and salt is white.

Figure 3.1: Silver is used to make sterling silver jewelry. Table salt is the mineral halite. Glass is produced from the mineral quartz. (1)

Natural Processes

Minerals are made by natural processes. A natural process occurs in or on the Earth. One common natural process that forms minerals is the crystallization of magma. Some natural processes shape Earth's features, while others include volcanic activity and the movement of tectonic plates. Rocks and minerals are formed in sedimentary layers of sand and mud and in the folding of those layers deep in the Earth, where they are exposed to high pressures and temperatures. A technician might make a gemstone in the laboratory, but this would have been created synthetically, not by natural processes.

Inorganic Substances

A mineral is an inorganic substance, which usually means it was not made by living organisms. Organic substances are all the carbon-based compounds made by living creatures, including proteins, carbohydrates, and oils. This definition includes fossil fuels such as coal and oil, which were originally made by living organisms millions of years ago. Everything else is considered inorganic. In a few exceptional cases, living organisms produce inorganic materials, such as the calcium carbonate shells of marine organisms.

Crystalline Solids

Minerals are crystalline solids. Therefore, natural inorganic substances that are liquids are not minerals. For example, liquid water is inorganic, but it is not a mineral because it is a liquid. Even some solids may not be crystalline. A **crystal** is a solid in which the atoms are arranged in a regular, repeating pattern. **Figure** 3.2 shows how the atoms are arranged in table salt (halite). Table salt contains the ions sodium and chloride. Notice how the atoms are arranged in an orderly way. Also, notice that pattern continues in all three dimensions.

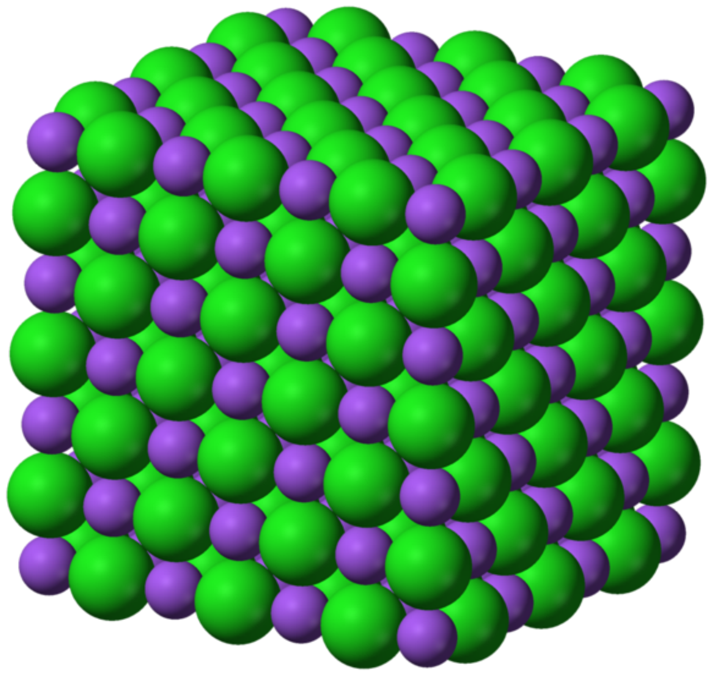

Figure 3.2: As you can see from this model, sodium ions bond with chloride ions in a certain way to form halite crystals. The green balls represent the chloride ions and the purple balls represent the sodium ions. (13)

The pattern of atoms in different samples of the same mineral is the same. Think about all of the grains of salt that are in a salt shaker. The atoms are arranged in the same way in every piece of salt.

Chemical Composition

All minerals have a specific chemical composition. Minerals are either pure elements or chemical compounds. An **element** is a substance in which all of the atoms have the same number of protons. (Protons are the positive particles in the center of every atom, the nucleus.) You cannot change an element into another element by chemical means because the number of protons does not change. Silver, sodium, silicon, and oxygen are a few of the elements found in minerals. A few minerals are made of only one kind of element. The mineral silver is a pure element because it is made up of only silver atoms.

Most minerals, such as halite and quartz, are made up of chemical compounds. A **chemical**

compound is a substance in which the atoms of two or more elements bond together. The elements in a chemical compound are in a certain ratio. Solid water (ice) is probably one of the simplest compounds that you know. As you can see in **Figure** 3.3, a molecule of the compound water is made of two hydrogen atoms and one oxygen atom. All water molecules have a ratio of two hydrogen atoms to one oxygen atom. In ice, all the water molecules are arranged in a definite, orderly pattern.

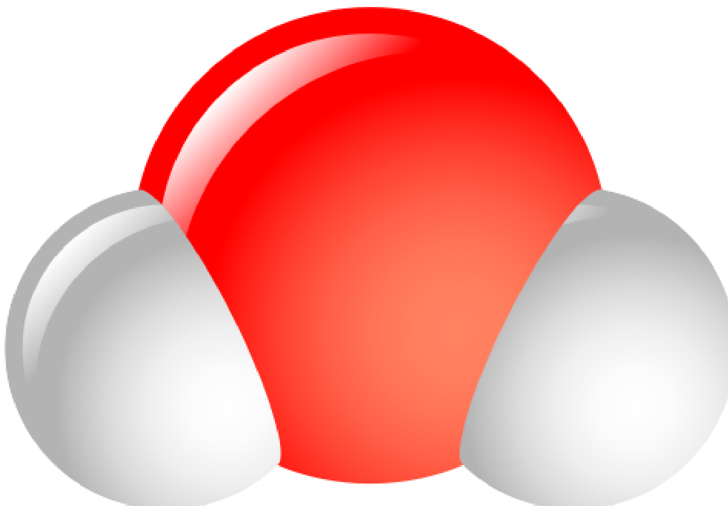

Figure 3.3: As this model of a water molecule shows, all water molecules have two hydrogen atoms (shown in gray) bonded to one oxygen molecule (Shown in red). (11)

Minerals that are not pure elements are made of compounds. For example, the mineral quartz is made of the compound silicon dioxide, or SiO_2. This compound has one atom of the element silicon for every two atoms of the element oxygen. When a mineral has a different chemical formula, it is a different mineral. For example, the mineral *hematite* has two iron atoms for every three oxygen atoms, while the mineral *magnetite* has three iron atoms for every four oxygen atoms. Many minerals contain more complex chemical compounds that are made of several elements. However, even the elements in more complicated compounds occur in certain ratios.

Structure of Minerals

The crystal structure of a mineral affects the mineral's physical properties. Imagine you have three samples of halite. Each sample was found in a different country. They are all different sizes and shapes. They may have even been formed by different geologic processes. Will the samples all have the same crystal structure? Yes! All halite has the same chemical composition and the same crystal structure, despite physical differences.

Crystals in Minerals

The shape of the crystals of a mineral is determined by the way the atoms are arranged. When crystals grow large, you can see how the arrangement of atoms influences the shape. Notice how the large halite crystal in **Figure** 3.1 has square shapes. This shape is the result of the pattern of sodium and chlorine atoms in crystal. Now, compare the crystal in **Figure** 3.1 with the grains of salt magnified under a microscope shown in **Figure** 3.4. These small crystals have similar shapes to the large crystal. You can see that the shapes of the crystals are made up of squares. You can try this at home. If you sprinkle salt into your hand and look carefully at each grain of salt, you will see that it is perfect little cube.

Figure 3.4: When you look at grains of table salt under a microscope, you can see that the crystals are made of square shapes. (32)

Large crystals only form when they have room to grow. Often, crystals are very small. Even if you cannot see the individual crystals in a mineral sample, the atoms are still ordered in a regular, repeating pattern. This pattern can be used to help identify an unknown mineral sample. A trained scientist may be able to determine the crystal structure by the shape of a large crystal. If they cannot figure out the crystal structure by looking at the mineral, scientists use an instrument that uses X rays to find out how the atoms are arranged in a mineral sample.

A mineral has both a characteristic chemical composition and a characteristic crystal structure. Sometimes, minerals have the same chemical composition, but different crystal structures. What do you know about diamond and graphite? Diamonds are valued as gems for jewelry. They are also very hard. Graphite is used as pencil lead and has a slippery feel. Compare the diamond with the pencil lead in **Figure** 3.5. Diamond and graphite are both made of only carbon, but they are not the same mineral. The crystal structure of diamond differs from the crystal structure of graphite. The carbon atoms in graphite bond to form layers. The bonds between each layer are weak, so the sheets can slip past each other. The carbon atoms in diamonds bond together in all three directions to form a strong network. As a result, the properties of diamond differ from the properties of graphite.

Figure 3.5: Even though they are both made of carbon, diamonds and graphite have different characteristics. (26)

Groups of Minerals

Imagine you were in charge of organizing more than 100 minerals for an exhibit at a museum near you. You want the people who visit your exhibit to learn as much as possible about the minerals they see. How would you group the minerals together in your exhibit? **Mineralogists** are scientists who study minerals. They use a system that divides minerals into groups based on chemical composition and structure. Even though there are over 4,000 minerals, most minerals fit into one of eight mineral groups. Minerals with similar crystal structures are grouped together.

Silicate Minerals

Silicate minerals make up over 90 percent of Earth's crust. When you think of the Earth's crust, you may think of the people, animals or trees that live on the Earth's surface. Yet living organisms are made of organic matter and there is only a small amount of organic matter in Earth's crust. About 1,000 silicate minerals have been identified, making the silicate minerals the largest mineral group.

Silicates are minerals that contain silicon atoms bonded to oxygen atoms. The basic building block for all silicate minerals is called a tetrahedron, where one silicon atom is bonded to 4 oxygen atoms (**Figure** 3.6). Silicate minerals also often contain other elements, such as calcium, iron, and magnesium.

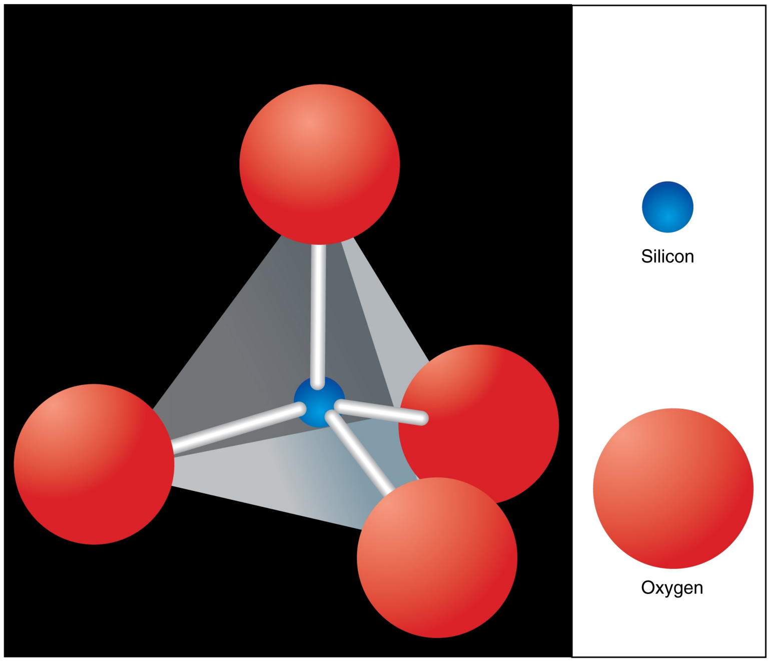

Figure 3.6: One silicon atom bonds to four oxygen atoms to form the building block of silicate minerals. (15)

Notice that the silicon and oxygen form a shape like a pyramid; this is the tetrahedron. The pyramid-shaped building blocks can combine together in numerous ways. The silicate mineral group is divided into six smaller groups, which are determined by the way the silicon-oxygen building blocks join together. The pyramids can stand alone, form into connected circles called rings, link into single and double chains, form large flat sheets of pyramids or join in three dimensions.

Feldspar and quartz are the two most common silicate minerals. Beryl is a silicate mineral, which forms rings from the tetrahedra. The gemstone emerald is a type of beryl that is green because of chemical impurities. Biotite is a mica, which is another silicate mineral that can be broken apart into thin, flexible sheets. Compare the beryl and the biotite shown in **Figure** 3.7.

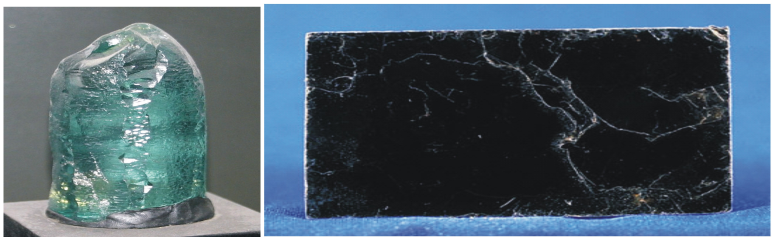

Figure 3.7: Beryl and biotite are both silicate minerals. (6)

Native Elements

Native elements are minerals that contain only atoms of one type of element. The elements are not combined with other elements. In nature most elements are combined with other elements to form chemical compounds. So, the native elements mineral group contains a relatively small number of minerals. Some of the minerals in this group are rare and valuable. Gold, silver, sulfur, and diamond are examples of native elements.

Carbonates

From the name "carbonate," what would you guess carbonate minerals contain? If you guessed carbon, you would be right! More specifically, all carbonates contain one carbon atom bonded to three oxygen atoms. Carbonates may include other elements, such as calcium, iron, and copper.

Carbonate minerals are often found in areas where ancient seas once covered the land. Some carbonate minerals are very common. Calcite is one such mineral. Calcite contains calcium, carbon, and oxygen. Have you ever been in a limestone cave or seen a marble tile? Calcite is in both limestone and marble. Azurite and malachite are also carbonate minerals, but they contain copper instead of calcium. They are not as common as calcite, as you can see in **Figure** 3.8, they are very colorful.

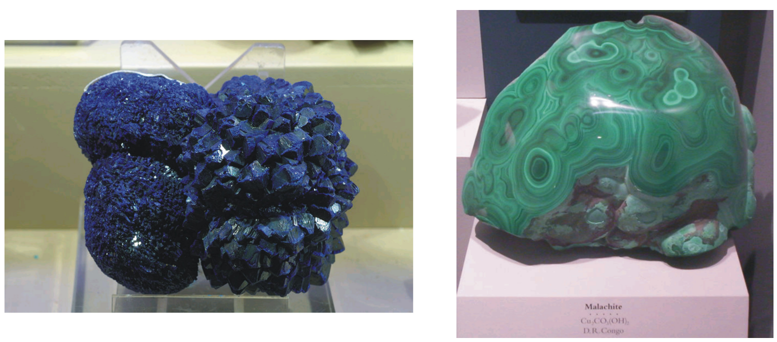

Figure 3.8: Azurite is a deep blue carbonate mineral. Malachite is an opaque green carbonate mineral. (20)

Halides

Halide minerals are salts that can form when salt water evaporates. This mineral class includes more than just table salt. It includes minerals that contain the elements fluorine, chlorine, bromine, or iodine. These elements combine with metal elements. Halite is a halide mineral that contains the elements chlorine and sodium. Fluorite is another type of halide that contains fluorine and calcium. Fluorite can be found in many colors. If you shine an ultraviolet light on some samples of fluorite, they will glow!

Oxides

Earth's crust contains a lot of oxygen, which combines with many other elements. Oxides are minerals that contain one or two metal elements combined with oxygen. Oxides are different from silicates because oxides do not contain silicon. Many important metals are found as oxides. For example, hematite and magnetite are both oxides that contain iron. Hematite (Fe_2O_3) has a ratio of two iron atoms to three oxygen atoms. Magnetite (Fe_3O_4) has a ratio of three iron atoms to four oxygen atoms. You might have noticed that the word *magnetite* contains the word *magnet.* Magnetite is a magnetic mineral.

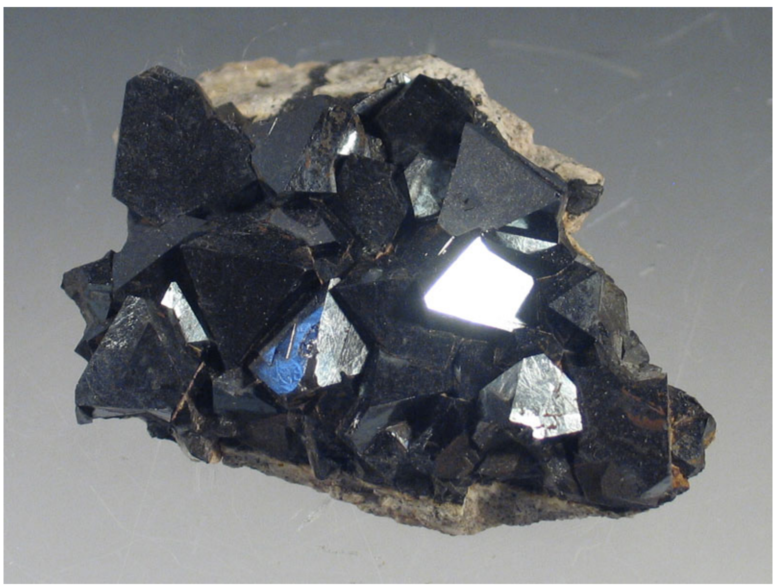

Figure 3.9: Magnetite (12)

Phosphates

Phosphates have a tetrahedron building block that is similar to that of the silicates. But, instead of silicon, phosphates have an atom of phosphorus, arsenic, or vanadium bonded to oxygen. Although there are many minerals in this group, most of the minerals are rare. The chemical composition of these minerals tends to be more complex than some of the other mineral groups. Turquoise is a phosphate mineral that contains copper, aluminum, and phosphorus. It is rare and is used to make jewelry.

Figure 3.10: Turquoise (5)

Sulfates

Sulfate minerals contain sulfur atoms bonded to oxygen atoms. Like halides, they can form in places where salt water evaporates. Many minerals belong in the sulfate group, but there are only a few common sulfate minerals. Gypsum is a common sulfate mineral that contains calcium, sulfate, and water. Gypsum is found in various forms. For example, it can be pink and look like it has flower petals. However, it can also grow into very large white crystals. Gypsum crystals that are 11 meters long have been found—that is about as long as a school bus! Gypsum also forms the white sands of White Sands National Monument in New Mexico, shown in **Figure** 3.11.

Sulfides

Sulfides contain metal elements combined with sulfur. Unlike sulfates, sulfides do not contain oxygen. Pyrite, a common sulfide mineral, contains iron combined with sulfur. Pyrite is also known as *fool's gold.* Gold miners have mistaken pyrite for gold because the two minerals look so similar.

Figure 3.11: The white gypsum sands at White Sands National Monument look like snow. (24)

Lesson Summary

- For a substance to be a mineral, it must be a naturally occurring, inorganic, crystalline solid that has a characteristic chemical composition and crystal structure.
- The atoms in minerals are arranged in regular, repeating patterns that can be used to identify a mineral.
- Minerals are divided into groups based on their chemical composition.

Review Questions

1. What is a crystal?
2. Which elements do all silicate minerals contain?
3. Obsidian is a glass that formed when lava cools so quickly that the atoms to not have a chance to arrange themselves in crystals. Is obsidian a crystal? Explain your reasoning.
4. What are the eight major mineral groups?
5. One mineral sample has a ratio of two iron atoms to three oxygen atoms. Another sample has a ratio of three iron atoms to four oxygen atoms. Explain whether the mineral samples are made of the same chemical compound.
6. How does the native elements mineral group differ from all of the other mineral groups?
7. You take a trip to the natural history museum with your friend. During your visit your friend sees two minerals that are similar in color. One mineral contains the elements zinc, carbon, and oxygen. The other mineral contains the elements zinc, silicon, oxygen, and hydrogen. Your friend tells you that the minerals are in the same mineral group. Would you agree with your friend? Explain your reasoning.

Further Reading / Supplemental Links

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Vocabulary

chemical compound A substance in which the atoms of two or more elements bond together.

crystal A solid in which all the atoms are arranged in a regular, repeating pattern.

element A substance in all of the atoms have the same number of protons.

mineral A naturally occurring, inorganic, crystalline solid with a characteristic chemical composition.

mineralogist A scientist who studies minerals.

silicates Minerals that contain silicon atoms bonded to oxygen atoms.

Points to Consider

- Scientists can make diamonds. The diamonds they make are called synthetic diamonds. Explain whether or not you think synthetic diamonds are minerals.
- Artists used to grind up the mineral azurite to make colorful pigments for paints. Is the powdered azurite still crystalline?
- What is one way you could tell the difference between two different minerals?

3.2 Identification of Minerals

Suppose you bought a new shirt with the money you saved from your allowance. How would you describe your shirt when you are talking to your best friend on the phone? You might describe the color, the way the fabric feels, and the length of the sleeves. These are all physical properties of your shirt. If you did a good job describing your shirt, your friend would recognize the shirt when you wear it. Minerals also have physical properties that are used to identify them.

Lesson Objectives

- Explain how minerals are identified.
- Describe how color, luster, and streak are used to identify minerals.
- Summarize specific gravity.
- Explain how the hardness of a mineral is measured.
- Describe the properties of cleavage and fracture.
- Identify additional properties that can be used to identify some minerals.

How are Minerals Identified?

Imagine you were given a mineral sample similar to the one shown in **Figure** 3.12. How would you try to identify your mineral? If you were a mineralogist, you would use certain properties to identify the mineral. **Mineralogists** are scientists who study minerals. You can observe some properties by looking at the mineral. For example, you can see that the mineral in **Figure** 3.12 is the color of gold and is shiny. But, you cannot see all mineral properties. You need to do simple tests to determine some properties, such as how hard the mineral is. You can use a mineral's properties to determine its identity because the properties are determined by the chemical composition and crystal structure, or the way that the atoms are arranged.

Figure 3.12: You can use the properties of a mineral to identify it. (22)

Color, Streak, and Luster

Diamonds have many valuable properties, but one of the reasons they are used in jewelry is because they are sparkly. Turquoise is another mineral that is used to make jewelry. However, turquoise is prized for its striking greenish-blue color. Even minerals that are not used to make jewelry often have interesting appearances. Specific terms are used to describe the appearance of minerals.

Color

Color is probably the easiest property to observe. Unfortunately, you can rarely identify a mineral only by its color. Sometimes different minerals are the same color. Take another look at **Figure** 3.12. The mineral is a gold color, so you might think that it is gold. The mineral is actually pyrite, or "fool's gold," which is made of iron and sulfide. It contains no gold atoms.

Often, the same mineral comes in different colors. **Figure** 3.13 shows two samples of quartz—one is colorless (although on a purple background) and one is purple. The purple color of the quartz comes from a tiny amount of iron in the crystal. The iron in quartz is a chemical impurity because it is not normally found in quartz. Many minerals are colored by chemical impurities. Other factors, such as weathering, can also affect a mineral's color. Weathering affects the surface of a mineral. Because color alone is unreliable, geologists identify minerals by several traits.


Figure 3.13: Even though these mineral samples are not the same color, they are both quartz. Amethyst is quartz that is purple. The white quartz on the left appears slightly purple only because it is on a purple background. (9)

Streak

Streak is the color of the powder of a mineral. To do a streak test, you scrape the mineral across an unglazed porcelain plate. The plate is harder than many minerals, causing the minerals to leave a streak of powder on the plate. The color of the streak often differs from the color of the larger mineral sample, as **Figure** 3.14 shows. If you did a streak test on the yellow-gold pyrite, you would see a blackish streak. This blackish streak tells you that the mineral is not gold because gold has a gold-colored streak.

Figure 3.14: You rub a mineral across an unglazed porcelain plate to determine the streak. The hematite shown here has a red-brown streak. (23)

Streak is a more reliable property than the color of the mineral sample. The color of a mineral may vary, but its streak does not vary. Also, different minerals may be the same color, but they may have a different color streak. For example, samples of hematite and galena can both be dark gray, but hematite has a red streak and galena has a gray streak.

Luster

Luster describes the way light reflects off of the surface of the mineral. You might describe diamonds as sparkly or pyrite as shiny, but mineralogists have special terms to describe the luster of a mineral. They first divide minerals into metallic and non-metallic luster. Minerals like pyrite that are opaque and shiny have a metallic luster. Minerals with a non-metallic luster do not look like metals. There are many types of non-metallic luster, six of which are described in the **Table** 3.1.

Table 3.1: **Minerals with Non-Metallic Luster**

Non-Metallic Luster	Appearance
Adamantine	Sparkly
Earthy	Dull, clay-like
Pearly	Pearl-like
Resinous	Like resins, such as tree sap
Silky	Soft-looking with long fibers
Vitreous	Glassy

(*Source:* http://en.wikipedia.org/wiki/Mineral, *License:* GNU-FDL)

Can you match the minerals in **Figure** 3.15 with the correct luster from **Table** (3.1 without looking at the caption?

Figure 3.15: Diamond has an adamantine luster. Quartz is not sparkly like a diamond is. It has a vitreous, or glassy, luster. Sulfur reflects less light than quartz, so it has a resinous luster. (8)

Density

You are going to visit a friend. You fill one backpack with books so you can study later. You stuff your pillow into another backpack that is the same size. Which backpack will be easier to carry? Even though the backpacks are the same size, the bag that contains your books is going to be much heavier. It has a greater density than the backpack with your pillow.

Density describes how much matter is in a certain amount of space. Substances that have more matter packed into a given space have higher densities. The water in a drinking glass has the same density as the water in a bathtub or swimming pool. All substances have characteristic densities, which does not depend on how much of a substance you have.

Mass is a measure of the amount of matter in an object. The amount of space an object takes up is described by its volume. So, density of an object depends on its mass and its volume. Density can be calculated using the following equation.

$$\text{Density} = \text{Mass/Volume}$$

Samples that are the same size, but have different densities, will have different masses. Gold has a density of about 19 g/cm^3. Pyrite has a density of only about 5 g/cm^3. Quartz is even less dense than pyrite and has a density of 2.7 g/cm^3. If you picked up a piece of pyrite and a piece of quartz that were the same size, the pyrite would seem almost twice as heavy as the quartz.

Hardness

Hardness is a mineral's ability to resist being scratched. Minerals that are not easily scratched are hard. You test the hardness of a mineral by scratching its surface with a mineral of a known hardness. Mineralogists use Mohs Scale, shown in **Table** 3.2, as a reference for mineral hardness. The scale lists common minerals in order of their relative hardness. You can use the minerals in the scale to test the hardness of an unknown mineral.

As you can see, diamond is a 10 on Mohs Scale. Diamond is the hardest mineral, which means that no other mineral can scratch a diamond. Quartz is a 7, so it can be scratched by topaz, corundum, and diamond. Quartz will scratch minerals, such as fluorite, that have a lower number on the scale. Suppose you tested a piece of pure gold for hardness. Calcite would scratch the gold, but gypsum would not because gypsum is a 2 and calcite is a 3. That would mean gold is between the hardness of gypsum and calcite, or 2.5 on the scale. A hardness of 2.5 means that gold is a relatively soft mineral. It is only about as hard as your fingernail.

Table 3.2: **Mohs Scale**

Hardness	Mineral
1	Talc
2	Gypsum
3	Calcite
4	Fluorite
5	Apatite
6	Orthoclase feldspar
7	Quartz
8	Topaz
9	Corundum
10	Diamond

(*Source:* `http://en.wikipedia.org/wiki/Mohs_scale,` *Adapted by:* Rebecca Calhoun, *License:* Public Domain)

Cleavage and Fracture

Minerals break apart in characteristic ways. Remember that all minerals are crystalline, which means that the atoms in a mineral are arranged in a repeating pattern. The pattern of atoms in a mineral determines how a mineral will break. When you break a mineral, you break chemical bonds. Because of the way the atoms are arranged, some bonds are weaker than other bonds. A mineral is more likely to break where the bonds between the atoms are weaker.

Cleavage is the tendency of a mineral to break along certain planes to make smooth surfaces. Minerals with different crystal structures will cleave in different ways, as **Figure** 3.16 shows. Halite tends to form cubes with smooth surfaces, mica tends to form sheets, and fluorite can form octahedrons.

Halite tends to form cubes when it cleaves. You can see how pieces of this halite crystal have broken off and formed smooth surfaces.

Mica tends to break off in sheets. You can see the layers of sheets that makeup this piece of mica.

Fluorite
Fluorite forms octahedrons, which have eight sides.

Figure 3.16: Minerals with different crystal structures have a tendency to break along certain planes. (17)

Minerals can form various shapes like the polygons, shown in **Figure** 3.17, when they are broken along their cleavage planes. The cleavage planes are important for people who cut gemstones, such as diamonds and emeralds. The planes determine how the crystals can be cut to make smooth surfaces.

Fracture describes how a mineral breaks when it is not broken along a cleavage plane. All minerals break but fracture describes a break when the resulting surface is not smooth and flat. You can learn about a mineral from the way it fractures. Jagged edges are usually formed when metals break. If a mineral splinters like wood it may be fibrous. Some minerals,

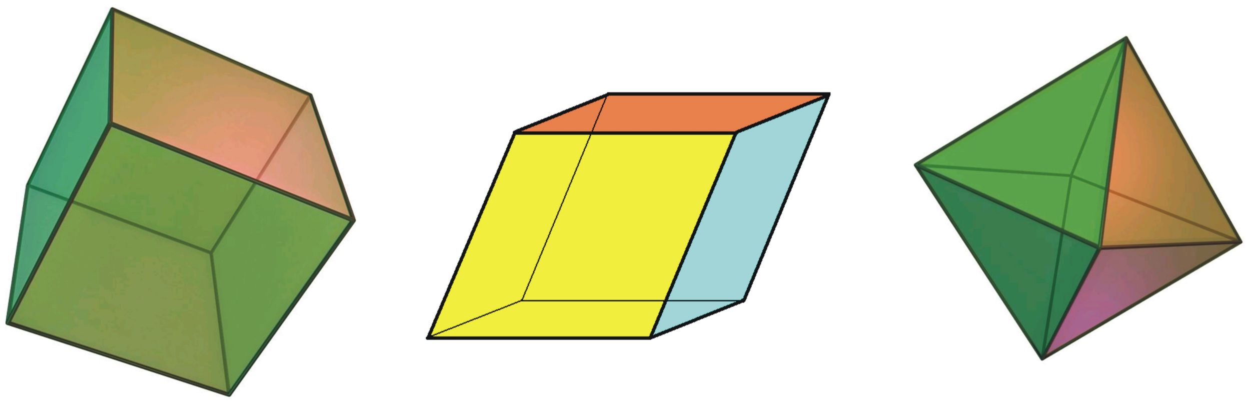

Figure 3.17: Cubes have six sides that are all the same size square. All of the angles in a cube are equal to 90°. Rhombohedra also have six sides, but the sides are diamond-shaped. Octahedra have eight sides that are all shaped like triangles. (4)

such as quartz, form smooth curved surfaces when they fracture. A mineral that broke forming a smooth, curved surface is shown in **Figure** 3.18.

Figure 3.18: This mineral formed a smooth, curved surface when it fractured (16)

Other Identifying Characteristics

Minerals have some other properties that can be used to identify them. For example, a mineral's crystal structure can be used to help identify the mineral. Sometimes, a trained mineralogist can tell the crystal structure just by looking at the shape of mineral. In other cases, the crystals in the mineral are too small to see and a mineralogist will use a special instrument that uses X rays to find out the crystal structure.

Some unusual and interesting properties can be used to identify certain minerals. Some of these properties are listed in the **Table** 3.3. Although these properties are rare, several minerals have them. An example of a mineral that has each property is also listed in the **Table** 3.3.

Table 3.3:

Property	Description	Example of Mineral
Fluorescence	Mineral glows under ultraviolet light	Fluorite
Magnetism	Mineral is attracted to a magnet	Magnetite
Radioactivity	Mineral gives off radiation that can be measured with Geiger counter	Uraninite
Reactivity	Bubbles form when mineral is exposed to a weak acid	Calcite
Smell	Some minerals have a distinctive smell	Sulfur (smells like rotten eggs)

Lesson Summary

- You can identify a mineral by its appearance and other properties.
- The color and luster describe the appearance of a mineral, and streak describes the color of the powdered mineral.
- A mineral has a characteristic density.
- Mohs hardness scale is used to compare the hardness of minerals.
- The way a mineral cleaves or fractures depends on the crystal structure of the mineral.
- Some minerals have special properties that can be used to help identify the mineral.

Review Questions

1. Which properties of a mineral describe the way it breaks apart?
2. A mineral looks dry and chalky. Why sort of luster does it have?
3. What causes a mineral to have the properties that it has?
4. You are trying to identify a mineral sample. Apatite scratches the surface of the mineral. Which mineral would you use next to text the mineral's hardness—fluorite or feldspar? Explain your reasoning.
5. Why is streak more reliable than color when identifying a mineral?

6. You have two mineral samples that are about the size of a golf ball. Mineral A has a density of 5 g/cm^3. Mineral B is twice as dense as Mineral A. What is the density of Mineral B?
7. Why do some minerals cleave along certain planes?

Further Reading / Supplemental Links

- http://en.wikibooks.org/wiki/Regents_Earth_Science_(High_School)#Properties_of_Minerals
- http://geology.csupomona.edu/alert/mineral/color.htm
- http://mineral.galleries.com/minerals/property/
- http://www.mindat.org/min-198.html
- http://geology.csupomona.edu/alert/mineral/streak.htm
- http://www.minsocam.org/MSA/collectors_corner/id/
- http://www.minerals.net/glossary/terms/r/resinous.htm
- http://mathworld.wolfram.com/Octahedron.html
- http://en.wikipedia.org/

Vocabulary

cleavage The tendency of a mineral to break along certain planes to make smooth surfaces.

density How much matter is in a certain amount of space; mass divided by volume.

fracture The way a mineral breaks when it is not broken along a cleavage plane.

hardness The ability to resist scratching.

luster The way light reflects off of the surface of the mineral.

mineralogist A scientist who study minerals.

streak The color of the powder of a mineral.

Points to Consider

- Some minerals are colored because they contain chemical impurities. How did the impurities get into the mineral?
- What two properties of a mineral sample would you have to measure to calculate its density?

3.3 Formation of Minerals

Minerals are all around you. They are used to make your house, your computer, even the buttons on your jeans. But, where do minerals come from? There are many types of minerals, and they do not all form in the same way. Some minerals form when salt water on Earth's surface evaporates. Others form from water mixtures that are seeping through rocks far below your feet. Still others form when mixtures of really hot molten rock cool.

Lesson Objectives

- Describe how melted rock produces minerals.
- Explain how minerals form from solutions.

Formation from Magma and Lava

You are on vacation at the beach. You take your flip-flops off to go swimming because it is one of the hottest days of the summer. The sand is so hot it hurts your feet, so you have to run to the water. Imagine if it were hot enough for the sand to melt. Some minerals start out in liquids that are that hot.

There are places inside Earth where rock will melt. Melted rock inside the Earth is also called molten rock, or **magma**. Magma is a molten mixture of substances that can be hotter than 1,000°C. Magma moves up through Earth's crust, but it does not always reach the surface. When magma erupts onto Earth's surface, it is known as **lava.** As lava flows from volcanoes it starts to cool, as **Figure** 3.19 shows. Minerals form when magma and lava cool.

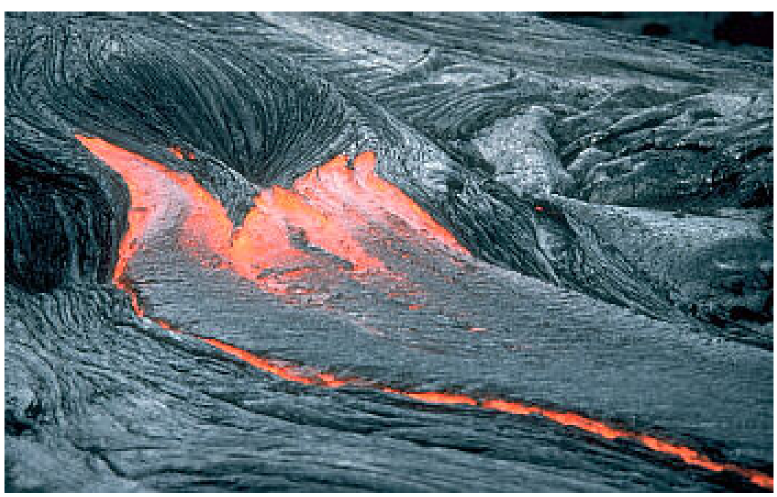

Figure 3.19: Lava is melted rock that erupts onto Earth's surface. (28)

Rocks from Magma

Magma cools slowly as it rises towards Earth's surface. It can take thousands to millions of years to become solid when it is trapped inside Earth. As the magma cools, solid rocks form. **Rocks** are mixtures of minerals. Granite, shown in the **Figure** 3.20, is a common rock that forms when magma cools. Granite contains the minerals quartz, plagioclase feldspar, and potassium feldspar. The different colored speckles in the granite are the crystals of the different minerals. The mineral crystals are large enough to see because the magma cools slowly, which gives the crystals time to grow.

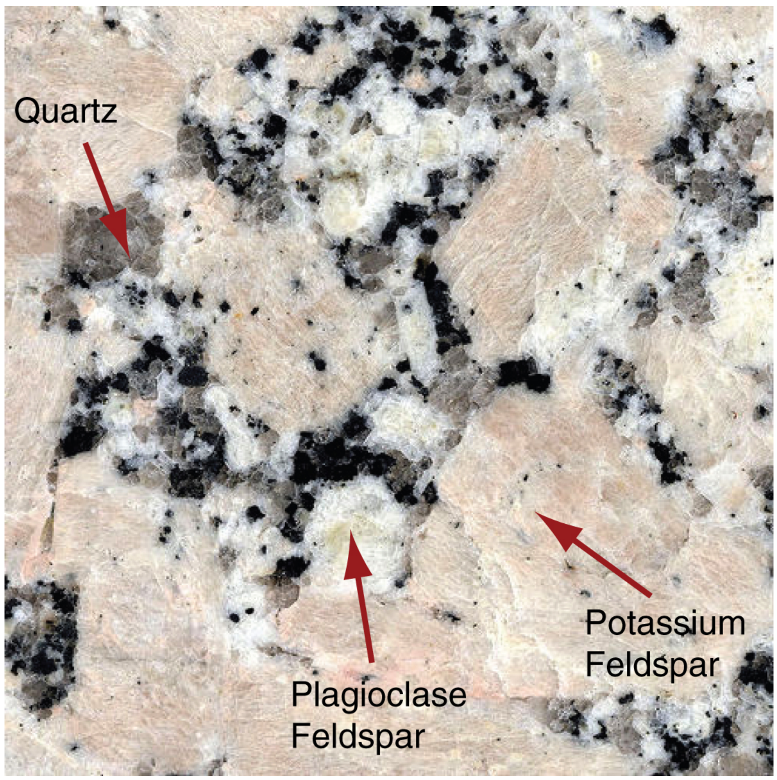

Figure 3.20: Granite is a type of rock that forms from magma. It contains the minerals quartz (clear), plagioclase feldspar (shiny white), potassium feldspar (pink), and other minerals. (27)

The magma mixture changes over time as different minerals crystallize out of the magma. A very small amount of water is mixed in with the magma. The last part of the magma to solidify contains more water than the magma that first formed rocks. It also contains rare chemical elements. The minerals formed from this type of magma are often valuable because they have concentrations of rare chemical elements. When magma cools very slowly, very large crystals can grow. These mineral deposits are good sources of crystals that are used to make jewelry. For example, magma can form large topaz crystals.

Minerals from Lava

Lava is on the Earth's surface so it cools quickly compared to magma in Earth. As a result, rocks form quickly and mineral crystals are very small. Rhyolite is one type of rock that is formed when lava cools. It contains similar minerals to granite. However, as you can see in **Figure** 3.21, the mineral crystals are much smaller than the crystals in the granite shown in **Figure** 3.20. Sometimes, lava cools so fast that crystals cannot form at all, forming a black glass called *obsidian*. Because obsidian is not crystalline, it is not a mineral.

Figure 3.21: Rhyolite rocks contain minerals that are similar to granite, but the crystal size is much smaller. (18)

Formation from Solutions

Minerals also form when minerals are mixed in water. Most water on Earth, like the water in the oceans, contains minerals. The minerals are mixed evenly throughout the water to make a solution. The mineral particles in water are so small that they will not come out when you filter the water. But, there are ways to get the minerals in water to form solid mineral deposits.

Minerals from Salt Water

Tap water and bottled water contain small amounts of dissolved minerals. For minerals to crystallize, the water needs to contain a large amount of dissolved minerals. Seawater and the water in some lakes, such as Mono Lake in California or Utah's Great Salt Lake. are salty enough for minerals to "precipitate out" as solids.

When water evaporates, it leaves behind a solid "precipitate" of minerals, which do not evaporate, as the **Figure** 3.22 shows. After the water evaporates, the amount of mineral left is the same as was in the water.

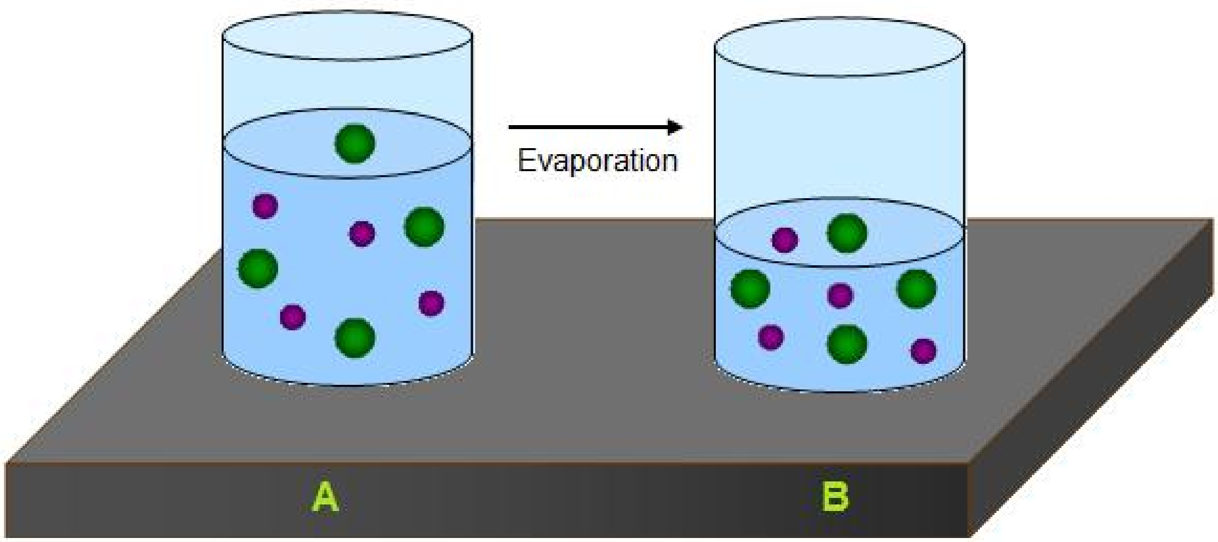

Figure 3.22: when the water in glass A evaporates, the dissolved mineral particles are left behind. (30)

Water can only hold a certain amount of dissolved minerals and salts. When the amount is too great to stay dissolved in the water, the particles come together to form mineral solids and sink to the bottom. Salt (halite) easily precipitates out of water, as does calcite, as the **Figure** 3.23 shows.

Minerals from Hot Underground Water

Cooling magma is not the only source for underground mineral formations. When magma heats nearby underground water, the heated water moves through cracks below Earth's surface.

Hot water can hold more dissolved particles than cold water. The hot, salty solution reacts with the rocks around it and picks up more dissolved particles. As it flows through open spaces in rocks, it deposits solid minerals. The mineral deposits that form when a mineral

Figure 3.23: The limestone towers are made mostly of calcite deposited in the salty and alkaline water of Mono Lake, in California. These rocks formed under water when calcium-rich spring water at the bottom of the lake bubbled up into the alkaline lake, forming theses calcite "tufa" towers. If the lake level drops, the tufa towers appear in interesting formations. (2)

fills cracks in rocks are called *veins.* **Figure** 3.24 shows white quartz veins. When the minerals are deposited in open spaces, large crystals can form. These special rocks are called geodes. **Figure** 3.25 shows a *geode* that was formed when amethyst crystals grew in an open space in a rock.

Figure 3.24: Quartz veins formed in this rock. (31)

Figure 3.25: An amethyst geode that formed when large crystals grew in open spaces inside the rock. (29)

Lesson Summary

- Mineral crystals that form when magma cools are usually larger than crystals that form when lava cools.
- Minerals are deposited from salty water solutions on Earth's surface and underground.

Review Questions

1. How does magma differ from lava?
2. What are two differences between granite and rhyolite?
3. What happens to the mineral particles in salt water when the water evaporates?
4. Explain how mineral veins form.

Further Reading / Supplemental Links

- Hydrothermal Mineral Deposit. (2007). In Encyclopedia Britannica. Retrieved 14, 2007, from Encyclopedia Britannica Online Library Edition. Available on the Web at:
- http://library.eb.com/eb/article-9041735.
- Mineral Deposit. (2007). In Encyclopedia Britannica. Retrieved 14, 2007, from Encyclopedia Britannica Online Library Edition. Available on the Web at:
- http://library.eb.com/eb/article-82171.
- http://socrates.berkeley.edu/~eps2/wisc/Lect3.html
- http://en.wikipedia.org/wiki/Mineralogy#Formation_environments
- http://volcanoes.usgs.gov/Products/Pglossary/magma.html
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- http://www.monolake.org/naturalhistory/chem.htm
- http://www.monolake.org/naturalhistory/tufa.htm
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- http://ut.water.usgs.gov/greatsaltlake/index.html
- http://en.wikipedia.org/

Vocabulary

lava Molten rock that has reached the Earth's surface.

magma Molten rock deep inside the Earth.

rocks Mixtures of minerals.

Points to Consider

- When most minerals form, they combine with other minerals to form rocks. How can these minerals be used?
- The same mineral can be formed by different processes. How can the way a mineral forms affect how the mineral is used?

3.4 Mining and Using Minerals

When you buy a roll of aluminum foil or some baby powder, do you think about how the products were made? Probably not. We take many everyday items that are made from minerals for granted. But, before the products can be put on store shelves, minerals have to be removed from the ground and made into the materials we need. A mineral deposit that contains enough minerals to be mined for profit is called an **ore.** Ores are rocks that contain concentrations of valuable minerals. The bauxite shown in the **Figure** 3.26 is a rock that contains minerals that are used to make aluminum.

Lesson Objectives

- Explain how minerals are mined.
- Describe how metals are made from mineral ores.
- Summarize the ways in which gemstones are used.
- Identify some useful minerals.

Figure 3.26: Aluminum is made from the minerals in rocks known as bauxite. (7)

Finding and Mining Minerals

Geologists need to find the ore deposits that are hidden underground. Different geologic processes concentrate mineral resources. They study geologic formations searching for areas that are likely to have ore deposits. They test the physical and chemical properties of soil and rocks. For example, they might test rocks to see if the rocks are magnetic or contain certain chemical elements. Then, geologists make maps of their findings to locate possible ore deposits. Today, satellites do some of the work for geologists. Satellites can make maps of large areas more quickly than geologists on the ground can.

After a mineral deposit is found, geologists determine how big it is. They also calculate how much of the valuable minerals they think they will get from mining the deposit. The minerals will only be mined if it is profitable. If is profitable to mine the ore, they decide the way it should be mined. The two main methods of mining are surface mining and underground mining.

Surface Mining

Surface mining is used to obtain mineral ores that are close to Earth's surface. The soil and rocks over the ore are removed by blasting. Typically, the remaining ore is drilled or blasted so that large machines can fill trucks with the broken rocks. The trucks take the rocks to factories where the ore will be separated from the rest of the rock. Surface mining includes open-pit mining, quarrying, and strip mining.

As the name suggests, open-pit mining creates a big pit from which the ore is mined. **Figure** 3.27 shows an open-pit diamond mine in Russia. The size of the pit grows until it is no longer profitable to mine the remaining ore. Strip mines are similar to pit mines, but the ore is removed in large strips. A quarry is a type of open-pit mine that produces rocks and minerals that are used to make buildings.

Figure 3.27: This diamond mine is more than 600 m deep. (21)

Placers are valuable minerals that have collected in stream gravels, either modern rivers or ancient riverbeds. California's nickname, the Golden State, can be traced back to the discovery of placer gold in 1848. The gold that attracted would-be miners from around the world weathered out of a hard rock, travelled downstream and then settled in a deposit of alluvium. The gold originated in the metamorphic belt in the western Sierra Nevada, which also contains deposits of copper, lead zinc, silver, chromite and other valuable minerals. Currently, California has active mines for gold and silver, and also for non-metal minerals like sand and gravel, which are used for construction.

Underground Mining

Underground mining is used for ores that are deep in Earth's surface. For deep ore deposits, it can be too expensive to remove all of the rocks above the ore. Underground mines can be very deep. The deepest gold mine in South Africa is more than 3,700 m deep (that is more than 2 miles)! There are various methods of underground mining. These methods are more expensive than surface mining because tunnels are made in the rock so that miners and equipment can get to the ore. Underground mining is dangerous work. Fresh air and lights must also be brought in to the tunnels for the miners. Miners breathe in lots of particles and dust while they are underground. The ore is drilled, blasted, or cut away from the surrounding rock and taken out of the tunnels. Sometimes there are explosions and sometimes mines collapse as ore is being drilled or blasted.

Mining and the Environment

Mining provides people with many resources they need, but care needs to be taken to reduce the environmental impact of mining. After the mining is finished, the area around the mine is supposed to be restored to its natural state. This process of restoring the natural area is called *reclamation.* Native plants are planted. Pit mines may be refilled or reshaped so that they can become natural areas again. They may also be allowed to fill with water and become lakes. They may also be turned into landfills. Underground mines may be sealed off or left open as homes for bats.

Mining can cause pollution. Chemicals released from mining can contaminate nearby water sources. **Figure** 3.28 shows water that is contaminated from a nearby mine. The United States government has standards that mines must follow to protect water quality. It is also important to use mineral resources wisely. It takes millions of years for new mineral deposits to form in Earth, so they are nonrenewable resources.

Figure 3.28: Scientists test water that has been contaminated by a mine. (10)

Making Metals from Minerals

We rely on metals, such as aluminum, copper, iron, and gold. Look around the room. How many objects have metal parts? Remember to include anything that uses electricity. Metals are used in the tiny parts inside your computer and on the outside of large building, such as the one shown in the **Figure** 3.29. Whether the metal makes the aluminum can that you drink out of or the copper wires in your computer, it started out as an ore. But the ore's journey to becoming a useable metal is only just beginning when the ore leaves the mine.

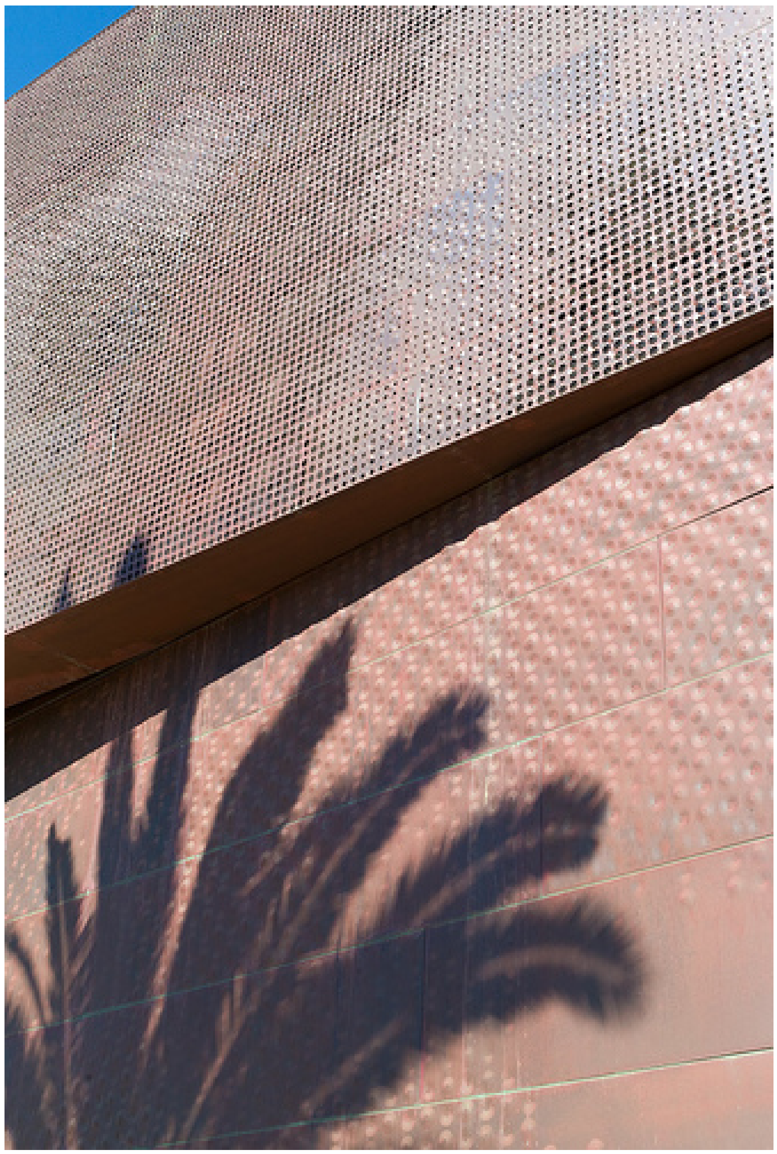

Figure 3.29: The De Young Museum in San Francisco is covered in copper panels. (14)

Mining produces a mixture of rocks that contain ore and other rocks that do not contain ore. So, the ore must be separated from unwanted rocks. Then, the minerals need to be separated out of the ore. The work is still not done once the mineral is separated from the unwanted materials (**Figure** 3.30).

Most minerals are not pure metals, but chemical compounds that contain metals and other elements. The minerals must go through chemical reactions to make pure metals. In order for the reactions to happen, chemicals must be added to ores that have been melted. High temperatures are needed to melt ores. Think about the ways you use aluminum foil in your home. It is put into hot ovens and over flames on a grill, but it does not melt. Making aluminum requires a lot of energy. Temperatures greater than 900°C are needed to make pure aluminum. Then, a huge amount of electricity is needed to separate the aluminum from other elements to produce pure aluminum. If you recycle just 40 aluminum cans, you will save the energy in one gallon of gasoline. We use over 80 billion cans each year. If all of these cans were recycled, we would save the energy in 2 billion gallons of gasoline!

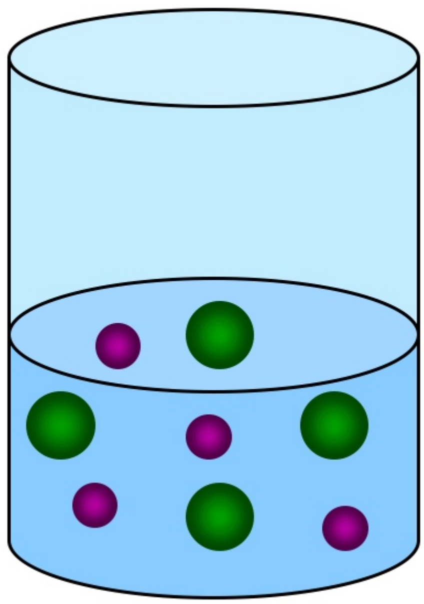

Figure 3.30: When the water in glass A evaporates, the dissolved mineral particles are left behind. (19)

Gemstones and Their Uses

Some minerals are valuable because they are beautiful. Jade has been used for thousands of years in China. Native Americans have been decorating items with turquoise since ancient times. Minerals like jade, turquoise, diamonds, and emeralds are gemstones. A **gemstone,** or gem, is a material that is cut and polished to use in jewelry. Many gemstones, such as those shown in the **Figure** 3.31, are minerals.

Figure 3.31: Gemstones come in many colors. (25)

In addition to being beautiful, gemstones are rare and do not break or scratch easily. Generally, rarer gems are more valuable. Other factors, such as how popular the gem is, its size and the way it is cut can also affect its value.

Most gemstones are not used exactly as they are found in nature. Gems are usually cut and polished. **Figure** 3.32 shows an uncut piece of ruby and a ruby that has been cut and polished. The way a mineral splits along a surface or cleaves determines how it can be cut to produce smooth surfaces. Notice that the cut and polished ruby seems more sparkly. Gems appear to be sparkly because light bounces back when it hits them. Some light passes through some gems, such as rubies and diamond. These gems are cut so that the most amount of light possible bounces back. Light does not pass through gemstones that are opaque, such as turquoise. So, these gems are not cut in the same way as diamonds and rubies.

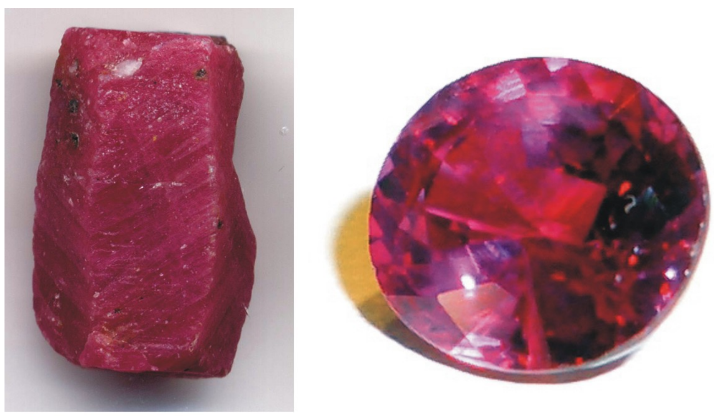

Figure 3.32: Ruby is cut and polished to make the gemstone sparkle(Left)Ruby Crystal(Right)Cut Ruby. (3)

Gemstones are known for their use in jewelry, but they do have other uses. Most diamonds are actually not used as gemstones. Diamonds are used to cut and polish other materials, such as glass and metals, because they are so hard. The mineral corundum, of which ruby and sapphire are varieties, is used in products like sandpaper. Synthetic rubies and sapphires are also used in lasers.

Other Useful Minerals

Metals and gemstones are often shiny, so they catch your eye. Many minerals that we use everyday are not so noticeable. For example, the buildings on your block could not have built without minerals. The walls in your home might use the mineral gypsum for the sheetrock. The glass in your windows is made from sand, which is mostly the mineral quartz. Talc was once commonly used to make baby powder. The mineral halite is mined for rock salt. Diamond is used as a gemstone but is commonly used in drill bits and saw blades to improve their cutting ability. Copper is used in electrical wiring and the ore bauxite is the source for the aluminum in your soda can.

Lesson Summary

- Geologists use many methods to find mineral deposits that will be profitable to mine.
- Ores that are close to the surface are mined by surface mining methods. Ores that are deep in Earth are mined using underground methods.
- Metals ores must be melted to make metals.
- Many gems are cut and polished to increase their beauty.
- Minerals are used in a variety of ways.

Review Questions

1. What type of mining would be used to extract an ore that is close to the Earth's surface?
2. Describe some methods used in surface mining.
3. What are some disadvantages of underground mining?
4. What are some ways an area can reclaimed, or returned to its natural state, after being mined?
5. What steps are taken to extract a pure metal from an ore?
6. What makes a gemstone valuable?

Further Reading / Supplemental Links

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Vocabulary

gemstone Any material that is cut and polished to use in jewelry.

ore A mineral deposit that contains enough minerals to be mined for profit.

Points to Consider

- Are all mineral deposits ores?
- An open-pit diamond mine may one day be turned into an underground mine. Why would this happen?
- Diamonds are not necessarily the rarest gem. Why do people value diamonds more than most other gems?

Image Sources

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(21) Stepanov Alexander. *This diamond mine is more than 600 m deep.*. GNU-FDL.

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(31) John C. Nichols, USDA National Forest Service. *Quartz veins formed in this rock.*. Public Domain.

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Chapter 4

Rocks

4.1 Types of Rocks

Lesson Objectives

- Define rock and describe what rocks are made of.
- Know how rocks are classified and described.
- Explain how each of the three main rock types are formed.
- Describe the rock cycle.

Introduction

Have you ever heard something described as "rock solid?" We usually use the phrase to describe something that does not and cannot change. It also means something is absolutely sure and will not fail or go wrong somehow. If we say a plan is rock solid that means the plan is a sure bet—it will not change and it will not go wrong. When you see pictures like this rocky mountainside in Costa Rica, it is easy to get the feeling that rocks neither change nor move, but instead always stay the same (**Figure** 4.1).

The Rock Cycle

The truth is, however, that rocks do change. All rocks on Earth change as a result of natural processes that take place all the time. These changes usually happen very slowly. They may even happen below Earth's surface so that we do not notice the changes. The physical and chemical properties of rocks are constantly changing in a natural, never-ending cycle called the rock cycle. The rock cycle describes how each of the main types of rocks is formed, and explains how rocks change within the cycle. This lesson will discuss the characteristics of

Figure 4.1: A rocky mountainside from Costa Rica. (16)

rocks, how rocks are classified, and details of the rock cycle. The following three lessons of this chapter will discuss the three main types of rocks in more detail.

A rock is a naturally-formed, nonliving Earth material. Rocks are made of collections of **mineral** grains that are held together in a firm, solid mass (**Figure** 4.2). The individual mineral grains that make up a rock may be so tiny that you can only see them with a microscope, or they may be as big as your fingernail. A rock may be made of grains of all one mineral type, or it may be made of a mixture of different minerals. Most rocks contain more than one mineral. Each rock has a unique set of minerals that make it up, and rocks are usually identified by the minerals observed in them. Since different minerals form under different environmental conditions, the minerals in a rock contain clues about the conditions, like temperature, that were present when the rock formed.

Rocks can also be described by their texture, which is a description of the size, shape, and arrangement of mineral grains. Rocks may be small pebbles less than a centimeter, or, they may be massive boulders that are meters wide (**Figure** 4.3). Smaller rocks form when larger rocks are broken apart and worn down.

Three Main Categories of Rocks

Rocks are classified according to how they were formed. The three main kinds of rocks are:

1. *Igneous Rocks* - form when **magma** (molten rock inside the Earth) or **lava** (molten rock that has erupted onto the surface of Earth) cools either at or below Earth's surface (**Figure** 4.4).

Figure 4.2: This rock contains several different minerals, as shown by the different colors and textures found in the rock. (11)

Figure 4.3: This massive boulder is an example of how large rocks can be. It is in Colorado Springs, Colorado. (17)

Figure 4.4: This flowing lava is an example of molten mineral material. It will harden into an igneous rock. (4)

2. *Sedimentary Rocks* - form by the compaction of **sediments**, like gravel, sand, silt or clay (**Figure** 4.5). Sediments may include fragments of other rocks that have been worn down into small pieces, materials made by a living organism or **organic** materials, or chemical **precipitates**, which are the solid materials left behind after a liquid evaporates. For example, if a glass of salt water is left in the sun, the water will eventually evaporate, but salt crystals will remain behind as precipitates in the bottom of the glass.

Figure 4.5: This sandstone is an example of a sedimentary rock. It formed when many small pieces of sand were cemented together to form a rock. (12)

3. *Metamorphic Rocks* - form when an existing rock (of any type) is changed by heat or pressure within the Earth, so that the minerals undergo some kind of change (**Figure** 4.6).

Figure 4.6: This quartzite is an example of a metamorphic rock. It formed when sandstone was changed by heat and pressure within the Earth. (2)

Rocks can be changed from one type to another, and the rock cycle describes how this happens. **Figure** 4.7 shows the rock cycle, and how the three main rock types are related to each other. The arrows within the circle show how one type of rock may change to rock of another type. For example, igneous rock may break down into small pieces of sediment and become sedimentary rock, or it may be buried within the Earth and become metamorphic rock, or it may change back to molten material and re-cool into a new igneous rock.

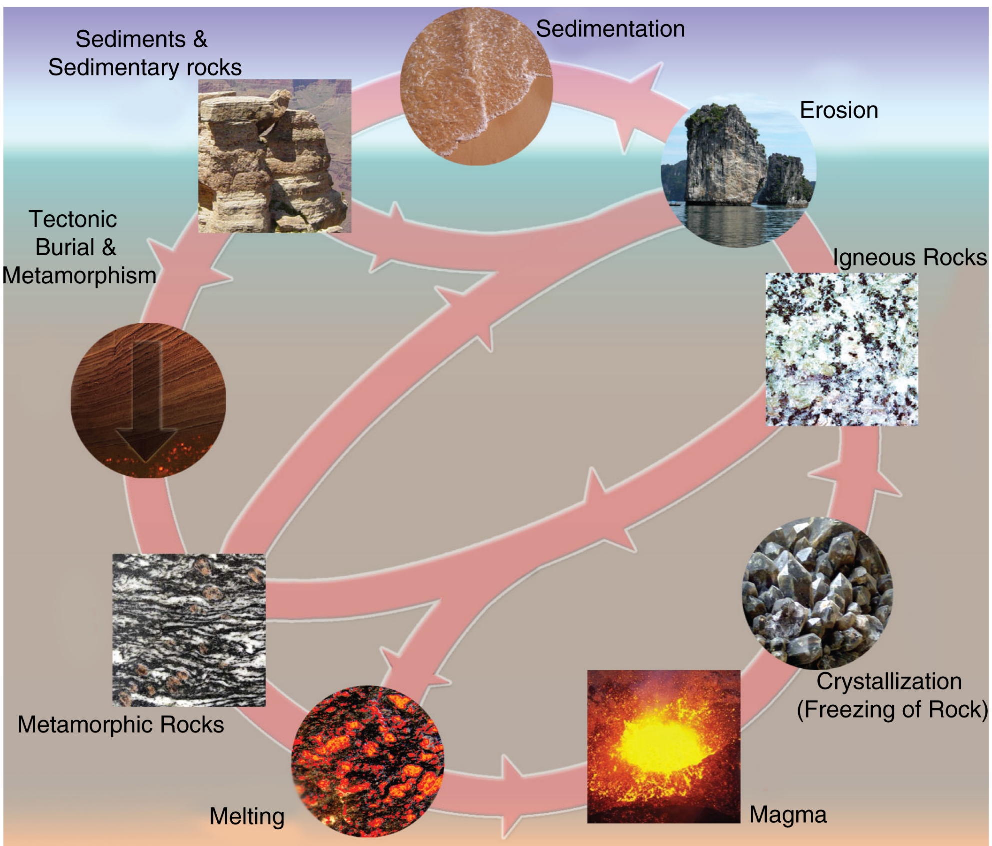

Figure 4.7: The Rock Cycle. (5)

Processes of the Rock Cycle

Any type of rock can undergo changes and become any new type of rock. Several processes are involved in the rock cycle that make this possible. The key processes of the rock cycle are crystallization, erosion and sedimentation, and metamorphism. Let's take a closer look at each of these:

Crystallization. Crystallization occurs when molten material hardens into a rock. An existing rock may be buried deep within the earth, melt into magma and then crystallize into an igneous rock. The rock may then be brought to Earth's surface by natural movements of the Earth. Crystallization can occur either underground when magma cools, or on the earth's surface when lava hardens.

Erosion and Sedimentation. Pieces of rock at Earth's surface are constantly worn down into smaller and smaller pieces. The impacts of running water, gravity, ice, plants, and animals all act to wear down rocks over time. The small fragments of rock produced are called sediments. Running water and wind transport these sediments from one place to another. They are eventually deposited, or dropped somewhere. This process is called erosion and sedimentation. The accumulated sediment may become compacted and cemented together into a sedimentary rock. This whole process of eroding rocks, transporting and depositing them, and then forming a sedimentary rock can take hundreds or thousands of years.

Metamorphism. Sometimes an existing rock is exposed to extreme heat and pressure deep within the Earth. Metamorphism happens if the rock does not completely melt but still changes as a result of the extreme heat and pressure. A metamorphic rock may have a new mineral composition and/or texture.

An interactive rock cycle diagram can be found here: Rock Cycle(http://www.classzone.com/books/earth_science/terc/content/investigations/es0602/es0602page02.cfm?chapter_no=investigation)

Note that the rock cycle really has no beginning and no end: therefore, it's a never-ending cycle. The concept of the rock cycle was first developed by James Hutton, an eighteenth century scientist often called the "father of geology" (**Figure** 4.8). Hutton spoke of the cyclic nature of rock formation and other geologic processes and said that they have "no [sign] of a beginning, and no prospect of an end." The processes involved in the rock cycle take place over hundreds or even thousands of years, and so in our lifetime, rocks appear to be fairly "rock solid" and unchanging. However, a study of the rock cycle shows us that change is always taking place. The next three lessons of this chapter will discuss each type of rock in more detail.

Lesson Summary

- There are three main types of rocks; igneous, sedimentary and metamorphic.
- Crystallization, erosion and sedimentation and metamorphism transform one type of rock into another type of rock or change sediments into rock.
- The rock cycle describes the transformations of one type of rock to another.

Figure 4.8: James Hutton is considered the "Father of Geology." (6)

Review Questions

1. Describe the difference between a rock and a mineral.
2. Why can the minerals in a rock be a clue about how the rock formed?
3. What is the difference between magma and lava?
4. What are the 3 main types of rocks and how does each form?
5. Describe how an igneous rock can change to a metamorphic rock.
6. Explain how sediments form.
7. In which rock type do you think fossils, which are the remains of past living organisms, are most often found?
8. Suppose that the interior of the Earth was no longer hot, but all other processes on Earth continued unchanged. How would this affect the distribution of rocks formed on Earth?

Vocabulary

chemical composition Description of the elements or compounds that make up a substance and how those elements are arranged in the substance.

deposited Put down or dropped by water or wind onto the ground.

lava Molten rock at the surface of Earth.

magma Molten rock below Earth's surface.

mineral Naturally-occurring solid that has a definite crystal structure.

molten Something that is melted.

organic Having to do with living things.

precipitates Solid substance that separates out of a liquid; a solid substance that was once dissolved in a liquid and gets left behind when the liquid evaporates.

sediments Small particles of soil or rock deposited by wind or water.

Points to Consider

- What processes on Earth are involved in forming rocks?
- Stone tools were important to early humans. Do you think rocks are still important to modern humans today?

4.2 Igneous Rocks

Lesson Objectives

- Describe how igneous rocks are formed.
- Describe the properties of some common types of igneous rocks.
- Relate some common uses of igneous rocks.

Introduction

This lesson will discuss igneous rocks, how they form, how they are classified, and some of their common uses. Igneous rocks may or may not be found naturally where you live, but chances are that you have seen materials made from igneous rocks. One of the most common igneous rocks is granite (**Figure** 4.9). Granite is used extensively in building materials and making statues. Perhaps you have used a pumice stone to smooth your skin or to do jobs around the house. Pumice is another example of an igneous rock (**Figure** 4.10). Pumice is used to make stone-washed denim jeans! Pumice stones are put into giant washing machines with newly-manufactured jeans and tumbled around to give jeans that distinctive "stone-washed" look. You also probably use igneous rock when you brush your teeth every morning. Ground up pumice stone is sometimes added to toothpaste to act as an abrasive material that scrubs your teeth clean.

Figure 4.9: Granite is an igneous rock used commonly in statues and building materials. (21)

Figure 4.10: Pumice is a light igneous rock used for abrasive materials. (18)

Crystallization

Igneous rocks form when molten material cools and hardens. They may form either below or above Earth's surface. They make up most of the rocks on Earth. Most igneous rock is buried below the surface and covered with sedimentary rock, and so we do not often see just how much igneous rock there is on Earth. In some places, however, large areas of igneous rocks can be seen at Earth's surface. **Figure** 4.11 shows a landscape in California's Sierra Nevada that consists entirely of granite, an igneous rock.

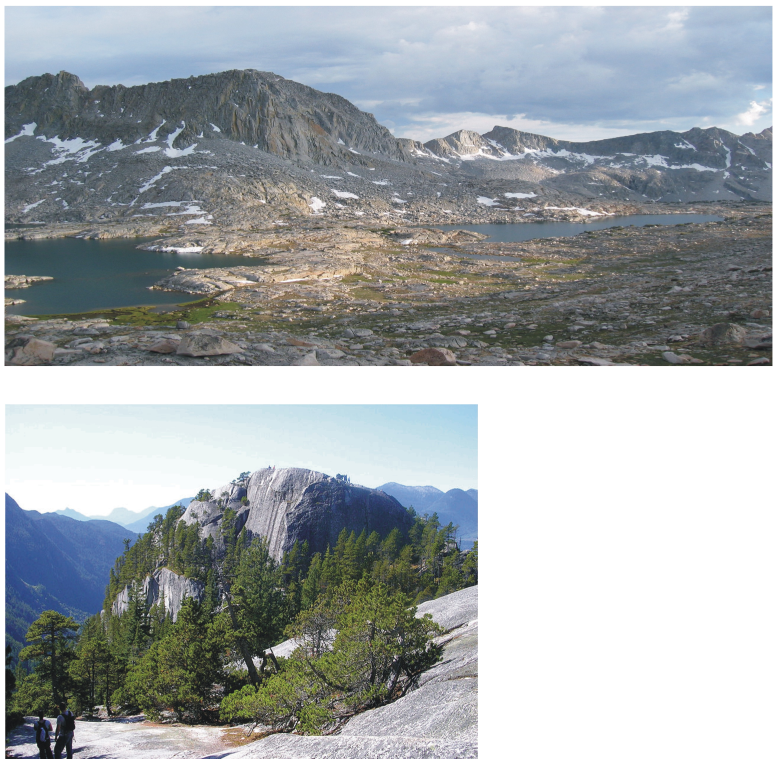

Figure 4.11: This landscape high in California's Sierra Nevada is completely made up of granite exposed at Earth's surface. (25)

Igneous rocks are called **intrusive** when they cool and solidify beneath the surface. Because they form within the Earth, cooling can proceed slowly, as discussed in the chapter "Earth's Minerals." Because such slow cooling allows time for large crystals to form, intrusive igneous rock has relatively large mineral crystals that are easy to see. Granite is the most common intrusive igneous rock (**Figure** 4.12).

Igneous rocks are called **extrusive** when they form above the surface. They **solidify** after molten material pours out onto the surface through an opening such as a volcano (**Figure** 4.13). Extrusive igneous rocks cool much more rapidly than intrusive rocks. They have smaller crystals, since the rapid cooling time does not allow time for large crystals to form. Some extrusive igneous rocks cool so rapidly that crystals do not develop at all. These form

Figure 4.12: A close-up of a granite sample. Notice the black and white portions. Each color represents a different mineral in the rock. You can easily see the mineral crystals that make up this intrusive igneous rock. (22)

a glass, such as obsidian (**Figure** 4.14). Others, such as pumice, contain holes where gas bubbles were trapped when the material was still hot and molten. The holes make pumice so light that it actually floats in water. The most common extrusive igneous rock is basalt, a rock that is especially common below the oceans (**Figure** 4.15).

Figure 4.13: Extrusive igneous rocks form after lava cools above the surface. The lava spills out from the Earth at a volcano. (14)

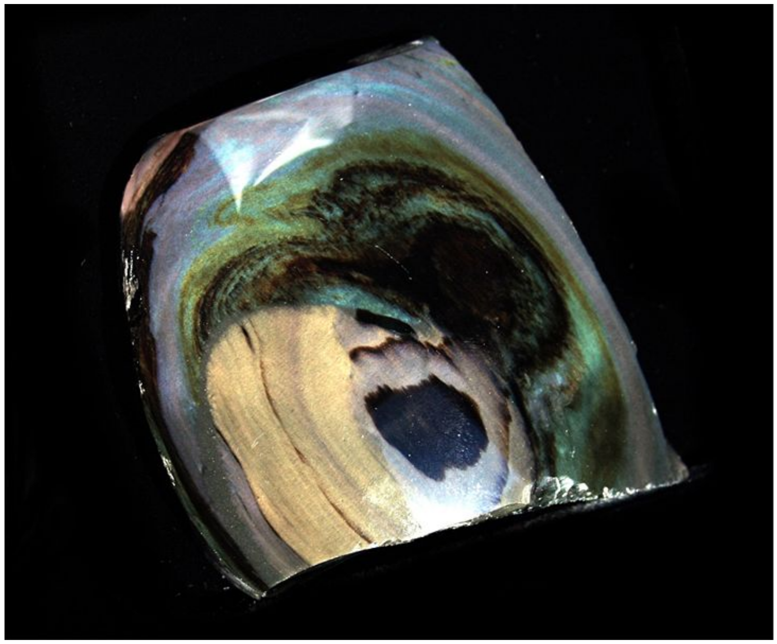

Figure 4.14: Obsidian is an extrusive igneous rock. It cools so rapidly that crystals do not form, and it has a glassy texture. (20)

Figure 4.15: These are examples of basalt below the South Pacific Ocean. Basalt is an extrusive igneous rock common below the oceans, though it is also found in some places on continents. (1)

Composition

Igneous rocks are classified according to how and where they formed (in other words, if they're intrusive or extrusive) and their mineral composition (describing the minerals they contain). The mineral compositions of igneous rocks are usually described as being felsic, intermediate, mafic, or ultramafic (as examples, see **Figure** 4.16 and **Figure** 4.17). Felsic rocks are made of light-colored, low-density minerals such as quartz and feldspar. Mafic rocks are made of dark-colored, higher-density minerals such as olivine and pyroxene. Intermediate rocks have compositions between felsic and mafic. Ultramafic rocks contain more than 90% mafic minerals and have very few light, felsic minerals in them. **Table** 4.1 shows some common igneous rocks classified by mode of occurrence and mineral composition.

Table 4.1: **Common Igneous Rocks**

Mode of Occurrence	Mineral Composition			
	Felsic	**Intermediate**	**Mafic**	**Ultramafic**
Extrusive	Rhyolite	Andesite	Basalt	Komatiite
Intrusive	Granite	Diorite	Gabbro	Peridotite

The rocks listed in the table above are the most common igneous rocks, but there are actually more than 700 different types of igneous rocks. Granite is perhaps the most useful one to humans. We use granite in many building materials and in art. As discussed in the introduction to this lesson, pumice is commonly used for abrasives. Peridotite is sometimes mined for peridot, a type of gemstone used in jewelry. Diorite is extremely hard and is commonly used for art. It was used extensively by ancient civilizations for vases and other decorative art work (**Figure** 4.18).

Lesson Summary

- Igneous rocks form either when they cool very slowly deep within the Earth or when magma cools rapidly at the Earth's surface.
- Composition of the magma will determine the minerals that will crystallize forming different types of igneous rocks.

Review Questions

1. What is the difference between an intrusive and an extrusive igneous rock?
2. Why do extrusive igneous rocks usually have smaller crystals than intrusive igneous rocks?
3. How are igneous rocks classified?

Figure 4.16: Rhyolite is an example of an extrusive felsic rock. Notice its light color and small crystals. (23)

Figure 4.17: This is a close-up photograph of peridotite, an extrusive ultramafic igneous rock. The green mineral is olivine. (10)

Figure 4.18: This vase was made by ancient Egyptians about 3,600 BC. It is made of the igneous rock diorite. (3)

4. Describe two ways granite is different from basalt.
5. List three common uses of igneous rocks.
6. Occasionally, igneous rocks will contain both large crystals and tiny mineral crystals. Propose a way that both these size crystals might have formed in the rock.
7. Why is the ocean floor more likely to have extrusive rocks than intrusive rocks?

Vocabulary

outcrop An exposure of rock that can be seen on the surface of Earth.

solidify To harden after cooling.

intrusive A type of igneous rock that forms inside the Earth.

extrusive A type of igneous rock that forms above Earth's surface.

felsic A type of igneous rock composition that is made mostly of light minerals such as quartz and feldspar.

mafic A type of igneous rock composition that is made mostly of dense, dark minerals like olivine and pyroxene.

intermediate A type of igneous rock composition that is in between felsic and mafic.

ultramafic A type of igneous rock that contains more than 90% mafic minerals.

Points to Consider

- Do you think igneous rocks could form where you live?
- Would all igneous rocks with the same composition have the same name? Explain why they might not.
- Could an igneous rock cool at two different rates? What would the crystals in such a rock look like?

4.3 Sedimentary Rocks

Lesson Objectives

- Describe how sedimentary rocks are formed.
- Describe the properties of some common sedimentary rocks.
- Relate some common uses of sedimentary rocks.

Introduction

Figure 4.19: The White House of the United States of America is made of a sedimentary rock called sandstone. (15)

You probably recognize the **Figure** 4.19 as the White House, the official home and workplace of the President of the United States of America. Do you know why the White House is white? Its color has a lot to do with the stone materials that were used to construct it.

Construction for the White House began in 1792, and most of the work was carried out by people who had only recently come to the newly formed country of America. Its outside walls are made of a type of sedimentary rock called sandstone. The sandstone that was used to construct the White House is very porous, which means that rainwater can easily penetrate the sandstone. This made the White House susceptible to water damage in its early days of construction. To stop the water damage, workers had to cover the sandstone in a mixture of salt, rice, and glue, giving the White House its distinct white color.

Sediments

In this lesson, you will learn about sedimentary rocks like sandstone, how they form, how they are classified, and how people often use sedimentary rocks.

Recall from Lesson 4.1 that sedimentary rocks are formed by the compaction of sediments. **Sediments** may include:

- fragments of other rocks that have been worn down into small pieces, like sand
- **organic** materials, or in other words, the remains of once-living organisms,
- or chemical **precipitates,** which are materials that get left behind after the water evaporates from a solution.

Most sediments settle out of water (**Figure** 4.20). For example, running water in rivers carries huge amounts of sediments. The river dumps these sediments along its banks and at the end of its course. When sediments settle out of water, they form horizontal layers. One layer at a time is put down. Each new layer forms on top of the layers that were already there. Thus, each layer in a sedimentary rock is younger than the layer under it and older than the layer over it. When the sediments harden, the layers are preserved. In large **outcrops** of sedimentary rocks, you can often see layers that show the position and order in which the original sediment layers were deposited. Scientists can figure out the relative ages of layers by knowing that older ones are on the bottom and younger ones are on top.

Figure 4.20: Most sediments settle out of running water, such as in this river. (13)

There are many different types of environments where sedimentary rocks form. Some places where you can see large deposits of sediments today include a beach and a desert. Sediments are also continuously depositing at the bottom of the ocean and in lakes, ponds, rivers, marshes and swamps. Avalanches produce large unsorted piles of sediment. The environment where the sediments are deposited determines the type of sedimentary rock that will form there.

Sedimentary Rock Formation

Sediments accumulate and over time may be hardened into rock. **Lithification** is the hardening of layers of loose sediment into rock (**Figure** 4.21). Lithification is made up of two processes: cementation and compaction. **Cementation** occurs when substances crystallize or fill in the spaces between the loose particles of sediment. These cementing substances come from the water that moves through the sediments. Sediments may also be hardened into rocks through **compaction.** This occurs when sediments are squeezed together by the weight of layers on top of them. Sedimentary rocks made of cemented, non-organic sediments are called *clastic* rocks. Those that form from organic remains are called *bioclastic* rocks, and sedimentary rocks formed by the hardening of chemical precipitates are called *chemical* sedimentary rocks. **Table** 4.2 shows some common types of sedimentary rocks and the types of sediments that make them up.

Figure 4.21: This cliff is made of a sedimentary rock called sandstone. The bands of white and red represent different layers of sediment. The layers of sediments were preserved during lithification. (9)

Table 4.2: **Common Sedimentary Rocks**

Picture	Rock Name	Type of Sedimentary Rock
	Conglomerate	Clastic (fragments of non-organic sediments)

Table 4.2: (continued)

Picture	Rock Name	Type of Sedimentary Rock
	Breccia	Clastic
	Sandstone	Clastic
	Siltstone	Clastic
	Shale	Clastic
	Rock Salt	Chemical precipitate

Table 4.2: (continued)

Picture	Rock Name	Type of Sedimentary Rock
 	Rock Gypsum	Chemical precipitate
	Dolostone	Chemical precipitate
	Limestone	Bioclastic (sediments from organic materials, or plant or animal remains)
	Coal	Organic

Note from the pictures in the table that clastic sedimentary rocks vary in the size of their sediments. Both conglomerate and breccia are made of individual stones that have been cemented together. In conglomerate, the stones are rounded; in breccia, the stones are angular around the edges. Sandstone is made of smaller, mostly sand-sized particles cemented together. Siltstone is made mostly of silt, particles that are smaller than sand but larger than clay. Shales have the smallest grain size, being made mostly of clay-sized particles and hardened mud.

Lesson Summary

- Weathering and erosion produce sediments. Once these sediments are deposited, they can become sedimentary rocks.
- Sediments must be compacted and cemented to make sedimentary rock. This process is called lithification.

Review Questions

1. What are three things that the sediments in sedimentary rocks may be made of?
2. If you see a sedimentary rock outcrop and red layers of sand are on top of pale layers of sand, what do you know for sure about the ages of the two layers?
3. Why do sedimentary rocks have layers of different colors sometimes?
4. Describe the two processes necessary for sediments to harden into rock.
5. What type of sedimentary rock is coal?
6. Think back to the story at the start of the lesson about why the White House originally was white. Why do you think sandstone would be a particularly porous rock?

Vocabulary

crystal Solid substance that has a regular geometric arrangement.

outcrop Large rock formation at the surface of the Earth.

fossil Something that is left behind by a once-living organism, such as bones or footprints.

organic Made from materials that were once living things.

precipitate The solid materials left behind after a liquid evaporates.

compaction Occurs when sediments are hardened by being squeezed together by the weight of layers on top of them.

cementation Occurs when substances harden crystallize in the spaces between loose sediments.

Points to Consider

- If you were interested in learning about Earth's history, which type of rocks would give you the most information?
- Could a younger layer of sedimentary rock ever be found under an older layer? How do you think this could happen?
- Could a sedimentary rock form only by compaction from intense pressure?

4.4 Metamorphic Rocks

Lesson Objectives

- Describe how metamorphic rocks are formed.
- Describe the properties of some common metamorphic rocks.
- Relate some common uses of metamorphic rocks.

Introduction

In this lesson you will learn about metamorphic rocks, how they form, and some of their common uses. **Figure** 4.22 shows a large outcrop of metamorphic rocks. Notice the platy layers that run from left to right within the rock. It looks as though you could easily break off layers from the front surface of the outcrop. This layering is a result of the process of metamorphism. Metamorphism is the changing of rocks by heat and pressure. During this process, rocks change either physically and/or chemically. They change so much that they become an entirely new rock.

Metamorphism

Metamorphic rocks start off as igneous, sedimentary, or other metamorphic rocks. These rocks are changed when heat or pressure alters the existing rock's physical or chemical make up. One ways rocks may change during metamorphism is by rearrangement of their mineral crystals. When heat and pressure change the environment of a rock, the crystals may respond by rearranging their structure. They will form new minerals that are more **stable** in the new environment. Extreme pressure may also lead to the formation of **foliation**, or flat layers in rocks that form as the rocks are squeezed by pressure. Foliation normally forms when pressure was exerted on a rock from one direction. If pressure is exerted from all directions, then the rock usually does not show foliation.

There are two main types of metamorphism:

Figure 4.22: The platy layers in this large outcrop of metamorphic rock show the effects of pressure on rocks during metamorphism. (19)

1. Contact metamorphism—occurs when magma contacts a rock, changing it by extreme heat (**Figure** 4.23).
2. Regional metamorphism—occurs when great masses of rock change over a wide area due to pressure deep within the earth or through extreme pressure from rock layers on top of it.

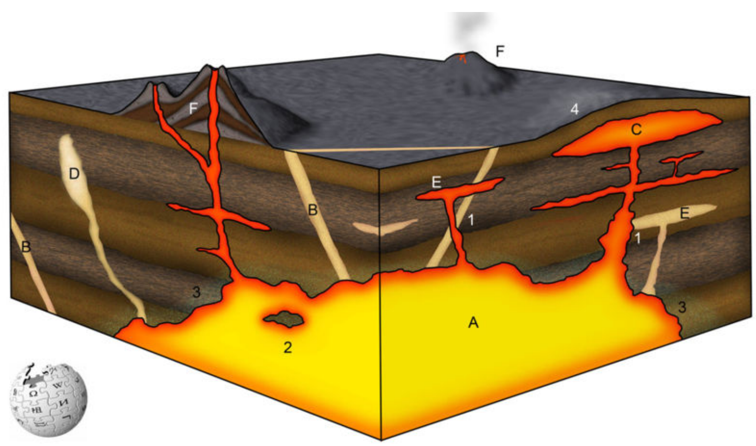

Figure 4.23: This diagram shows hot magma within the earth contacting various rock layers. This is an example of contact metamorphism. (7)

It is important to note that metamorphism does not cause complete melting of the initial rock. It only causes changes to a rock by heat or pressure. The rearrangement of the mineral crystals is the most common way that we notice these changes. **Table** 4.3 shows some common metamorphic rocks and the original rocks that they come from.

Table 4.3: **Common Metamorphic Rocks**

Picture	Rock Name	Type of Metamorphic Rock	Comments
	Slate	Foliated	Metamorphism of shale
	Phyllite	Foliated	Metamorphism of slate, but under greater heat and pressure than slate
	Schist	Foliated	Often derived from metamorphism of claystone or shale; metamorphosed under more heat and pressure than phyllite
	Gneiss	Foliated	Metamorphism of various different rocks, under extreme conditions of heat and pressure
	Hornfels	Non-foliated	Contact metamorphism of various different rock types

Table 4.3: (continued)

Picture	Rock Name	Type of Metamorphic Rock	Comments
	Quartzite	Non-foliated	Metamorphism of sandstone
	Marble	Non-foliated	Metamorphism of limestone
	Metaconglomerate	Non-foliated	Metamorphism of conglomerate

Hornfels, with its alternating bands of dark and light crystals is a good example of how minerals rearrange themselves during metamorphism. In this case, the minerals separated by density and became banded. Gneiss forms by regional metamorphism from both high temperature and pressure.

Quartzite and marble are the most commonly used metamorphic rocks. They are frequently chosen for building materials and artwork. Marble is used for statues and decorative items like vases (**Figure** 4.24). Ground up marble is also a component of toothpaste, plastics, and paper. Quartzite is very hard and is often crushed and used in building railroad tracks (**Figure** 4.25). Schist and slate are sometimes used as building and landscape materials.

Lesson Summary

- Metamorphic rocks form when heat and pressure transform an existing rock into a new rock.
- Contact metamorphism occurs when hot magma transforms rock that it contacts.
- Regional metamorphism transforms large areas of existing rocks under the tremendous heat and pressure created by tectonic forces.

Figure 4.24: Marble is used for decorative items and in art. (8)

Figure 4.25: Crushed quartzite is sometimes placed under railroad tracks because it is very hard and durable. (24)

Review Questions

1. Why do the minerals in a rock sometimes rearrange themselves when exposed to heat or pressure?
2. What is foliation in metamorphic rocks?
3. Describe the different conditions that lead to foliated versus non-foliated metamorphic rocks.
4. List and describe the two main types of metamorphism.
5. How can metamorphic rocks be a clue to how they were formed?
6. Suppose a phyllite sample was metamorphosed again. How might it look different after this second round of metamorphism.

Vocabulary

stable Steady and not likely to change significantly any more.

contact metamorphism Results from temperature increases when a body of magma contacts a cooler existing rock.

regional metamorphism Occurs when great masses of rock change over a wide area due to pressure.

foliation Property of some metamorphic rocks in which flat layers are formed; seen as evidence of squeezing by pressure.

Points to Consider

- What type of plate boundary would produce the most intense metamorphism of rock?
- Do you think new minerals could form when an existing rock is metamorphosed?

Image Sources

(1) http://en.wikipedia.org/wiki/Image:Pillow_basalt_crop_l.jpg. GNU-FDL.

(2) http://commons.wikimedia.org/wiki/Image:Quartzite.jpg. GNU-FDL.

(3) http://en.wikipedia.org/wiki/Diorite. GNU-FDL.

(4) http://en.wikipedia.org/wiki/Lava. GNU-FDL.

(5) *The Rock Cycle.*. GNU-FDL.

(6) http://en.wikipedia.org/wiki/Image:James_Hutton.jpg. GNU-FDL.

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(23) http://en.wikipedia.org/wiki/Rhyolite. GNU-FDL.

(24) http://en.wikipedia.org/wiki/Track_ballast. GNU-FDL.

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Chapter 5

Earth's Energy

5.1 Energy Resources

Lesson Objectives

- Compare ways in which energy is changed from one form to another.
- Discuss what happens when we burn a fuel.
- Describe the difference between renewable and nonrenewable resources, and classify different energy resources as renewable or nonrenewable.

Introduction

Did you know that everything you do takes energy? Even while you are sitting still, your body is using energy to breathe, to keep your blood circulating, and to control many different processes. But it's not just you. Everything that moves or changes in any way—from plants to animals to machines—needs energy. Have you ever wondered where all of this energy comes from?

The Need for Energy

Energy can be defined as the ability to move or change matter. Every living thing needs energy to live and grow. Your body gets its energy from food, but that is only a small part of the energy you use every day. Cooking your food takes energy, and so does keeping it cold in the refrigerator or the freezer. The same is true for heating or cooling your home. Whether you are turning on a light in the kitchen or riding in a car to school, you are using energy all day long. And because billions of people all around the world use energy, there is a huge need for resources to provide all of this energy. Why do we need so much energy?

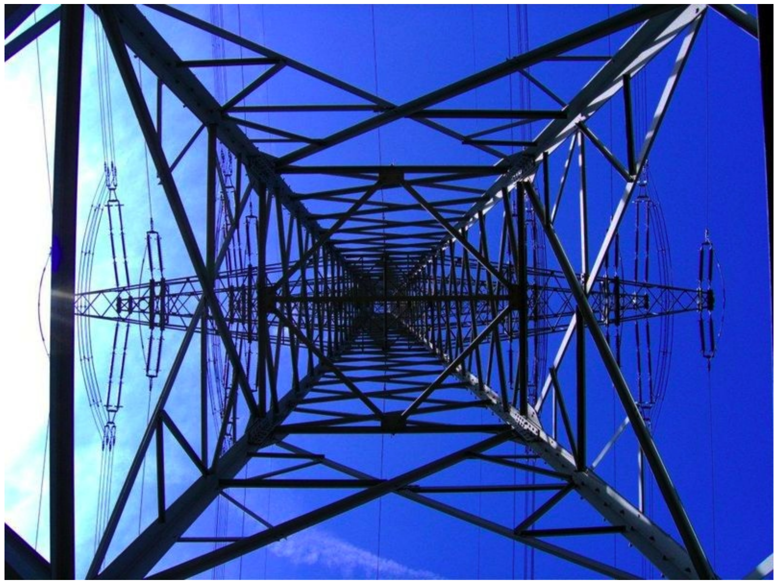


Figure 5.1: Electrical transmission towers like the one shown in this picture help deliver the electricity that you use for energy every day. (4)

The main reason is that almost everything that happens on Earth involves energy. Most of the time when something happens, energy is changing forms.

Even though energy does change form, the total amount of energy always stays the same. The Law of Conservation of Energy says that energy cannot be created or destroyed. Scientists discovered this law by noticing that any time they observed energy changing from one form to another, they could measure that the overall amount of energy did not change.

For an example of how energy changes from one form to another, think about what goes on when you kick a soccer ball. Your body gets its energy from food. When your body breaks down the food you eat, it stores the energy from the food in a form called **chemical energy**. But some of this stored energy has to be released to make your leg muscles move. When this happens, the energy that is released changes from chemical energy to another form, called **kinetic energy**. Kinetic energy is the energy of anything in motion. Your muscles move your leg, your foot kicks the ball, and the ball gains kinetic energy by being kicked. So you can think of the action of kicking the ball as a story of energy moving and changing forms. The same is true for anything that happens involving movement or change. **Potential energy** is energy that is stored. Potential energy has the potential to do work or the potential to be converted into other forms of energy. An example of potential energy might be the ball you kicked, if it ended up at the top of a hill.

Energy, Fuel, and Heat

As you have learned, energy is the ability to move or change matter. To put it another way, you could say that energy is the ability to do work. But what makes energy available whenever you need it? If you have ever accidentally unplugged a lamp while you were using it, you have seen that the lamp does not have a supply of energy to keep itself lit. When the lamp is plugged into an outlet, it has the source of energy it needs—electricity. The electricity comes from a power plant, and the power plant has to have energy to produce this electricity (**Figure** 5.1). The energy to make the electricity comes from a fuel, which stores the energy and releases it when it is needed. A fuel is any material that can release energy in a chemical change. The food you eat acts as a *fuel* for your body. You probably hear the word fuel most often when someone refers to its use in transportation. Gasoline and diesel fuel are two fuels that provide the energy for most cars, trucks, and buses. But many different kinds of fuel are used to meet the wide variety of needs for energy storage.

For a fuel to be useful, its energy must be released in a way that can be controlled. Controlling the release of the energy makes it possible for the energy to be used to do work. When a fuel is used for its energy, the fuel is usually burned, and most of the energy is released as heat. The heat can be used to do work. For an example of how the energy in a fuel is released mostly as heat, think about what happens when someone starts a fire in a fireplace. First, the person strikes a match and uses it to set some small twigs on fire. After the twigs have burned for a while, they get hot enough to make some larger sticks burn. The fire keeps getting hotter, and soon it is hot enough to burn whole logs.

You might think at first that the heat comes from starting the fire. After all, someone struck a match to start the fire, and then the fire just spread, right? But if you think about this fire in terms of energy, almost all of the heat comes from the energy that has been stored in the wood. In other words, the wood is the fuel for the fire. There is a reason why it is easy to be confused about the source of the fire's heat. The reason is that some energy has to be put into *starting* the fire before any energy can come out of the fire. At first, there is energy stored in the head of the match as chemical energy. When someone strikes a match, this chemical energy is released as heat.

The lit match gives off enough heat to set the twigs on fire. This heat is enough energy to start changing the chemical energy in the wood (and the oxygen in the air, which the wood needs in order to burn) into heat. What happens is that the heat from the match breaks chemical bonds in the twigs. When these bonds break, the atoms in the twigs are free to move around and form new bonds. When the atoms form new bonds, they release more heat. This heat causes more and more of the wood to change its stored chemical energy into heat. So, what started as a fairly small amount of heat from the match turns into a much, much larger amount of heat from the wood. The same thing is true for any fuel. We have to add some energy to the fuel to get it started. But once the fuel starts burning, it keeps changing its chemical energy into heat. As long as the conditions are right, the fuel will keep turning its energy into heat until the fuel is all gone.

Types of Energy Resources

Energy resources can be put into two categories—either renewable or nonrenewable. Resources that are *nonrenewable* are used faster than they can be replaced (**Figure** 5.2). Other resources that are called *renewable* will never run out. In most cases, these resources are replaced as quickly as they are used.

In a way, the difference between nonrenewable and renewable resources is like the difference between ordinary batteries and rechargeable ones. If you have a flashlight at home that uses ordinary batteries, and you accidentally leave the flashlight on all night long, you will need to buy new batteries once the ones in the flashlight have died. The energy in the ordinary batteries is nonrenewable. But if the flashlight has rechargeable batteries, you can put them in a battery charger and use them in the flashlight again. In this way, the energy in the rechargeable batteries is "renewable."

Fossil fuels are the most common example of nonrenewable energy resources. Renewable energy resources include solar, water, and wind power. If you traced the energy in all of these resources back to its origin, you would find that almost all energy resources—not just solar energy—come from the sun. Fossil fuels are made of the remains of plants and animals that stored the sun's energy millions of years ago. These plants and animals got all of their energy from the sun, either directly or indirectly. The sun heats some areas more than others, which causes wind. The sun's energy drives the water cycle, which moves water over the surface of the Earth. Both wind and water power can be used as renewable resources.

Types of Nonrenewable Resources

Fossil fuels, which include coal, oil, and natural gas are nonrenewable resources. Millions of years ago, plants used energy from the sun to form sugars, carbohydrates, and other energy-rich carbon compounds that were later transformed into coal, oil, or natural gas. The solar energy stored in these fuels is a rich source of energy, but while fossil fuels took millions of

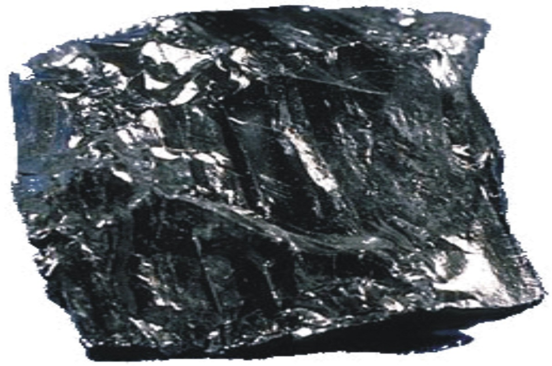


Figure 5.2: Like other fossil fuels, this piece of anthracite coal is a nonrenewable energy resource. (10)

years to form, we are using them up in a matter of decades and will soon run out. Fossil fuels are nonrenewable resources. The burning of fossil fuels also releases large amounts of the greenhouse gas carbon dioxide.

Types of Renewable Resources

Renewable energy resources include solar, water, wind, biomass, and geothermal power. These resources can usually be replaced at the same rate that we use them. Scientists know that the sun will continue to shine for billions of years and we can use the energy from the sun as long as we have a sun. Water flows from high places to lower ones and wind blows from areas of high pressure to areas of low pressure. We can use the flow of wind and water to generate power and we can count on wind and water to continue to flow. Some examples of biomass energy are burning something like wood or changing grains into biofuels. We can plant new trees or crops to replace the ones we use. Geothermal energy uses water in the rocks that has been heated by magma. The magma will heat more water in the rocks as we take hot water out.

Even renewable resources can come with problems, though. We could cut down too many trees or we might need grains to be used for food rather than biofuels. Some renewable resources have been too expensive to be widely used or cause some types of environmental problems. As the technology improves and more people use renewable energy, the prices may come down. And, as we use up fossil fuels, they will become more expensive. At some point, even if renewable energy is expensive, nonrenewable energy will be even more expensive. Ultimately, we will have to use renewable sources (and conserve).

Important Things to Consider About Energy Resources

With both renewable and nonrenewable resources, there are at least two important things to consider. One is that we have to have a practical way to turn the resource into a useful form of energy. The other is that we have to consider what happens when we turn the resource into energy.

For example, if we get much less energy from burning a fuel than we put into making it, then that fuel is probably not a practical energy resource. On the other hand, if another fuel gives us large amounts of energy but also creates large amounts of pollution, that fuel also may not be the best choice for an energy resource.

Lesson Summary

- According to the law of conservation of energy, energy is neither created or destroyed.
- Renewable resources can be replaced at the rate they are being used.
- Nonrenewable resources are available in limited amounts or are being used faster than they can be replaced.

Interdisciplinary Connection

Health: Read the nutrition labels on some food packages in your kitchen or at the grocery store. How is the energy in food measured? What are some foods that provide the most energy per serving? Are the foods that contain the most energy the most healthful foods?

Review Questions

1. What is needed by anything that moves or changes in any way
2. What is the original source of most of our energy?
3. When your body breaks down the food you eat, in what form does it store the energy from the food?
4. When we burn a fuel, what is released that allows work to be done?
5. For biomass, coal, natural gas, oil and geothermal energy, identify each energy resource as renewable or nonrenewable. Explain your reasoning.
6. What factors are important in judging how helpful an energy resource is to us?
7. Is a rechargeable battery a renewable source of energy? Explain.

Further Reading / Supplemental Links

- Kydes, Andy, ”Primary Energy.” Encyclopedia of Earth, 2006. Available on the Web at:

- http://www.eoearth.org/article/Primary_energy
- http://www.earthportal.org/

Vocabulary

chemical energy Energy that is stored in the connections between atoms in a chemical substance.

energy The ability to move or change matter.

fuel Material that can release energy in a chemical change.

kinetic energy The energy that an object in motion has because of its motion.

law of conservation of energy Law stating that energy cannot be created or destroyed.

potential energy Energy stored within a physical system.

Points to Consider

- How long do fossil fuels take to form?
- Are all fossil fuels nonrenewable resources?
- Do all fossil fuels affect the environment equally?

5.2 Nonrenewable Energy Resources

Lesson Objectives

- Describe the natural processes that formed different fossil fuels.
- Describe different fossil fuels, and understand why they are nonrenewable resources.
- Explain how fossil fuels are turned into useful forms of energy.
- Understand that when we burn a fossil fuel, most of its energy is released as heat.
- Describe how the use of fossil fuels affects the environment.
- Describe how a nuclear power plant produces energy.

Introduction

Have you ever seen dinosaur fossils at a museum? If so, you may have read about how the dinosaur bones turned into fossils. The same processes that formed these fossils also formed some of our most important energy resources. These resources are called fossil fuels. Fossil fuels provide a very high quality energy, but because of our demand for energy, we are using up these resources much faster than they formed.

Formation of Fossil Fuels

As you might guess from their name, fossil fuels are made from fossils. Fossil fuels come from materials that began forming about 500 million years ago. As plants and animals died, their remains settled on the ground and at the bottom of bodies of water. Over time, these remains formed layer after layer. Eventually, all of these layers were buried deep enough that they were under an enormous mass of earth. The weight of the earth pressing down on these layers created intense heat and pressure.

After millions of years of heat and pressure, the material in these layers turned into chemicals called *hydrocarbons,* which are compounds of carbon and hydrogen. The hydrocarbons in these layers are what we call fossil fuels. The hydrocarbons could be solid, liquid, or gaseous. The solid form is what we know as coal. The liquid form is petroleum, or crude oil. We call the gaseous hydrocarbons natural gas.

You may be surprised to learn that anything that used to be alive could change enough to become something so different, such as coal or oil. There is enough heat and pressure deep below the earth's surface even to create diamonds, which are the hardest natural material in the world.

Like fossil fuels, diamond is made of carbon. In fact, diamond is a type of pure carbon, so it does not contain the hydrogen that fossil fuels do. What determines whether the remains of living things deep in the earth turn into coal, oil, natural gas, diamond, or something else? All of these materials form under high heat and pressure, but the conditions are different for each material.

Coal

Coal is the solid fossil fuel that forms from dead plants that settled at the bottom of swamps millions of years ago. The water and mud in the swamps affected how the remains of plants broke down as they were compressed. The water and mud in the swamp keep oxygen away from the plant material. When plants are buried without oxygen, the organic material can be preserved or fossilized. Then, other material, such as sand and clay, settles on top of the decaying plants and squeezes out the water and some other substances. Over time, the pressure removes most of the material other than carbon, and the carbon-containing material forms a layer of rock that we know as coal.

Coal is black or brownish-black in appearance. Coal is a rock that burns easily. Most forms of coal are *sedimentary* rock. But the hardest type of coal, anthracite, is a *metamorphic* rock, because it is exposed to higher temperature and pressure as it forms. Coal is mostly carbon, but some other elements can be found in coal, including sulfur.

Around the world, coal is the largest source of energy for electricity. The United States is rich in coal, which is used for electricity. California once had a number of small coal mines but the state no longer produces coal.

A common way of turning coal into a useful form to make electricity starts with crushing the coal into powder. Then, a power plant burns the powder in a furnace that has a boiler. Like other fuels, coal releases most of its energy as heat when it burns. The heat that the burning coal releases in the furnace is enough to boil the water in the boiler, making steam. The power plant uses this steam to spin turbines, and the spinning turbines make generators turn to create electricity.

For people to use coal as an energy source, they need to get it out of the ground. The process of removing coal from the ground is known as coal mining. Coal mining can take place underground or at the surface. The process of coal mining, especially surface mining, affects the environment. Surface mining exposes minerals from underground to air and water from the surface. These minerals contain the chemical element sulfur, and sulfur mixes with air and water to make sulfuric acid, which is a highly corrosive chemical. The sulfuric acid gets into nearby streams and can kill fish, plants, and animals that live in or near the water. The process of burning coal causes other problems for the environment. A little later, we will look at these other pollution problems, when we explore problems with fossil fuels in general.

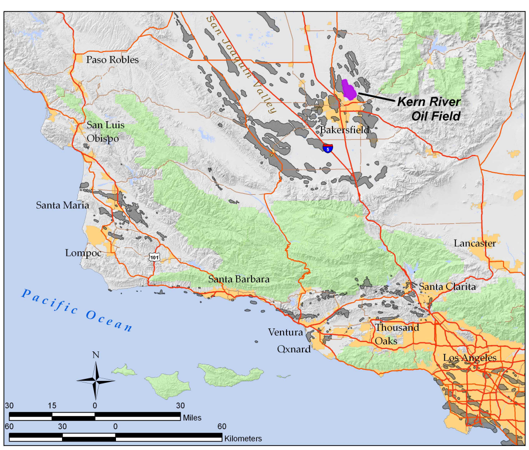
Oil

Oil is a thick liquid that is usually dark brown or black in appearance. It is found mostly in formations of porous rock in the upper layers of the Earth's crust. Oil is currently the single largest source of energy in the world. How does oil form? The process of making oil is similar in many ways to the process of making coal. The main difference is in the size of the living things—the organisms—whose remains turn into these fossil fuels. The organisms that die and became the material for making oil are much smaller than the plants that turned into coal. These organisms are called plankton and algae. When the plankton and algae die, their remains settle to the bottom of the sea. There, they were buried away from oxygen, just as the plants did in the process of becoming coal. As layers of sediment pile on top of these decaying organisms, heat and pressure increase. Over a period of millions of years, the heat and pressure turn the material into liquid oil.

The United States produces oil, although only about one-quarter as much as it uses. The

Figure 5.3: Refineries like this one separate crude oil into many useful fuels and other chemicals. (1)

main oil producing regions are the Gulf of Mexico, Texas, Alaska, and California. Most of California's oil fields are in the southern San Joaquin Valley. Compression from when the region was a convergent plate boundary produced a set of anticlines that are parallel to the San Andreas Fault. Oil collects in permeable sediments that are capped by an impermeable cap rock. Oil is also pumped on and off the southern California coast.



Oil as it comes out of the ground is called crude oil. Crude oil is a mixture of many different hydrocarbons. Oil refining is used to separate the compounds in this mixture from one another (**Figure** 5.3). We can separate crude oil into several useful fuels because each hydrocarbon compound in crude oil boils at a different temperature. An oil refinery heats the crude oil enough to boil the mixture of compounds. Special equipment in the refinery separates these compounds from one another as they boil.

Most of the compounds that come out of the refining process are fuels. The rest make up waxes, plastics, fertilizers, and other products. The fuels that come from crude oil, including gasoline, diesel, and heating oil, are rich sources of energy that can be easily transported. Because of this, fuels from oil provide about 90% of the energy used for transportation around the world.

We get gasoline from refining oil. Like oil, gasoline is most commonly used for transportation because it is a concentrated form of energy that is easily carried. Let's consider how gasoline powers a car. Like other fuels you have learned about, gasoline burns and releases most of its energy as heat. When it burns, the gasoline turns into carbon dioxide gas and water vapor. The heat makes these gases expand, like the heated air that fills a hot-air balloon. The expanding gases create enough force to move pistons inside an engine, and the engine makes enough power to move the car.

When a resource like gasoline is concentrated in energy; it contains a large amount of energy for its weight. This is important because the more an object weighs, the more energy it takes to move that object. If we could only get a little energy from a certain amount of gasoline, a car would have to carry more of it to be able to travel very far. But carrying more gasoline would make the car heavier, so moving the car would take even more energy. So a resource with highly concentrated energy is a practical fuel to power cars and other forms of transportation.

Unfortunately, using gasoline to power automobiles also affects the environment. The exhaust fumes from burning gasoline include gases that cause many different types of pollution, including smog and ground-level ozone. These forms of pollution cause air-quality problems for cities where large numbers of people drive every day. Burning gasoline also produces carbon dioxide, which is a cause of global warming.

Natural Gas

Natural gas is a fuel that is a mixture of methane and several other chemical compounds. It is often found along with coal or oil in underground deposits. The conditions that create natural gas are similar to those that create oil. In both cases, small organisms called plankton and algae die and settle to the bottom of the sea. In both cases, the remains of these organisms decay without oxygen being present. The difference is that natural gas forms at higher temperatures than oil does.

The largest natural gas reserves in the United States is found are in the Rocky Mountain states, Texas and the Gulf of Mexico region. California also has natural gas, mostly in the northern Sacramento Valley and the Sacramento Delta. In that region, a sediment filled trough formed aside an ancient convergent margin. Organic material buried in the sediments hardened to become a shale formation that is the source of the gas.

Because it is a mixture of different chemicals, natural gas must be processed before it can be used as a fuel. Some of the chemicals in unprocessed natural gas are poisonous to humans. Other parts, such as water, make the gas a less useful fuel. The processing removes almost everything but methane from natural gas. At this point, the gas is ready to be delivered and used.

Natural gas, often known simply as gas, is delivered to homes for uses such as cooking and heating. Many ranges and ovens use natural gas as a fuel, and gas-powered furnaces, boilers, water heaters, and clothes dryers are also common.

Natural gas is a major source of energy for powering gas turbines and steam turbines to make electricity. When it is used in this way, natural gas works similarly to the way coal does in producing energy for electricity. Like coal and other fuels, natural gas releases most of its energy as heat when it burns. The power plant is able to use this heat, either in the form of hot gases or steam from heated water, to spin turbines. The spinning turbines turn generators, and the generators create electricity.

Processing and using natural gas does have some harmful effects on the environment. Natural gas does burn cleaner than other fossil fuels, meaning that it causes less air pollution. It also produces less carbon dioxide than the other fossil fuels for the same amount of energy.

Problems with Fossil Fuels

Although they are rich sources of energy, fossil fuels do present many problems. Because these fuels are nonrenewable resources, their supplies will eventually run out. Safety can be a problem, too, because these fuels burn so easily. For example, a natural gas leak in a building or an underground pipe can lead to a deadly explosion.

Using fossil fuels affects the environment in a variety of ways. There are impacts to the environment when we extract these resources. There are problems that arise because we are running out of supplies of these resources. Burning these fuels can cause air pollution and burning them releases carbon dioxide, which is a major factor in global warming (**Figure** 5.4).

Many of the problems with fossil fuels are worse for coal than for oil or natural gas. Coal contains less energy for the amount of carbon it contains than oil or gas. As a result, burning coal releases more carbon dioxide than burning either oil or gas (for the same energy). And yet coal is the most common fossil fuel and so we continue to burn large amounts of it. Coal is the biggest contributor to global warming.

Another problem with coal is that it usually contains sulfur. When coal burns, the sulfur goes into the air as sulfur dioxide. Sulfur dioxide is the main cause of acid rain, which can be deadly to plants, animals, and whole ecosystems. Burning coal also puts other polluting chemicals and a large number of small solid "particulates" into the air. These particles are dangerous to people, especially those who have an illness, like asthma, that makes breathing hard for them.

Figure 5.4: Coal power plants like this one release large amounts of steam and smoke into the air. (5)

Nuclear Energy

When scientists learned how to split the nucleus of an atom, they released a huge amount of energy. Scientists and engineers have learned to control this release of energy. The controlled release of this energy is called *nuclear energy*. Nuclear power plants use uranium that has been processed and concentrated in fuel rods (**Figure** 5.5). The uranium atoms are split apart when they are hit by other extremely tiny particles. These extremely tiny particles need to be controlled or they would cause a dangerous explosion.

Nuclear power plants use the energy they produce to heat water. Once the water is heated, the process is a lot like what happens in a coal power plant. The hot water or steam causes a turbine to spin. When the turbine spins, it makes a generator turn, which in turn produces electricity.

Many countries around the world use nuclear energy as a source of electricity. For example, France gets about 80% of its electricity from nuclear energy. In the United States, a little less than 20% of electricity comes from nuclear energy.

Nuclear energy does not pollute the air. In fact, a nuclear power plant releases nothing but steam into the air. But nuclear energy does create other environmental problems. The process of splitting atoms creates a dangerous by-product called radioactive waste. The radioactive wastes produced by nuclear power plants remain dangerous for thousands or hundreds of thousands of years. So far, concerns about this waste have kept nuclear energy from being a larger source of energy in this country. Scientists and engineers are looking for ways to keep this waste safely away from people.

Figure 5.5: Nuclear power plants like this one provide France with almost 80% of its electricity. (6)

Lesson Summary

- Coal, oil and natural gas are all fossil fuels formed from the remains of once living organisms.
- Coal is our largest source of energy for producing electricity.
- Mining and using coal produce many environmental impacts, including carbon dioxide emissions and acid rain.
- Oil and natural gas are important sources of energy for many types of vehicles and uses in our homes and industry.
- Nuclear energy is produced by splitting atoms. It also produces radioactive wastes that are very dangerous for many years.
- Fossil fuels are nonrenewable sources of energy that produce environmental damage.

Interdisciplinary Connection

Social Studies: Find a map that shows the location of oil refineries in the United States. Which states have the most refineries?

Review Questions

1. How does a fossil fuel form?
2. The hardest type of coal is called anthracite. Why is anthracite harder than other

kinds of coal?
3. What product of nuclear energy has caused concerns about the use of this resource?
4. What is one important fuel that comes out of the oil refining process?
5. Which chemical element exposed in surface coal mining can cause environmental problems in nearby bodies of water?
6. Waxes can be made from the processing of which fossil fuel?
7. Why does natural gas need to be processed before we can use it as a fuel?
8. What are some problems with using coal? but not for using gasoline?
9. What characteristic of gasoline is most important in making it a useful fuel for transportation? Explain.
10. Does nuclear energy cause air pollution? Explain.

Further Reading / Supplemental Links

- Perry, Mildred, "Coal." Encyclopedia of Earth, 2007. Available on the Web at
- http://www.eoearth.org/article/Coal
- http://www.earthportal.org/

Vocabulary

corrosive Able to cause chemical changes to a substance that weaken or destroy the substance.

hydrocarbon A chemical compound that contains only carbon and hydrogen.

metamorphic A type of rock that forms when existing rock is exposed to high temperature and pressure.

nuclear energy Energy that is released from the nucleus of an atom when it is changed into another atom.

sedimentary A type of rock that forms from layers of sediment under high pressure.

Points to Consider

1. How are renewable sources of energy different from nonrenewable sources of energy?
2. Are all renewable energy sources equally practical?
3. Are all renewable energy sources equally good for the environment?

5.3 Renewable Energy Resources

Lesson Objectives

- Describe different renewable resources, and understand why they are renewable.
- Understand that the sun is the source of most of Earth's energy.
- Describe how energy is carried from one place to another as heat and by moving objects.
- Understand how conduction, convection, and radiation transfer energy as heat when renewable energy sources are used.
- Understand that some renewable energy sources cost less than others and some cause less pollution than others.
- Explain how renewable energy resources are turned into useful forms of energy.
- Describe how the use of different renewable energy resources affects the environment.

Introduction

What if we could have all of the energy we needed and never run out of it? What if we could use this energy without polluting the air and water? In the future, renewable sources of energy may be able to provide all of the energy we need. Some of these resources can give us "clean" energy that causes little or no pollution.

Plenty of clean energy is available for us to use. The largest amount of energy to reach Earth's surface is from solar radiation. Each year is 174 petawatts (1.74 x 1017 W) of energy from the sun enter the Earth's atmosphere. Because the planet's interior is hot, heat flows outward from the interior, providing about 23 terawatts (2.3 x 1013 W) of energy per year. By contrast, the total world power consumption is around 16 terawatts (1.6 x 1013W) per year. So solar or geothermal energy alone could provide all of the energy needed for people if it could be harnessed.

Solar Energy

When you think of the sun, you probably think of two things—light and heat. The sun is Earth's main source of energy, and light and heat are two different kinds of energy that the sun makes. The sun makes this energy when one element, called hydrogen, changes into another element, called helium. Changing hydrogen into helium releases huge amounts of energy. The energy travels to the Earth mostly as visible light. The light carries the energy through the empty space between the sun and the Earth in a process called **radiation**. We can use this light from the sun as an energy resource called solar energy (**Figure** 5.6).

Solar energy is a resource that has been used on a small scale for hundreds of years. Its use on a larger scale is just starting to ramp up and people increase production of renewable energy sources. One focus of solar power development in the United States is the desert southwest.

Figure 5.6: Solar panels like these can turn the sun's energy into electricity to provide power to homes. (2)

Solar power plants are in the works for southeastern California, near the California-Nevada border.

Solar energy is used to heat homes, to heat water, and to make electricity. Solar energy can be used to heat the water in your pool or to heat tile floors in your home. In recent years, scientists and engineers have found new ways to get more and more energy from this resource (Figure below). Because there are many different uses for solar energy, there are also many different ways of turning the sun's energy into useful forms. One of the most common ways is by using solar cells. Solar cells are devices that can turn sunlight directly into electricity. You may have seen solar panels on roof tops. Lots of solar cells make up an individual solar panel.

Solar power plants turn sunlight into electricity using a large group of mirrors to focus sunlight on one place, called a receiver (**Figure** 5.8). When a liquid, such as oil or water flows through this receiver, the focused sunlight heats the liquid to a high temperature. Then, this heated liquid transfers its heat by **conduction**. In conduction, energy moves between two objects that are in contact with one another. The object that is at a higher temperature transfers energy as heat to the object that is at a lower temperature. For example, when you heat a pot of water on a stove top, conduction causes energy to move from the pot to its metal handle, and the handle gets very hot. In the case of the solar power plant, the energy conducted by the heated liquid is used to make electricity.

Solar energy has many benefits. It does not produce any pollution. Also, there is plenty of it available. In fact, the amount of energy that reaches Earth from the sun every day is many times more than all of the energy we use. For this reason, we consider solar energy a renewable form of energy. For as long as sunlight continues to warm the Earth, we will never run out of this resource. One problem with solar energy is that it cannot be used at night, unless a special battery stores extra energy during the day for use at night. The technology for most uses of solar energy is still expensive. Until this technology becomes more affordable, most people will prefer to get their energy from other sources. As you learned earlier, most of the Earth's energy comes from the sun. Other renewable resources also come from the sun originally. You will be learning about these resources later in this lesson.

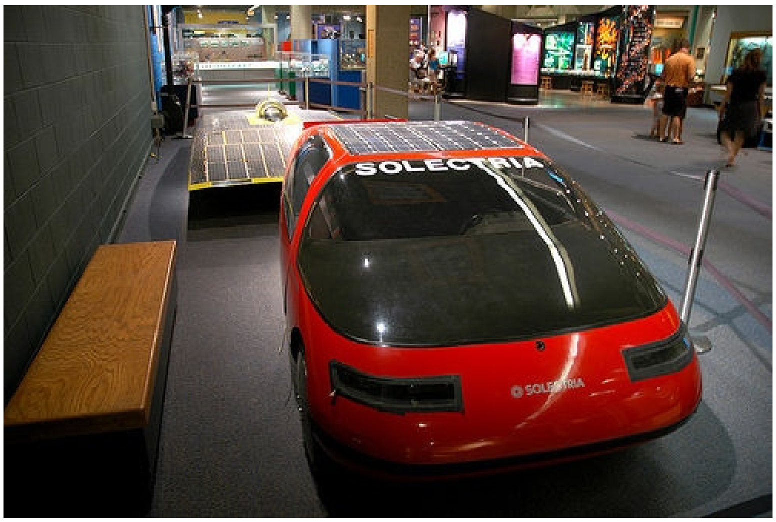


Figure 5.7: This experimental car is one example of the many uses that engineers have found for solar energy. (7)

Figure 5.8: This solar power plant uses mirrors to focus sunlight on the tower in the center. The sunlight heats a liquid inside the tower to a very high temperature, producing energy to make electricity. (9)

Figure 5.9: Hydroelectric dams like this one use the power of moving water to create electricity. (8)

Water Power

Earlier in this lesson, you learned that energy can travel in the form of light and heat, just as it does when it travels from the sun to the Earth. Now, you will learn about one way in which energy can travel in the form of a moving object. In this case, the moving object is water (**Figure** 5.9). Water power uses the energy of water in motion to make electricity. It is the most widely used form of renewable energy in the world, and it provides almost one fifth of the world's electricity.

In most power plants that use water power, a dam holds water back from where it would normally flow. Instead, the water is allowed to flow into a large turbine. Because the water is moving, it has energy of motion, called kinetic energy. The energy of this moving water makes the turbine spin. The turbine is connected to a generator, which makes electricity.

Many of the streams in the United States where water flows down a slope have probably been developed for hydroelectric power. This is a major source of California's electricity, about 14.5 percent of the total. Most of California's nearly 400 hydropower plants are located in the eastern mountain ranges where large streams descend down a steep grade.

One big benefit of water power is that it does not burn a fuel. This benefit gives water power an advantage over most other energy resources in how it affects the environment. Because water power does not burn a fuel, it causes less pollution than many other kinds of energy. Another benefit of water power is that, like the other resources you are learning about in this lesson, it is a renewable resource. We use energy from the water's movement, but we are not using up the water itself. Water keeps flowing into our rivers and lakes, so wherever we can build plants to use it, water will be available as a source of energy. The energy of waves and tides can also be used to produce water power.

Water power does have its problems, though. When a large dam is built, this creates a reservoir, changing the ecosystem upstream. Large river ecosystems are inundated, killing all the plants and animals. The dams and turbines also change the downstream environment for fish and other living things. Dams also slow the release of silt, so that downstream deltas retreat and seaside cities become dangerously exposed to storms and rising sea levels. Tidal power stations may need to close off a narrow bay or estuary. Wave power applications have to be able to withstand coastal storms and the corrosion of seawater.

Wind Power

Figure 5.10: Wind turbines like the ones shown above turn wind into electricity without creating pollution. (3)

As you learned earlier, the sun provides plenty of energy to the Earth. The energy from the sun also creates wind (**Figure** 5.10). Learning about what causes wind will help you understand that energy can move as heat, not just by radiation and conduction, but also by convection. Wind happens when the sun heats some parts of the Earth differently. For example, sunlight hits the equator much more directly than it hits the North and South Poles. Hot air rises and cooler air moves in, so when the air near the equator is heated much more than the air near the poles, the air begins to move carrying heat through the air in a process called **convection**. This movement of air is wind.

Wind power uses moving air as a source of energy. Some examples of wind power have been around for a long time. Windmills have been used to grind grain and pump water for hundreds of years. Ships with sails have depended on wind for even longer. Wind can be used to generate electricity, too. Like the moving water that creates water power, the moving air can make a turbine spin to make electricity.

To help you understand how moving air can be used to make electricity, you could think back to what you have learned about energy of motion, called kinetic energy. Any form of matter that is moving has kinetic energy. Even though you cannot see air, it is matter, because it takes up space and has mass. So, when wind makes the air move, this air has kinetic energy. When the moving air hits the blades of a turbine, it makes those blades move, and the turbine spins. The spinning of the turbine creates electricity.

Wind power has many advantages. It is clean energy, meaning that it does not cause pollution or release carbon dioxide. Also, wind is plentiful almost everywhere. One problem with wind energy is that the wind does not blow all of the time. One solution is to find efficient ways to store energy for later use. Until then, another energy source needs to be available when the wind is not blowing. Lastly, windmills are expensive and wear out quickly. For the amount of energy they generate, windmills are more expensive than some other forms of renewable energy.

California was an early adopter of wind power. Windmills are found in mountain passes, especially where cooler Pacific ocean air is sucked across the passes and into the warmer inland valleys. Large fields of windmills can be seen at Altamont pass in the eastern San Francisco Bay Area, San Gorgonio Pass east of Los Angeles, and Tehachapi Pass at the southern end of the San Joaquin Valley.

Biomass

Another renewable source of energy is biomass. Biomass is the material that comes from plants and animals that were recently living. Biomass also includes the waste that plants and animals produce. People can use biomass directly for heating. For example, many people burn wood in fireplaces or in wood-burning stoves.

Besides burning biomass directly for heating, people can process biomass to make fuel. This processing makes what is called biofuel. Biofuel is a fairly new type of energy that is becoming more popular. People can use fuels from biomass in many of the same ways that they use fossil fuels. For example, some mechanics have made changes to car, truck, and bus engines to allow them to use a fuel called biodiesel. Other engines can run on pure vegetable oil or even recycled vegetable oil.

If we use fuels made from biomass, we can cut down on the amount of fossil fuel that we use. Because living plants take carbon dioxide out of the air, growing plants for biofuel can mean that we will put less of this gas into the air overall. This could help us do something about the problem of global warming.

Geothermal Energy

Geothermal energy is a source of energy that comes from heat deep below the surface of the Earth. This heat produces hot water and steam from rocks that are heated by magma. Power plants that use this type of energy get to the heat by drilling wells into these rocks. The hot water or steam comes up through these wells. Then, the hot water or steam makes a turbine spin to make electricity. Because the hot water or steam can be used directly to make a turbine spin, geothermal energy is a resource that can be used without processing. The fact that it does not need to be processed makes geothermal energy different from most other energy resources. Geothermal energy is clean and safe. It is renewable, too, because the power plant can pump the hot water back into the underground pool. There, the water can pick up heat to make more steam.

This source of energy is an excellent resource in some parts of the world. For example, Iceland is a country that gets about one fourth of its electricity from geothermal sources. In the United States, California leads all states in producing geothermal energy. Geothermal energy in California is concentrated in a few areas in the northern part of the state. The largest geothermal power plant in the state is in the Geysers Geothermal Resource Area in Napa and Sonoma Counties. The source of heat is thought to be a large magma chamber lying beneath the area, a part of the Pacific Ring of Fire. Many parts of the world do not have underground sources of heat that are close enough to the surface for building geothermal power plants.

Lesson Summary

- Solar energy, water power, wind power, biomass energy and geothermal energy are renewable energy sources.
- Solar energy can be used either by passively storing and holding the sun's heat, converting it to electricity or concentrating it.
- There are many ways to use the energy of moving water including hydroelectric dams.

- Wind power uses the energy of moving air to turn turbines.
- Biomass energy uses renewable materials like wood or grains to produce energy.
- Geothermal energy uses heat from deep within the earth to heat homes or produce steam that turns turbines.

Review Questions

1. If you turn on the burner on a gas stove under a pan of cold water, energy moves from the burner to the pan of water. What is this energy called? How does this energy move?
2. What are some ways that we can use solar power?
3. If you burn wood in a fireplace, which type of energy resource are you using?
4. Which form of energy is an important factor in making electricity from water power?
5. When the air moves around as wind, it carries heat from warmer areas to cooler areas. What is this movement of heat called?
6. Most of the energy that travels from the sun to the Earth arrives in the form of visible light. What is this movement of energy called?
7. Explain how mirrors can be useful in some solar energy plants.
8. Explain how wind power uses kinetic energy.

Further Reading / Supplemental Links

- Cleveland, Cutler, "Energy Transitions Past and Future." Encyclopedia of Earth, 2007. Available on the Web at:
- http://www.eoearth.org/article/Energy_transitions_past_and_future
- http://www.earthportal.org/

Vocabulary

conduction The process in which energy moves through matter as heat, moving from an area of higher temperature to an area of lower temperature.

convection The movement of heat in an air current from a warmer space to a cooler space.

radiation The movement of energy through empty space.

Points to Consider

- What areas do you think would be best for using solar energy?

- What causes the high temperatures deep inside the Earth that make geothermal energy possible?
- Do you think your town or city could use wind or water power?

Image Sources

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Chapter 6

Plate Tectonics

6.1 Inside Earth

Lesson Objectives

- Compare and describe each of Earth's layers.
- Compare some of the ways geologists learn about Earth's interior.
- Define lithosphere, oceanic and continental crust.
- Describe how heat moves, particularly how convection takes place in the mantle.
- Compare the two parts of the core and describe why they are different from each other.

Introduction

Plate tectonics is the unifying theory of geology. This important theory explains why Earth's geography has changed through time and continues to change today. It explains why some places are prone to earthquakes and some are not; why some regions have deadly volcanic eruptions, some have mild ones, and some have none at all; and why mountain ranges are located where they are. Plate tectonic motions affect Earth's rock cycle, climate, and the evolution of life. Plate tectonic theory was developed through the efforts of many scientists during the twentieth century.

Before you can learn about plate tectonics, you need to know something about the layers that are found inside Earth. From outside to inside, the planet is divided into crust, mantle, and core. Often geologists talk about the lithosphere, which is the crust and the uppermost mantle. The lithosphere is brittle–it is easily cracked or broken–whereas the mantle beneath it behaves plastically; it can bend. Geologists must use ingenious methods, such as tracking the properties of earthquake waves, to learn about the interior of our planet.

Exploring Earth's Interior

Earth is composed of several layers. On the outside is the relatively cold, brittle **crust**. Below the crust is the hot, convecting **mantle**. At the center is the dense, metallic inner core. How do scientists know this? Rocks yield clues, but geologists can only see the outermost rocky layer. Rarely, a rock or mineral, like a diamond, may come to the surface from deeper down in the crust or the mantle. Mostly, though, Earth scientists must use other clues to figure out what lies beneath the planet's surface.

One way scientists learn about Earth's interior is by looking at **seismic waves** (**Figure** 6.1). Seismic waves travel outward in all directions from where the ground breaks at an earthquake. There are several types of seismic waves, each with different properties. Each type of wave moves at different speeds though different types of material and the waves bend when they travel from one type of material to another. Some types of waves do not travel through liquids or gases and some do. So scientists can track how seismic waves behave as they travel through Earth and can use the information to understand what makes up the planet's interior. Much more about earthquakes and seismic waves will be presented in the Earthquakes lesson.

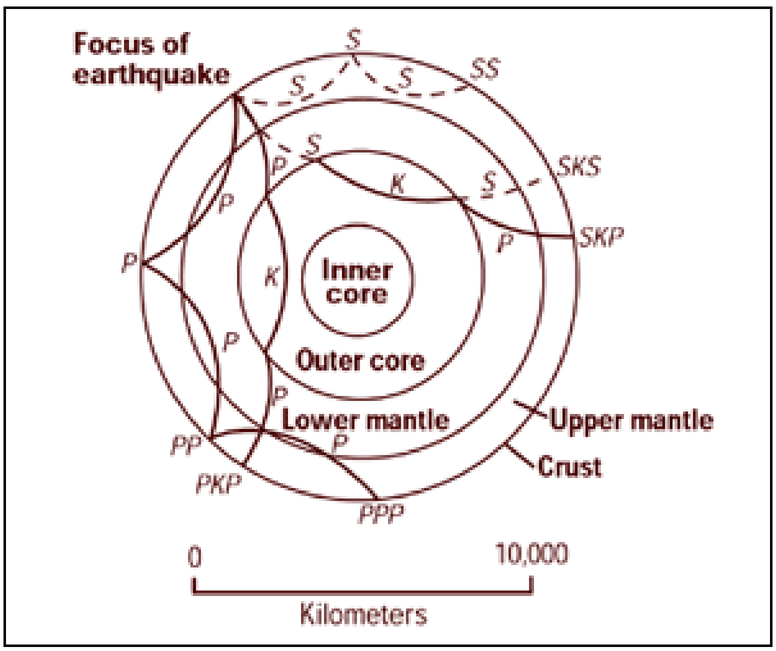

Figure 6.1: Different types of seismic waves bend or even disappear as they travel encounter the different properties of the layers that make up Earth's interior. Letters describe the path of an individual P wave or S wave. (3)

Scientists also learn about Earth's interior from rocks from outer space. **Meteorites** are the remains of the material that the early solar system formed from. Some iron and nickel meteorites are thought to be very similar to Earth's core (**Figure** 6.2). For this reason they give scientists clues as to the core's makeup and density. An iron meteorite is the closest thing to a sample of the core that scientists can hold in their hands!

Figure 6.2: An iron meteorite, which is thought to be representative of the Earth's core. (7)

Crust and Lithosphere

Of course, scientists know the most about Earth's outermost layer and less and less about layers that are found deeper in the planet's interior (**Figure** 16.3). Earth's outer surface is its crust; a thin, brittle outer shell made of rock. Geologists call the outermost, brittle, mechanical layer the **lithosphere**. The difference between crust and lithosphere is that lithosphere includes the uppermost mantle, which is also brittle.

The crust is the very thin, outermost physical layer of the Earth. The crust varies tremendously; from thinner areas under the oceans to much thicker areas that make mountains. Just by looking around and thinking of the places you've been or seen photos of, you can guess that the crust is not all the same. Geologists make an important distinction between two very different types of crust: oceanic crust and continental crust. Each type has its own distinctive physical and chemical properties. This is one of the reasons that there are ocean basins and continents.

Oceanic crust is relatively thin, between 5 to 12 kilometers thick (3 - 8 miles). This crust is made of basalt lavas that erupt onto the seafloor. Beneath the basalt is gabbro, an igneous intrusive rock that comes from basalt magma but that cools more slowly and develops larger crystals. The basalt and gabbro of the oceanic crust are dense (3.0 g/cm^3) when compared to the average of the rocks that make up the continents. Sediments cover much of the oceanic

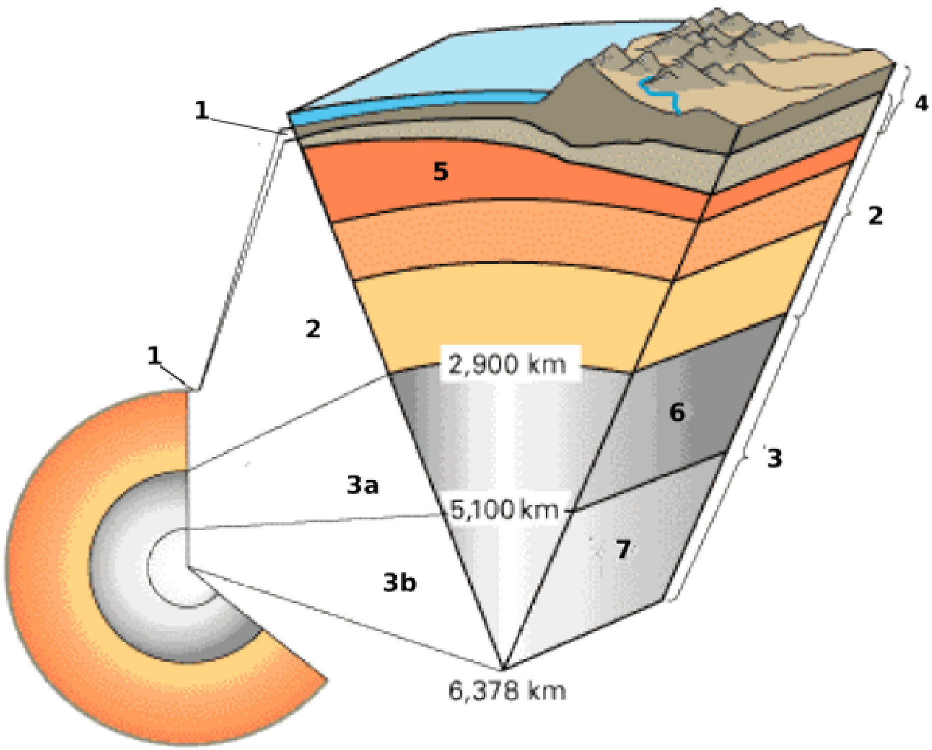

Figure 6.3: A cross section of Earth showing the following layers: (1) crust (2) mantle (3a) outer core (3b) inner core (4) lithosphere (5) asthenosphere (6) outer core (7) inner core. The lithosphere is made of the crust plus the uppermost part of the mantle. The asthenosphere is directly under the lithosphere and is part of the upper mantle. (25)

crust, primarily rock dust and the shells of microscopic sea creatures, called plankton. Near shore, the seafloor is thick with sediments that come off the continents in rivers and on wind currents.

Continental crust is much thicker than oceanic crust, around 35 kilometers (22 miles) thick on average. Continental crust is made up of many different rocks of all three major types: igneous, metamorphic, and sedimentary. The average composition of continental crust is about that of granite. Granite is much less dense (2.7 g/cm^3) than the basalt and gabbro of the oceanic crust. Because it is thick and has relatively low density, continental crust rises higher above the mantle than oceanic crust, which sinks into the mantle to form basins. When filled with water these basins form the planet's oceans.

Since it is a combination of the crust and uppermost mantle, lithosphere is thicker than crust. Oceanic lithosphere is about 100 kilometers (62 miles) thick. Continental lithosphere is about 250 kilometers (155 miles) thick.

Mantle

Beneath the crust, lies the mantle. Like the crust, mantle is made of rock. Evidence from seismic waves and meteorites let scientists know that the mantle is made of iron- and magnesium-rich silicate minerals that are part of the rock peridotite. These types of ultramafic rocks are rarely found at Earth's surface. One very important feature of the mantle is that it is extremely hot. This is mainly due to heat rising from the core. Through the process of **conduction**, heat flows from warmer objects to cooler objects until all are the same temperature. Knowing the ways that heat flows is important for understanding how the mantle behaves.

Heat can flow in two ways within the Earth. If the material is solid, heat flows by conduction, and heat is transferred through the rapid collision among atoms. If a material is fluid and able to move—that is, it is a gas, liquid, or a solid that can move (like toothpaste)—heat can also flow by **convection.** In convection, currents form so that warm material rises and cool material sinks. This sets up a **convection cell** (**Figure** 16.4).

Convection occurs when a pot of water is heated on a stove. The stove heats the bottom layer of the water, which makes it less dense than the water above it, so the warmer bottom water rises. Since the layer of water on the top of the pot is not near the heat source, it is relatively cool. As a result, it is denser than the water beneath it and so it sinks. Within the pot, convection cells become well established as long as there is more heat at the bottom of the pot than on the top.

Convection cells are also found in the mantle (**Figure** 6.5). Mantle material is heated by the core and so it rises upwards. When it reaches the surface of the Earth, it moves horizontally. As the material moves away from the core's heat, it cools. Eventually the mantle material at the top of the convection cell becomes cool and dense enough that it sinks back down into

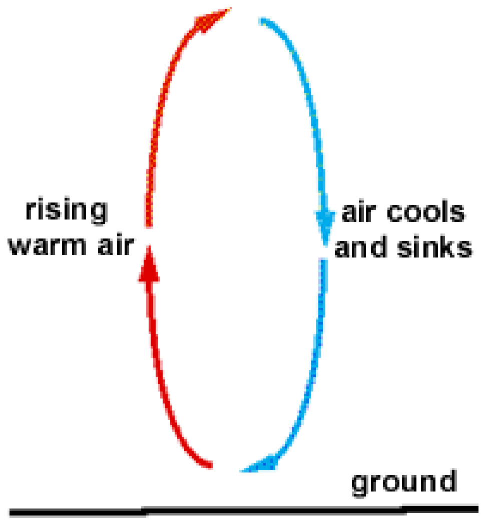

Figure 6.4: In a convection cell, warm material rises and cool material sinks. In mantle convection, the heat source is the core. (22)

the deeper mantle. When it reaches the bottom of the mantle, it travels horizontally just above the core. Then it reaches the location where warm mantle material is rising, and the mantle convection cell is complete. The relationship between mantle convection and plate tectonics will be discussed in the final section of this chapter.

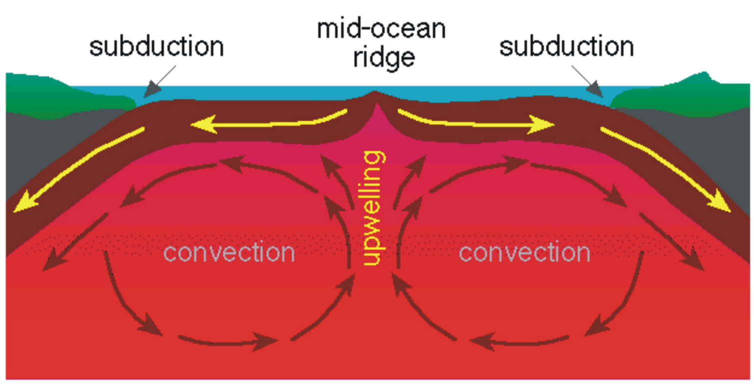

Figure 6.5: Diagram of convection within Earth's mantle. (16)

Core

At the planet's center lies a dense metallic core. Scientists know that the core is metal for two reasons: The first is that some meteorites are metallic and they are thought to be representative of the core. The second is that the density of Earth's surface layers is much less than the overall density of the planet. We can calculate Earth's density using our planet's rotation. If the surface layers are less dense than the average for the planet, then the interior must be denser than the average. Calculations indicate that the core is about 85% iron metal with nickel metal making up much of the rest. These proportions agree with those seen in metallic meteorites. Seismic waves indicate that the outer core must be liquid and the inner core must be solid.

If Earth's core were not metallic, the planet would not have a magnetic field. Metal conducts electricity, but rock—which makes up the mantle and crust—does not. The best conductors are metals that can move, so scientists assume that the magnetic field is due to convection in the liquid outer core. These convection currents form in the outer core because the base of the outer core is heated by the even hotter inner core.

Lesson Summary

- The Earth is made of three layers: the crust, mantle and core.
- The brittle crust and uppermost mantle are together called the lithosphere.
- Beneath the lithosphere, the mantle is solid rock that can flow, or behave plastically.
- The hot core warms the base of the mantle, which cause mantle convection.
- Mantle convection is very important to the theory of plate tectonics.

Review Questions

1. List two ways that scientists learn about what makes up the planet's interior.
2. What types of rock make up the oceanic crust?
3. What types of rock make up the continental crust?
4. List two reasons that scientists know that the outer core is liquid.
5. Describe the properties of each of these parts of the Earth's interior: lithosphere, mantle, and core. What are they made of? How hot are they? What are a few of their physical properties?
6. Suppose that Earth's interior contains a large amount of lead. Based on your prior knowledge, how dense is lead? Would the lead be more likely to be found in the crust, mantle, or core?
7. When you put your hand near a pan above a pan filled with boiling water, does your hand warm up because of convection or conduction? If you touch the pan, does your hand warm up because of convection or conduction? Based on your answers, which type of heat transfer moves heat more easily and efficiently?

Vocabulary

conduction The process in which energy moves through matter as heat by direct contact, moving from an area of higher temperature to an area of lower temperature.

convection The transport of heat by movement.

convection cell A circular pattern of warm material rising and cool material sinking.

continental crust The crust that makes up the continents.

core The dense metallic center of the Earth. The outer core is liquid and the inner core is solid.

crust The rocky outer layer of the Earth's surface. The two types of crust are continental and oceanic.

lithosphere The layer of solid, brittle rock that makes up the Earth's surface. The lithosphere is composed of the crust and the uppermost mantle.

mantle The middle layer of the Earth, between the crust and the core. The mantle is made of hot rock that circulates by convection.

meteorite Fragments of planetary bodies such as moons, planets, asteroids and comets that strike Earth.

oceanic crust The crust that underlies the oceans.

plate tectonics The theory that the Earth's surface is divided into lithospheric plates that move on the planet's surface. The driving force behind plate tectonics is mantle convection.

seismic waves Also called earthquake waves. Seismic waves give scientists information on Earth's interior.

Points to Consider

- The oceanic crust is thinner and denser than continental crust. All crust sits atop the mantle. What might our planet be like if this were not true.
- If sediments fall onto the seafloor over time, what can sediment thickness tell scientists about the age of the seafloor in different regions?
- How might convection cells in the mantle affect the movement of plates of lithosphere on the planet's surface?

6.2 Continental Drift

Lesson Objectives

- Be able to explain the continental drift hypothesis.
- Describe the evidence Wegener used to support his continental drift idea.
- Describe how the north magnetic pole appeared to move, and how that is evidence for continental drift.

Introduction

An important piece of plate tectonic theory is the continental drift idea. This was developed in the early part of the 20th century, mostly by a single scientist, Alfred Wegener. His hypothesis states that continents move around on Earth's surface and that they were once joined together as a single supercontinent (**Figure** 6.6). Wegener's idea eventually helped to form the theory of plate tectonics, but while Wegener was alive, scientists did not believe that the continents could move.

The Continental Drift Idea

Find a map of the continents and cut each one out. Better yet, use a map where the edges of the continents show the continental shelf. In this case, your continent puzzle piece includes all of the continental crust for that continent and reflects the true size and shape of the continent. Can you fit the pieces together? The easiest link is between the eastern Americas and western Africa and Europe, but the rest can fit together too!

Alfred Wegener, an early 20th century German meteorologist believed that the continents could fit together. He proposed that the continents were not stationary but that they had moved during the planet's history. He suggested that at one time, all of the continents had been united into a single supercontinent. He named the supercontinent Pangaea, meaning *entire earth* in ancient Greek. Wegener further suggested that Pangaea broke up long ago and that the continents then moved to their current positions. He called his hypothesis **continental drift**.

Evidence for Continental Drift

Besides the fit of the continents, Wegener and his supporters collected a great deal of evidence for the continental drift hypothesis. Wegener found that this evidence was best explained if the continents had at one time been joined together.

Wegener discovered that identical rocks could be found on both sides of the Atlantic Ocean.

Figure 6.6: The continents fit together like pieces of a puzzle. This is how they looked 250 million years ago. (31)

These rocks were the same type and the same age. Wegener understood that the rocks had formed side-by-side and that the land has since moved apart. Wegener also matched up mountain ranges that had the same rock types, structures, and ages, but that are now on opposite sides of the Atlantic Ocean. The Appalachians of the eastern United States and Canada, for example, are just like mountain ranges in eastern Greenland, Ireland, Great Britain, and Norway. Wegener concluded that they formed as a single mountain range that was separated as the continents drifted.

Wegener also found evidence from ancient fossils (**Figure** 6.7). He found fossils of the same species of extinct plants and animals in rocks of the same age, but on continents that are now widely separated. Wegener suggested that the continents could not have been in their current positions because the organisms would not have been able to travel across the oceans. For example, fossils of the seed fern *Glossopteris* are found across all of the southern continents. But the plants' seeds were too heavy to be carried across the ocean by wind. *Mesosaurus* fossils are found in South America and South Africa, but the reptile only could only swim in fresh water. *Cynognathus* and *Lystrosaurus* were reptiles that lived on land. Both of these animals were unable to swim, let alone swim across wide seas! Their fossils have been found across South America, Africa, India and Antarctica. Wegener proposed that the organisms had lived side by side, but that the lands had moved apart after they were dead and fossilized.

Wegener also looked at evidence from ancient glaciers. Large glaciers are most commonly found in frigid climates, usually in the far northern and southern latitudes. Using the distribution of grooves and rock deposits left by ancient glaciers on many different continents, Wegener traced the glaciers back to where they must have started. He discovered that if the continents were in their current positions, the glaciers would have formed in the middle of the ocean very close to the equator. Wegener knew that this was impossible! However, if the continents had moved, the glaciers would have been centered over the southern land mass much closer to the South Pole.

Wegener also found evidence for his hypothesis from warm climate zones. Coral reefs and the swamps that lead to the formation of coal are now found only in tropical and subtropical environments. But Wegener discovered ancient coal seams and coral reefs in parts of the continents that were much too cold today. The coral reef fossils and coal had drifted to new locations since the coal and coral formed.

Although Wegener's evidence was sound, most geologists at the time rejected his hypothesis of continental drift. These scientists argued that there was no way to explain *how* solid continents could plow through solid oceanic crust. At the time, scientists did not understand how solid material could move. Wegener's idea was nearly forgotten until technological advances presented puzzling new information and gave scientists the tools to develop a mechanism for Wegener's drifting continents.

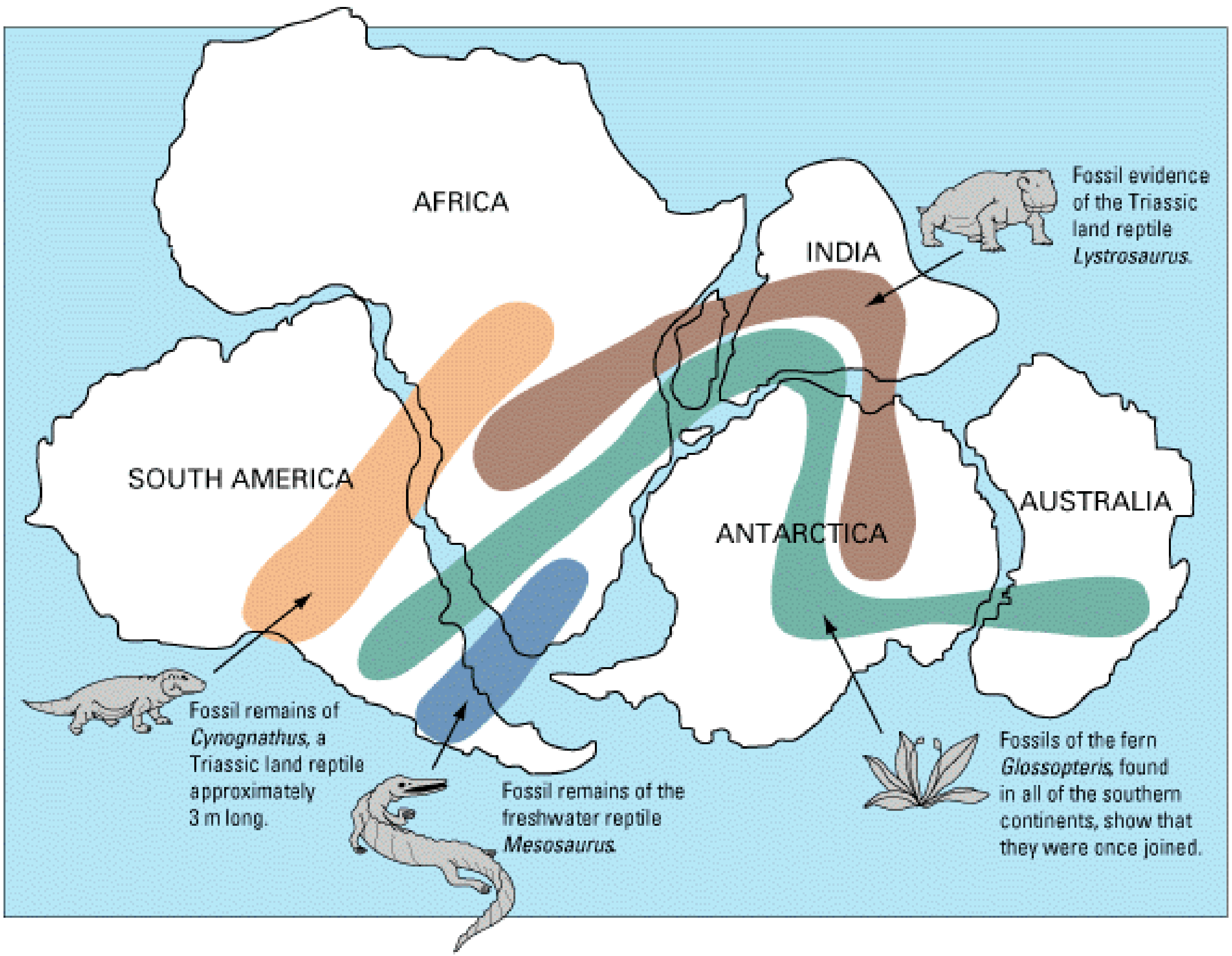

Figure 6.7: Wegener used fossil evidence to support his continental drift hypothesis. The fossils of these organisms are found on lands that are now far apart. Wegener suggested that when the organisms were alive, the lands were joined and the organisms were living side-by-side. (20)

Magnetic Polarity Evidence

The puzzling new evidence came from studying Earth's magnetic field and how it has changed. If you have ever been hiking or camping, you may have used a compass to help you find your way. A compass uses the Earth's magnetic field to locate the magnetic North Pole. Earth's **magnetic field** is like a bar magnet with the ends of the bar sticking out at each pole (**Figure** 6.8). Currently, the field's north and south magnetic poles are very near to the Earth's north and south geographic poles.

Some iron-bearing minerals, like tiny **magnetite** crystals in igneous rocks, point to the north magnetic pole as they crystallize from magma. These little magnets record both the strength and direction of the Earth's magnetic field. The direction is known as the field's **magnetic polarity.** In the 1950's, scientists began using **magnetometers** to look at the magnetic properties of rocks in many locations.

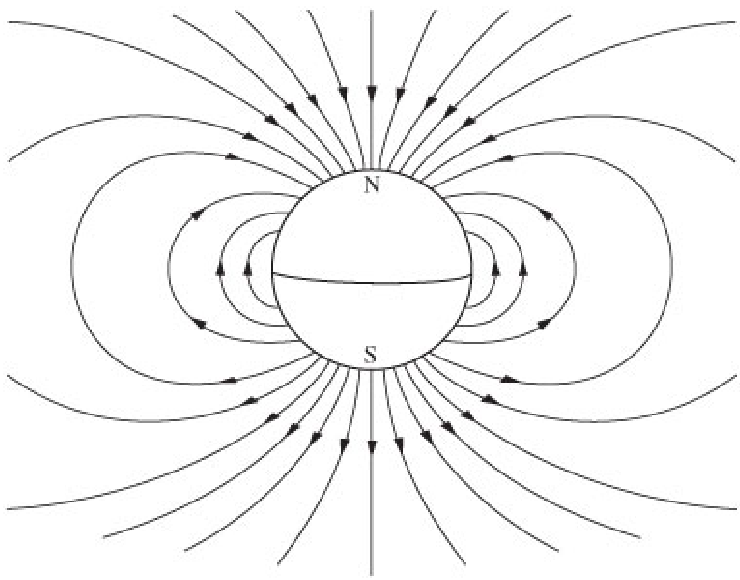

Figure 6.8: Earth's magnetic field is like a magnet with its north pole near the geographic north pole and the south pole near the geographic south pole. (32)

Geologists noted that magnetite crystals in fresh volcanic rocks pointed to the current magnetic north pole. This happened no matter where the rocks were located, whether they were on different continents or in different locations on the same continent. But for older volcanic rocks, this was not true. Rocks that were the same age and were located on the same continent pointed to the same point, but that point was not the current north magnetic pole. Moving back in time, rocks on the same continent that were the same age pointed at the same point. But these rocks did not point to the same point as the rocks of different ages or the current magnetic pole. In other words, although the magnetite crystals were pointing to the magnetic north pole, the location of the pole seemed to wander. For example, 400 millon year old lava flows in North America indicated that the north magnetic pole was located in the western Pacific Ocean, but 250 million year old lava flows indicated a pole in Asia, and 100 million year old lava flows had a pole in northern Asia. Scientists were amazed to find that the north magnetic pole changed location through time (**Figure** 6.9)!

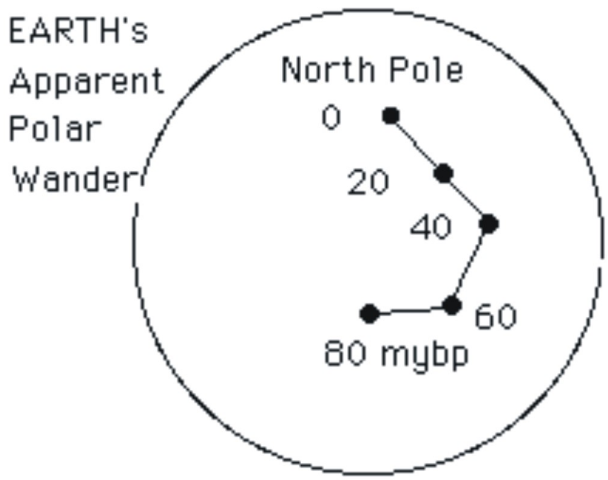

Figure 6.9: The magnetic north pole appears to move around with time. This diagram shows where the pole was 80 million years before present (mybp), then 60, 40, 20 and now. Since we know that the pole does not move, this path is called apparent polar wander. (11)

There were three possible explanations for this puzzling phenomenon: (1) the continent remained fixed and the north magnetic pole moved (2) the north magnetic pole stood still and the continent moved (3) both the continent and the north pole moved.

The situation got stranger when scientists looked at where magnetite crystals pointed for rocks of the same age but on different continents. They found these rocks pointed to different magnetic north poles! For example, 400 million years ago the European north pole was different from the North American north pole at that same time. At 250 million years, the north poles were also different for the two continents. The scientists again looked at the three possible explanations. If the correct explanation was that the continents had remained fixed while the north magnetic pole moved, then there had to be two separate north poles. Since there is only one north pole today, they decided that the best explanation had to involve only one north magnetic pole. This meant that the second explanation must be correct, that the north magnetic pole had remained fixed but that the continents had moved.

To test this, geologists fitted the continents together as Wegener had done. They discovered that there had indeed been only one magnetic north pole but that the continents had drifted. They renamed the phenomenon of the magnetic pole that seemed to move but actually did not **apparent polar wander**. This evidence for continental drift gave geologists renewed interest in understanding how continents could move about on the planet's surface. And we know that the magnetic pole wanders, too, so the correct explanation was that both the continents and the magnetic poles move (**Figure** 6.10).

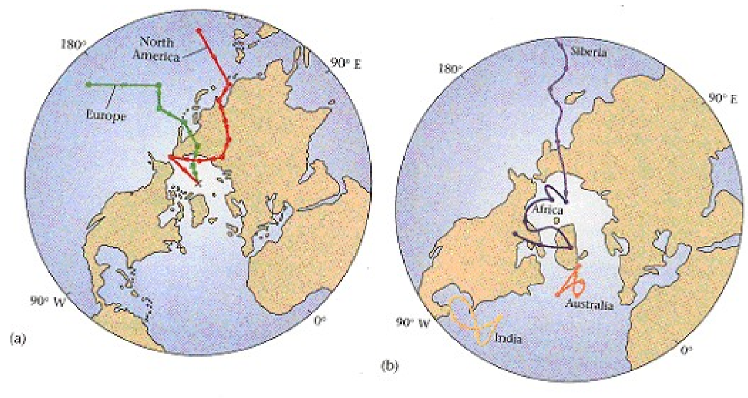

Figure 6.10: The left side image shows the apparent north pole locations for two different continents, Europe and North America, if the continents were always in their current locations. When continental drift is taken into account, the two paths merge into one since there is only one magnetic north pole. (6)

Lesson Summary

- In the early part of the 20th century, scientists began to put together evidence that the continents could move around on Earth's surface.
- The evidence for continental drift included the fit of the continents; the distribution of ancient fossils, rocks, and mountain ranges; and the locations of ancient climatic zones.
- Although the evidence was extremely strong, scientists could not think of a mechanism that could drive solid continents to move around on the solid earth and most rejected the idea.
- Continental drift would resurface after World War II when a mechanism was discovered.

Review Questions

1. Why can paper cutouts of the continents including the continental margins be pieced together to form a single whole?
2. How can the locations where ancient fossils are found be used as evidence for continental drift?
3. To show that mountain ranges on opposite sides of the Atlantic formed as two parts of the same range and were once joined, what would you look for?
4. What are the three possible explanations for apparent polar wander when the rocks are all on one continent? If the rocks are on more than one continent, which explanation

is the only one likely to be true and why?
5. In the face of so much evidence in support of continental drift, how could scientists reject the idea?
6. Look at a world map. Besides the coast of west Africa and eastern South America, what are some other regions of the world that look as they could be closely fit together?

Further Reading / Supplemental Links

- http://www.youtube.com/watch?v=gO2qYMsNHGk
- http://www.exploratorium.edu/origins/antarctica/ideas/gondwana2.html

Vocabulary

apparent polar wander The path on the globe showing where the magnetic pole appeared to move over time.

continental drift The hypothesis developed in the early 20th century that states that the continents move about on the surface.

magnetite A magnetic mineral that takes on the polarity of the Earth's magnetic field at the time it forms.

magnetic field The region around a magnet that is susceptible to the magnetic force. Earth's magnetic field is like a magnet.

magnetic polarity The direction of the Earth's magnetic field, north is normal or south is reversed.

magnetometer An instrument that measures the magnetic field intensity.

Points to Consider

- Why is continental drift referred to as a hypothesis (or idea) and not a theory?
- Why was Wegener's continental drift idea rejected by the scientific community and why is it accepted today?
- Explain how each of these phenomena can be used as evidence for continental drift:

6.3 Seafloor Spreading

Lesson Objectives

- List the main features of the seafloor: mid-ocean ridges, deep sea trenches, and abyssal plains.
- Describe what seafloor magnetism tells scientists about the seafloor.
- Describe the process of seafloor spreading.

Introduction

Perhaps surprisingly, it was World War II that gave scientists the tools to find the mechanism for continental drift that had eluded Wegener and his colleagues. Scientists used maps and other data gathered during the war to develop the seafloor spreading hypothesis. This hypothesis traces oceanic crust from its origin at a mid-ocean ridge to its destruction at a deep sea trench. Scientists realized that seafloor spreading could be the mechanism for continental drift that they had been looking for.

Seafloor Bathymetry

During the war, battleships and submarines carried **echo sounders** to locate enemy submarines (**Figure** 6.11). Echo sounders produce sound waves that travel outward in all directions, bounce off the nearest object, and then return to the ship. The round-trip time of the sound wave is then recorded. By knowing the speed of sound in seawater, scientists can calculate the distance to the object that the sound wave hit. During the war, the sound wave rarely encountered an enemy submarine, and so most of the sound waves ricocheted off the ocean bottom.

After the war, scientists pieced together the bottom depths to produce a a map of the seafloor. This is known as a **bathymetric map** and is similar to a topographic map of the land surface. While a bathymetric map measures the distance of the seafloor below sea level, a topographic map gives the elevation of the land surface above sea level. Bathymetric maps reveal the features of the ocean floor as if the water were taken away.

The bathymetric maps that were produced at this time were astonishing! Most people had thought that the ocean floor was completely flat but the maps showed something completely different. As we know now, majestic mountain ranges extend in a line through the deep oceans. Amazingly, the mountain ranges are connected as if they were the seams on a baseball. These mountain ranges are named **mid-ocean ridges.** The mid-ocean ridges and the areas around them rise up high above the deep seafloor (**Figure** 6.12).

Another astonishing feature is the deep sea **trenches** that are found at the edges of conti-

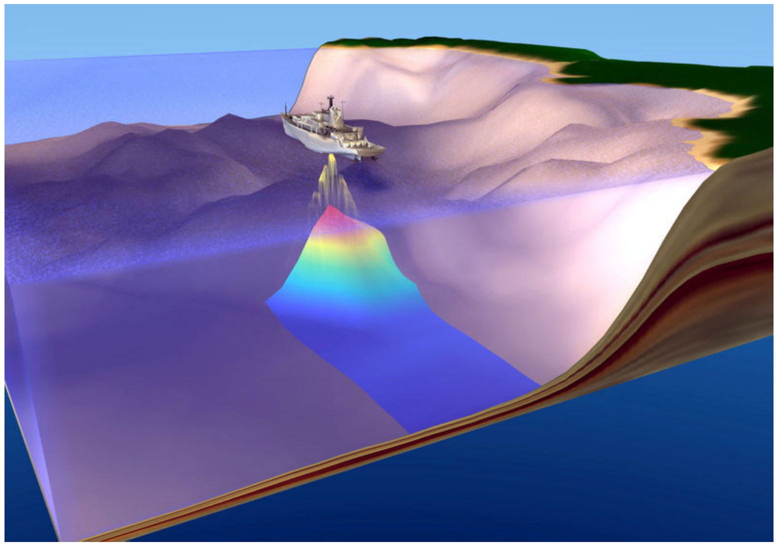

Figure 6.11: A ship sends out sound waves to create a picture of the seafloor below it. The echo sounder pictured has many beams and as a result it creates a three dimensional map of the seafloor beneath the ship. Early echo sounders had only a single beam and created a line of depth measurements. (13)

nental margins or in the sea near chains of active volcanoes. Trenches are the deepest places on Earth. The deepest trench is the Marianas Trench in the southwestern Pacific Ocean, which plunges about 11 kilometers 35,840 feet (35,840 feet) beneath sea level. Near the trenches, the seafloor is also especially deep.

Besides these dramatic features, there are lots of flat areas, called **abyssal plains**, just as the scientists had predicted. But many of these plains are dotted with volcanic mountains. These mountains are both large and small, pointy and flat-topped, by themselves as well as in a line. When they first observed the maps, the amazing differences made scientists wonder what had formed these features.

Seafloor Magnetism

In the previous lesson, you learned that magnetometers used on land were important in recognizing apparent polar wander. Magnetometers were also important in understanding the magnetic polarity of rocks in the deep sea. During WWII, magnetometers that were attached to ships to search for submarines discovered a lot about the magnetic properties of the seafloor.

In fact, using magnetometers, scientists discovered an astonishing feature of Earth's magnetic field. Sometimes, no one really knows why, the magnetic poles switch positions. North becomes south and south becomes north! When the north and south poles are aligned as

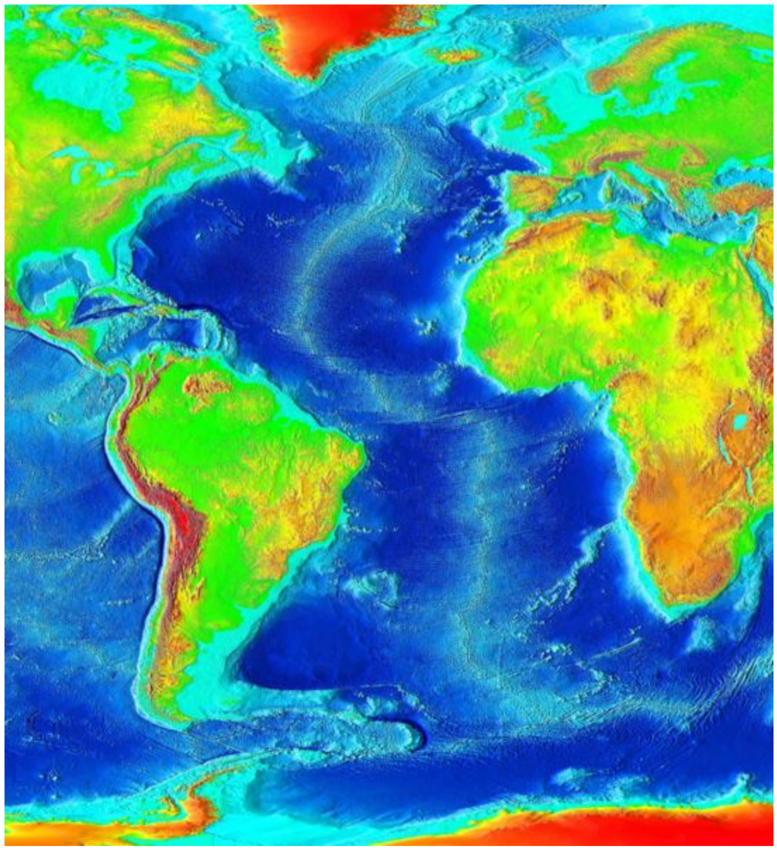

Figure 6.12: A modern map of the eastern Pacific and Atlantic Oceans. Darker blue indicates deeper seas. A mid-ocean ridge can be seen running through the center of the Atlantic Ocean. Deep sea trenches are found along the west coast of Central and South America and in the mid-Atlantic east of the southern tip of South America. Isolated mountains and flat featureless regions can also be spotted. (29)

they are now, geologists say the polarity is normal. When they are in the opposite position, they say that the polarity is reversed.

Scientists were surprised to discover that the normal and reversed magnetic polarity of seafloor basalts creates a pattern of magnetic stripes! There is one long stripe with normal polarity, next to one long stripe with reversed polarity and so on across the ocean bottom. Another amazing feature is that the stripes are form mirror images on either side of the mid-ocean ridges. The ridge crest is of normal polarity and there are two stripes of reversed polarity of roughly equal width on each side of the ridge. Further distant are roughly equal stripes of normal polarity, beyond that, roughly equal stripes of reversed polarity, and so on. The magnetic polarity maps also show that the magnetic stripes end abruptly at the edges of continents, which are sometimes lined by a deep sea trench (**Figure** 6.13).

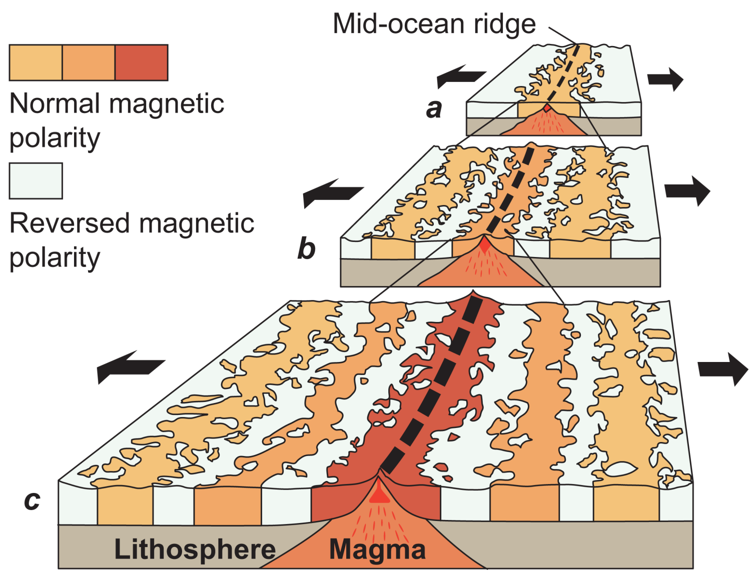

Figure 6.13: Scientists found that magnetic polarity in the seafloor was normal at mid-ocean ridges but reversed in symmetrical patterns away from the ridge center. This normal and reversed pattern continues across the seafloor. (8)

The scientists used geologic dating techniques to find the ages of the rocks that were found with the different magnetic polarities. It turns out that the rocks of normal polarity are located along the axis of the mid-ocean ridges and these are the youngest rocks on the seafloor. The ages of the rocks increases equally and symmetrically on both sides of the ridge.

Scientists also discovered that there are virtually no sediments on the seafloor at the axis, but the sediment layer increases in thickness in both directions away from the ridge axis. This was additional evidence that the youngest rocks are on the ridge axis and that the rocks are older with distance away from the ridge (**Figure** 6.14). The scientists were surprised to find that oldest seafloor is less than 180 million years old while the oldest continental crust is around 4 billion years old. They realized that some process was causing seafloor to be created and destroyed in a relatively short time.

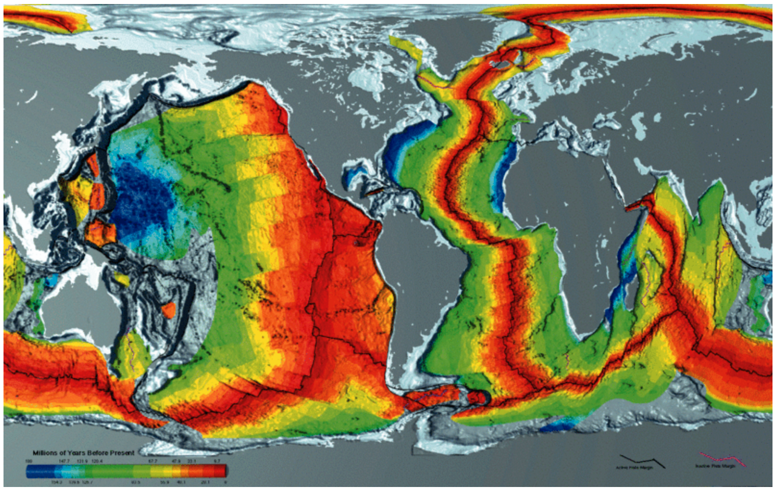

Figure 6.14: Seafloor is youngest near the mid-ocean ridges and gets progressively older with distance from the ridge. Orange areas show the youngest seafloor. The oldest seafloor is near the edges of continents or deep sea trenches. (23)

The scientists also discovered that the seafloor was thinner at the ridge axis and grew thicker as the crust became older. This is because over time, additional magma cools to form rock. The added sediments also increase the thickness of the older crust.

The Seafloor Spreading Hypothesis

Scientists brought all of these observations together in the early 1960s to create the **seafloor spreading** hypothesis. They suggested that hot mantle material rises up toward the surface at mid-ocean ridges. This hot material is buoyant and causes the ridge to rise, which is one reason that mid-ocean ridges are higher than the rest of the seafloor.

The hot magma at the ridge erupts as lava that forms new seafloor. When the lava cools, its magnetite crystals take on the current magnetic polarity. The polarity is locked in when the lava solidifies and the magnetite crystals are trapped in position. Reversals show up as magnetic stripes on opposite sides of the ridge axis. As more lava erupts, it pushes the seafloor that is at the ridge horizontally away from ridge axis. This continues as the formation of new seafloor forces older seafloor to move horizontally away from the ridge axis.

The magnetic stripes continue across the seafloor. If the oceanic crust butts up against a continent, it pushes that continent away from the ridge axis as well. If the oceanic crust reaches a deep sea trench, it will sink into it and be lost into the mantle. In either case, the oldest crust is coldest and lies deepest in the ocean.

It is the creation and destruction of oceanic crust, then, that is the mechanism for Wegener's drifting continents. Rather than drifting across the oceans, the continents ride on a conveyor belt of oceanic crust that takes them around the planet's surface.

One of the fundamental lines of evidence for continental drift is the way the coastlines of continents on both sides of the Atlantic Ocean fit together. So let's look at how seafloor spreading moves continents in the Atlantic by looking more closely at figure 3 above. New oceanic crust is forming at the mid-ocean ridge that runs through the center of the Atlantic Ocean basins, which is called the Mid-Atlantic Ridge. Stripes of different magnetic polarity are found on opposite sides of the Mid-Atlantic Ridge. These stripes go all the way to the continents, which lie on opposite sides of the Atlantic. So new seafloor forming at the Mid-Atlantic Ridge is causing the Americas and Eurasia to move in opposite directions!

Lesson Summary

- Using technologies developed to fight World War II, scientists were able to gather data that allowed them to recognize that seafloor spreading is the mechanism for Wegener's drifting continents.
- Bathymetric maps revealed high mountain ranges and deep trenches.
- Magnetic polarity stripes give clues as to seafloor ages and the importance of mid-ocean ridges in the creation of oceanic crust.
- Seafloor spreading processes create new oceanic crust at mid-ocean ridges and destroy older crust at deep sea trenches.

Review Questions

1. Describe how sound waves are used to develop a map of the features of the seafloor.
2. Why has no ocean crust been located that is older than about 180 million years when the oldest continental crust is about 4 billion years old?
3. Describe the major features of mid-ocean ridges, deep sea trenches, and abyssal plains and their relative ages.
4. Describe continents move across the ocean basins as if they are on a conveyor belt rather than as if they are drifting, as we Wegner's original idea.
5. Explain why the following scenario is impossible: Oceanic crust is not destroyed at oceanic trenches, but new crust is still created at mid-ocean ridges.
6. If you were a paleontologist who studies fossils of very ancient life forms, where would be the best place to look for very old fossils: on land or in the oceans?
7. Imagine that Earth's magnetic field was fixed in place and the polarity didn't reverse. What effect would this have on our observations of seafloor basalts?

Further Reading / Supplemental Links

- http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/p_seafloorspreading.html

Vocabulary

abyssal plains Very flat areas that make up most of the ocean floor.

bathymetric map A map of the seafloor created from the measurement of water depths.

echo sounder A device that uses sound waves to measure the depth to the seafloor.

mid-ocean ridge The location on the seafloor where magma upwells and new seafloor forms. Mid-ocean ridges are the dominant feature of divergent plate boundaries found in the oceans.

seafloor spreading The mechanism for moving continents. The formation of new seafloor at spreading ridges pushes lithospheric plates on the Earth's surface.

trench A deep hole in the seafloor where subduction takes place. Trenches are the deepest places on Earth.

Points to Consider

- How were the technologies that were developed to fight World War II used by scientists for the development of the seafloor spreading hypothesis?
- In what two ways did magnetic data lead scientists to understand more about continental drift and plate tectonics?
- How does seafloor spreading provide a mechanism for continental drift?
- The features of the Atlantic Ocean basin are described in terms of seafloor spreading and continental drift. Now look at the features of the North Pacific Ocean basin and explain them in those terms as well.

6.4 Theory of Plate Tectonics

Lesson Objectives

- Describe what a plate is and how scientists can recognize its edges.

- Explain how mantle convection moves lithospheric plates.
- Describe the three types of plate boundaries and whether they are prone to earthquakes and volcanoes.
- Describe how plate tectonics processes lead to changes in Earth's surface features.

Introduction

Wegener's continental drift hypothesis had a great deal of evidence in its favor but it was largely abandoned because there was no plausible explanation for how the continents could drift. In the meantime, scientists developed explanations to explain the locations of fossils on widely different continents (land bridges) and the similarity of rock sequences across oceans (geosynclines), which were becoming more and more cumbersome. When seafloor spreading came along, scientists recognized that the mechanism to explain drifting continents had been found. Like the scientists did before us, we are now ready to merge the ideas of continental drift and seafloor spreading into a new all-encompassing idea: the theory of plate tectonics.

Earth's Tectonic Plates

Now you know that seafloor and continents move around on Earth's surface. But what is it that is actually moving? In other words, what is the "plate" in plate tectonics? This question was also answered due to war, in this case the Cold War.

Although seismographs had been around for decades, during the 1950s and especially in the early 1960s, scientists set up seismograph networks to see if enemy nations were testing atomic bombs. Seismographs record seismic waves. Modern seismographs are sensitive enough to detect nuclear explosions. While watching for enemy atom bomb tests, the seismographs were also recording all of the earthquakes that were taking place around the planet. These seismic records could be used to locate an earthquake's **epicenter,** the point on Earth's surface directly above the place where the earthquake occurs. Earthquakes are associated with large cracks in the ground, known as **faults.** Rocks on opposite sides of a fault move in opposite directions.

Earthquakes are not spread evenly around the planet, but are found mostly in certain regions. In the oceans, earthquakes are found along mid-ocean ridges and in and around deep sea trenches. Earthquakes are extremely common all around the Pacific Ocean basin and often occur near volcanoes. The intensity of earthquakes and volcanic eruptions around the Pacific led scientists to name this region the Pacific Ring of Fire (**Figure** 6.15). Earthquakes are also common in the world's highest mountains, the Himalaya Mountains of Asia, and across the Mediterranean region.

Scientists noticed that the earthquake epicenters were located along the mid-ocean ridges, trenches and large faults that mark the edges of large slabs of Earth's lithosphere (**Figure** 6.16). They named these large slabs of lithosphere **plates**. The movements of the plates

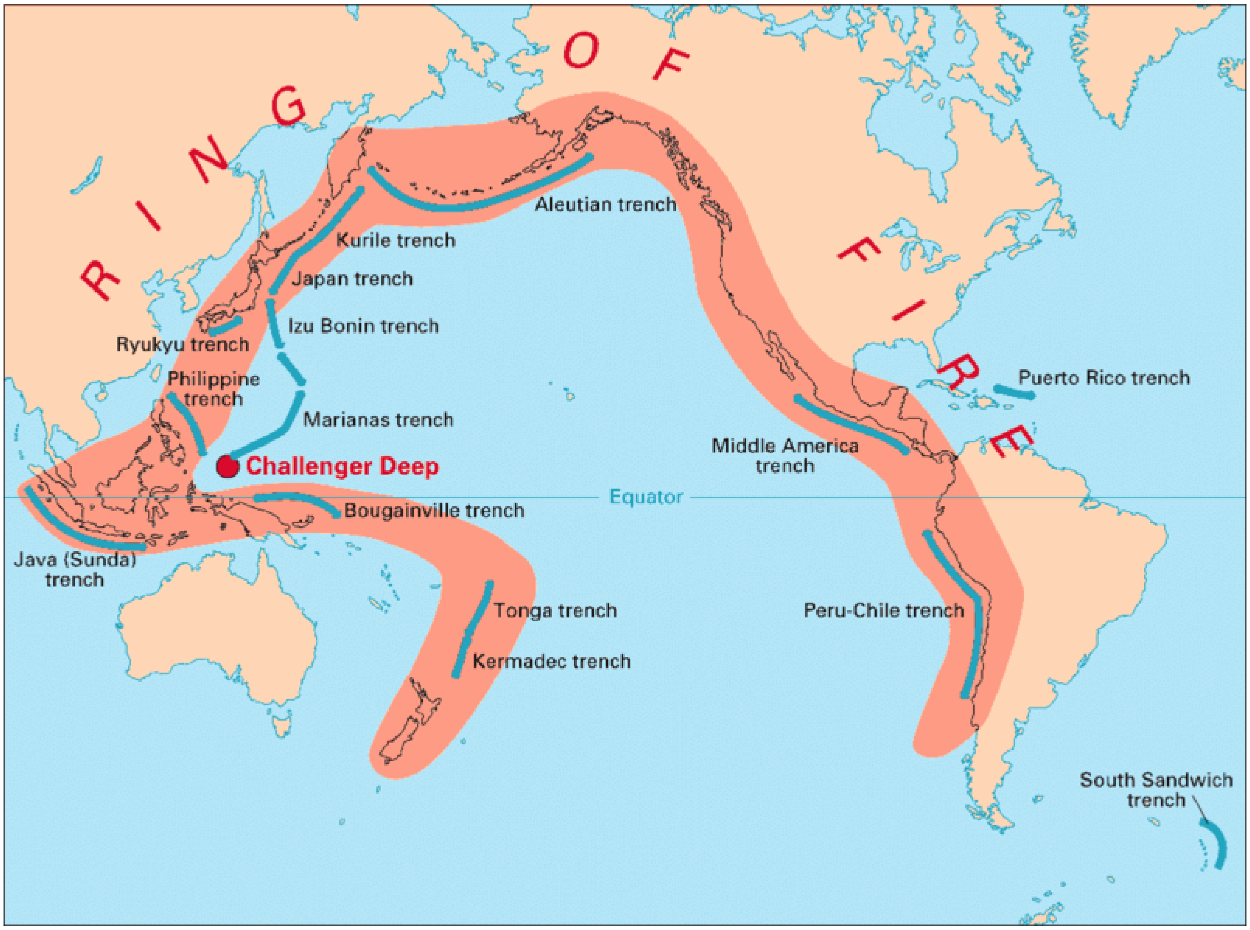

Figure 6.15: The bold pink swatch outlines the volcanoes and active earthquake areas found around the Pacific Ocean basin, which is called the Pacific Ring of Fire. (28)

were then termed **plate tectonics**. A single plate can be made of all oceanic lithosphere or all continental lithosphere, but nearly all plates are made of a combination of both.

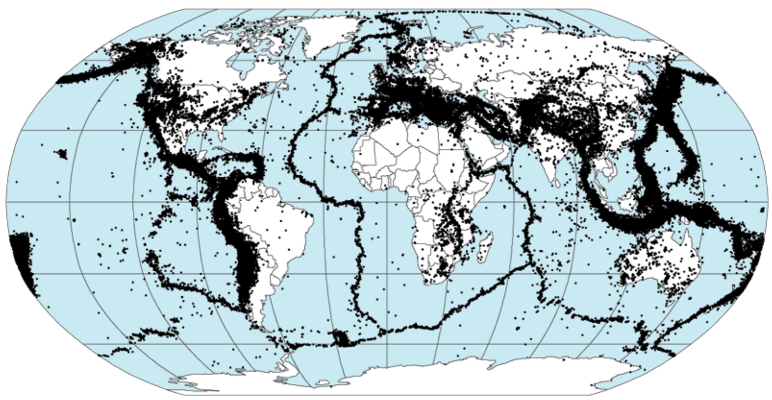

Figure 6.16: A map of earthquake epicenters shows that earthquakes are found primarily in lines that run up the edges of some continents, through the centers of some oceans, and in patches in some land areas. (2)

The lithosphere is divided into a dozen major and several minor plates. The plates' edges can be drawn by the connecting the dots that are earthquakes epicenters. Scientists have named each of the plates and have determined the direction that each is moving (**Figure** 6.17). Plates move around the Earth's surface at a rate of a few centimeters a year, about the same rate fingernails grow.

How Plates Move

We know that seafloor spreading moves the lithospheric plates around on Earth's surface but what drives seafloor spreading? The answer is in lesson one of this chapter: mantle convection. At this point it would help to think of a convection cell as a rectangle or oval (**Figure** 6.18). Each side of the rectangle is a limb of the cell. The convection cell is located in the mantle. The base is deep in the mantle and the top is near the crust. There is a limb of mantle material moving on one side of the rectangle, one limb moving horizontally across the top of the rectangle, one limb moving downward on the other side of the rectangle, and the final limb moving horizontally to where the material begins to move upward again.

Now picture two convection cells side-by-side in the mantle. The rising limbs of material from the two adjacent cells reach the base of the crust at the mid-ocean ridge. Some of the hot magma melts and creates new ocean crust. This seafloor moves off the axis of the mid-ocean ridge in both directions when still newer seafloor erupts. The oceanic plate moves outward due to the eruption of new oceanic crust at the mid-ocean ridge.

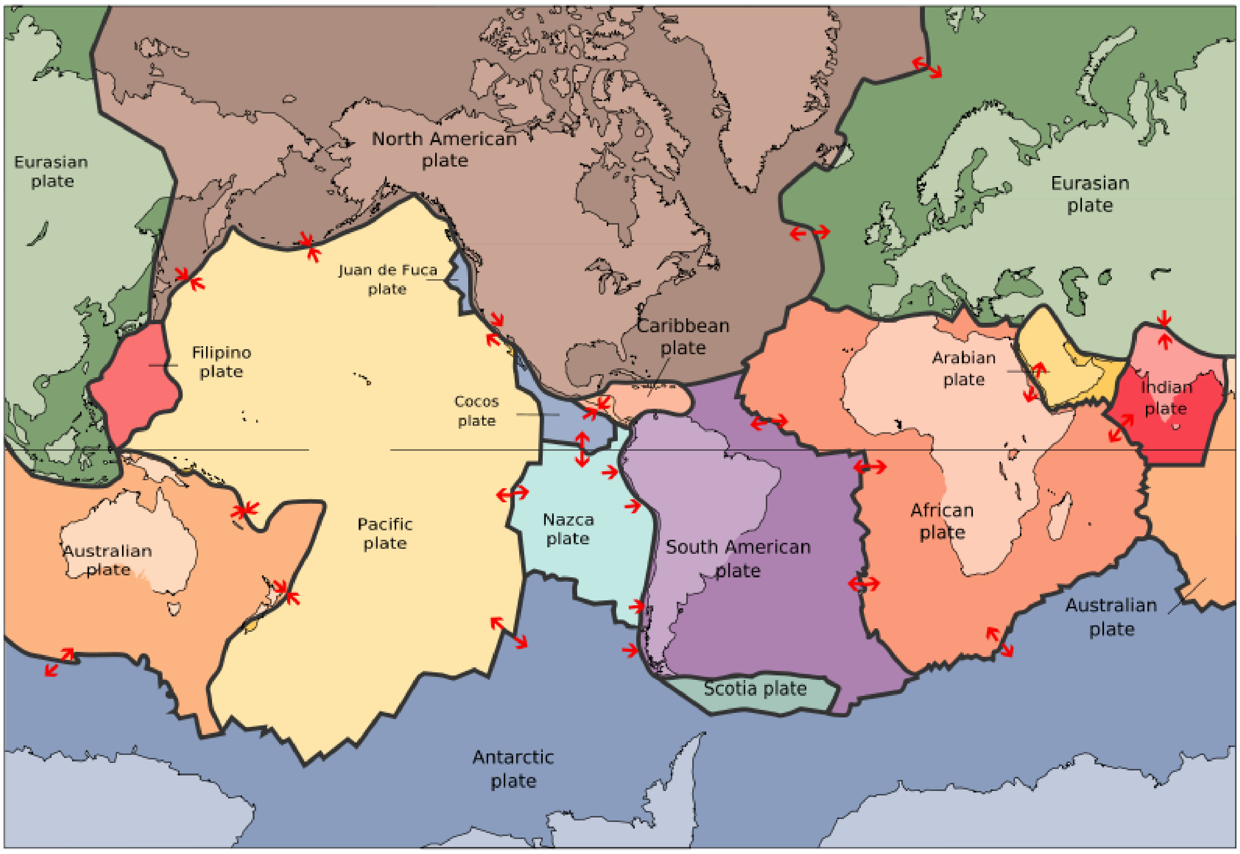

Figure 6.17: The lithospheric plates and their names. The arrows show whether the plates are moving apart, moving together, or sliding past each other. (9)

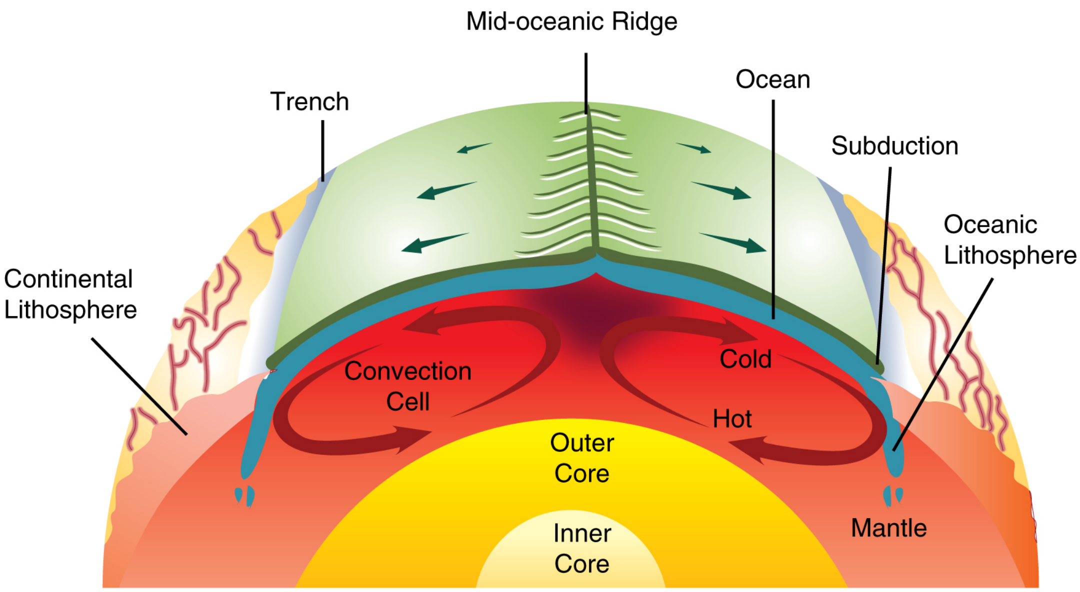

Figure 6.18: Convection in the mantle is the driving force of plate tectonics. Hot material rises at mid-ocean ridges and sinks at deep sea trenches, which keeps the plates moving along the Earth's surface. (17)

Beneath the moving crust is the laterally moving top limb of the mantle convection cells. Each convection cell is moving seafloor away from the ridge in opposite directions. This horizontal mantle flow moves with the crust across the ocean basin and away from the ridge. As the material moves horizontally, the seafloor thickens and both the new crust and the mantle beneath it cool. Where the limbs of the convection cells plunge down into the deeper mantle, oceanic crust is dragged into the mantle as well. This takes place at the deep sea trenches. As the crust dives into the mantle its weight drags along the rest of the plate and pulls it downward. The last limbs of the convection cells flow along the core. The material is heated and so is ready to rise again when it reaches the rising limb of the convection cell. As you can see, each convection cell is found beneath a different lithospheric plate and is responsible for the movement of that plate.

Plate Boundaries

Back at the planet's surface, the edges where two plates meet are known as **plate boundaries.** Most geologic activity, including volcanoes, earthquakes, and mountain building, takes place at plate boundaries where two enormous pieces of solid lithosphere interact.

Think about two cars moving around a parking lot. In what three ways can those cars move relative to each other? They can move away from each other, they can move toward each other, or they can slide past each other. These three types of relative motion also define the three types of plate boundaries:

- **Divergent plate boundaries:** the two plates move away from each other.
- **Convergent plate boundaries:** the two plates move towards each other.
- **Transform plate boundaries:** the two plates slip past each other.

What happens at plate boundaries depends on which direction the two plates are moving relative to each other. It also depends on whether the lithosphere on the two sides of the plate boundary is oceanic crust, continental crust, or one piece of each type. The type of plate boundary and the type of crust found on each side of the boundary determines what sort of geologic activity will be found there: earthquakes, volcanoes, or mountain building.

Divergent Plate Boundaries

Plates move apart, or diverge, at mid-ocean ridges where seafloor spreading forms new oceanic lithosphere. At these mid-ocean ridges, lava rises, erupts, and cools. Magma cools more slowly beneath the lava mostly forming the igneous intrusive rock gabbro. The entire ridge system, then, is igneous. Earthquakes are also common at mid-ocean ridges since the movement of magma and oceanic crust result in crustal shaking. Although the vast majority of mid-ocean ridges are located deep below the sea, we can see where the Mid-Atlantic Ridge surfaces at the volcanic island of Iceland (**Figure** 6.19).

Figure 6.19: The Leif the Lucky Bridge straddles the Mid-Atlantic ridge separating the North American and Eurasian plates on Iceland. (18)

Although it is uncommon, a divergent plate boundary can also occur within a continent. This is called **continental rifting** (**Figure** 6.20). Magma rises beneath the continent, causing it to thin, break, and ultimately split up. As the continental crust breaks apart, oceanic crust erupts in the void. This is how the Atlantic Ocean formed when Pangaea broke up. The East African Rift is currently splitting eastern Africa away from the African continent.

Convergent Plate Boundaries

What happens when two plates converge depends on the types of crust that are colliding. Convergence can take place between two slabs of continental lithosphere, two slabs of oceanic lithosphere, or between one continental and one oceanic slab. Most often, when two plates collide, one or both are destroyed.

When oceanic crust converges with continental crust, the denser oceanic plate plunges beneath the continental plate. This process occurs at the oceanic trenches and is called **subduction** (**Figure** 6.21). The entire region is known as a **subduction zone.** Subduction zones have a lot of intense earthquakes and volcanic eruptions. The subducting plate causes melting in the mantle. The magma rises and erupts, creating volcanoes. These volcanoes are found in a line above the subducting plate. The volcanoes are known as a **continental arc.** The movement of crust and magma causes earthquakes. The Andes Mountains, which line the western edge of South America, are a continental arc. The volcanoes are the result of the Nazca plate subducting beneath the South American plate (**Figure** 6.22).

Figure 6.20: The Arabian, Indian, and African plates are rifting apart, forming the Great Rift Valley in Africa. The Dead Sea fills the rift with seawater. (24)

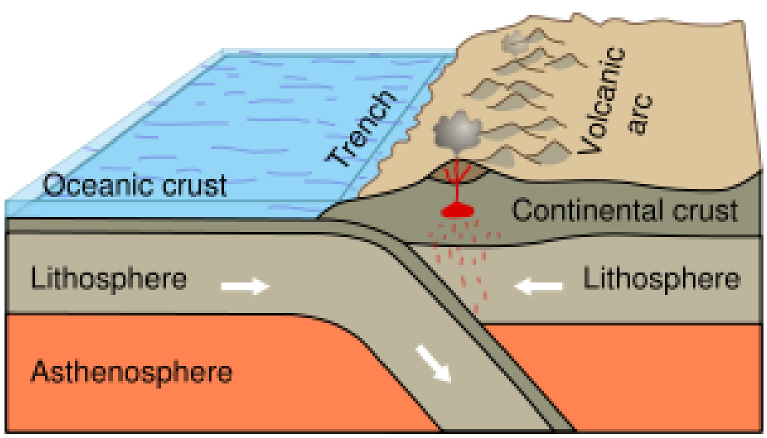

Figure 6.21: Subduction of an oceanic plate beneath a continental plate forms a line of volcanoes known as a continental arc and causes earthquakes. (27)

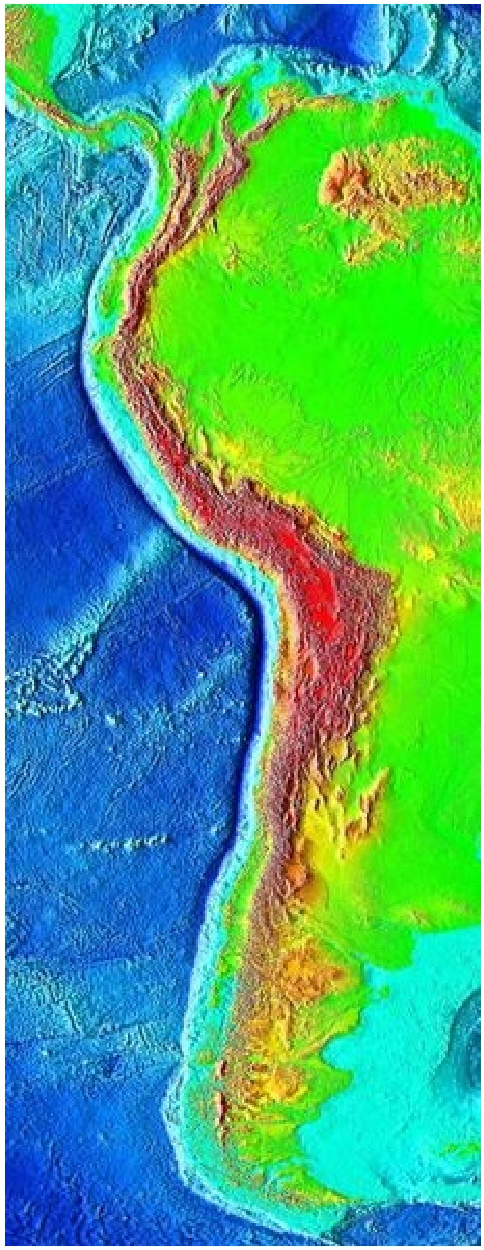

Figure 6.22: This satellite image shows the trench lining the western margin of South America where the Nazca plate is subducting beneath the South American plate. The resulting Andes Mountains line western South America and are seen as brown and red uplands in this image. (30)

The volcanoes of northeastern California—Lassen Peak, Mount Shasta, and Medicine Lake volcano—along with the rest of the Cascade Mountains of the Pacific Northwest, are the result of subduction of the Juan de Fuca plate beneath the North American plate (**Figure** 6.23). Mount St. Helens, which erupted explosively on May 18, 1980, is the most famous and currently the most active of the Cascades volcanoes.

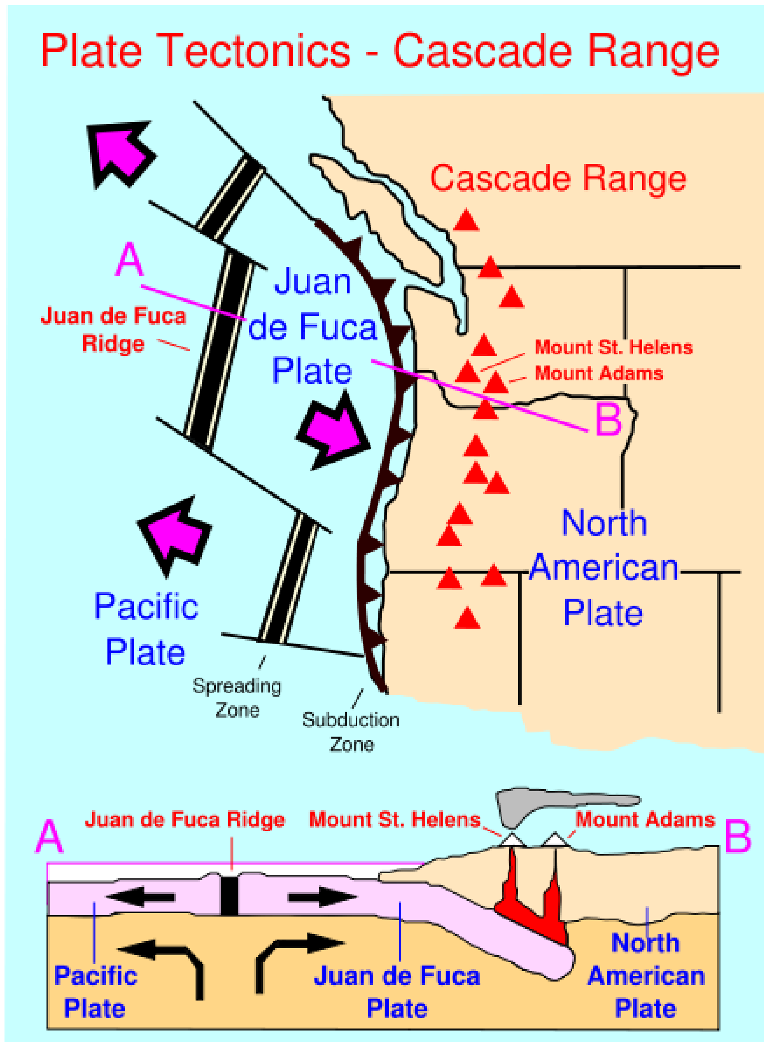

Figure 6.23: The Cascade Mountains of the Pacific Northwest are formed by the subduction of the Juan de Fuca plate beneath the North American plate. The Juan de Fuca plate forms near the shoreline at the Juan de Fuca ridge. (5)

Sometimes the magma does not rise all the way through the continental crust beneath a volcanic arc. This usually happens if the magma is rich in silica. These viscous magmas form large areas of intrusive igneous rock, called batholiths, which may someday be uplifted to form a mountain range. The Sierra Nevada batholith cooled beneath a volcanic arc roughly 200 million years ago (**Figure** 6.24). Similar batholiths are likely forming beneath the Andes and Cascades today.

Figure 6.24: The granite batholith of the Sierra Nevada Mountain range is well exposed here at Mount Whitney, the highest mountain in the range at 14,505 feet (4,421 meters) and the second highest mountain in North America. (1)

When two oceanic plates converge, the older, denser plate will sink beneath the other plate and plunge into the mantle. As the plate is pushed deeper into the mantle, it melts, which forms magma. As the magma rises it forms volcanoes in a line known as an **island arc**, which is a line of volcanic islands (**Figure** 6.25).

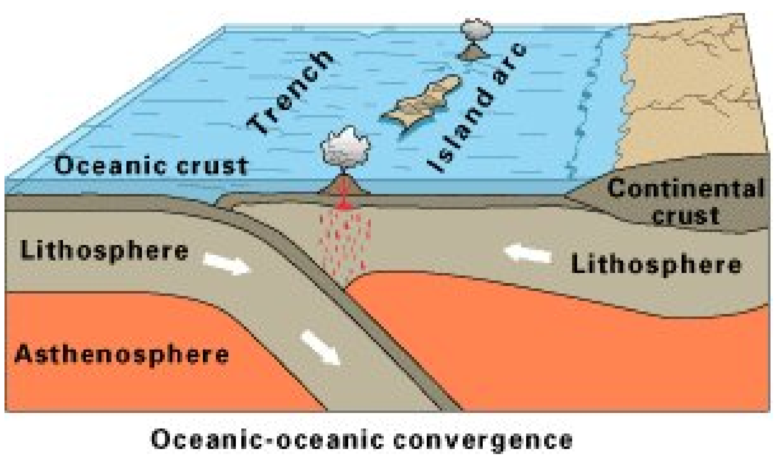

Figure 6.25: A convergent plate boundary subduction zone between two plates of oceanic lithosphere. Melting of the subducting plate causes volcanic activity and earthquakes. (4)

The Japanese, Indonesian, and Philippine islands are examples of island arc volcanoes. The volcanic islands are set off from the mainland in an arc shape as seen in this satellite image of Japan (**Figure** 6.26).

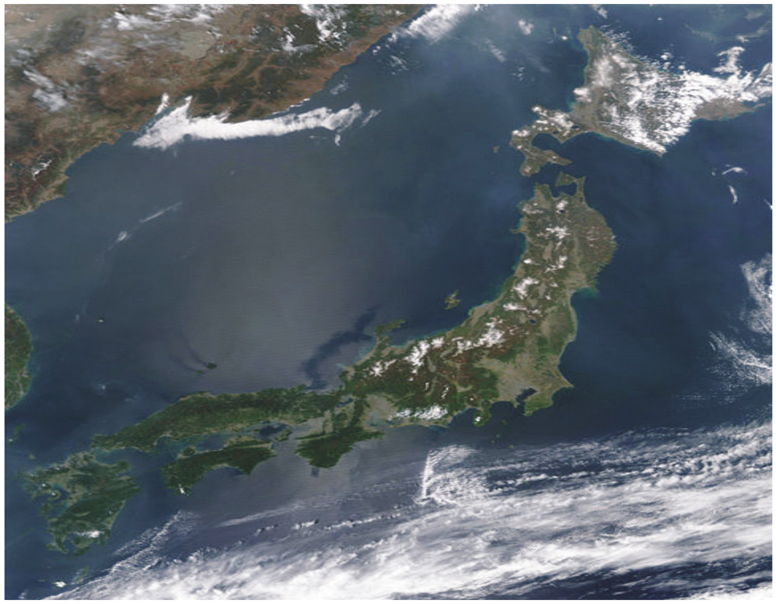

Figure 6.26: Japan is an island arc composed of volcanoes off the Asian mainland, as seen in this satellite image. (21)

When two continental plates collide, they are too thick to subduct. Just like if you put your hands on two sides of a sheet of paper and bring your hands together, the material has nowhere to go but up (**Figure** 6.27)! Some of the world's largest mountains ranges are created at continent-continent convergent plate boundaries. In these locations, the crust is too thick for magma to penetrate so there are no volcanoes, but there may be magma. Metamorphic rocks are common due to the stress the continental crust experiences. As you might think, with enormous slabs of crust smashing together, continent-continent collisions bring on numerous earthquakes.

The world's highest mountains, the Himalayas, are being created by a collision between the Indian and Eurasian plates (**Figure** 6.28). The Appalachian Mountains are the remnants of a large mountain range that was created when North America rammed into Eurasia about 250 million years ago.

Transform Plate Boundaries

Transform plate boundaries are seen as **transform faults.** At these earthquake faults, two plates move past each other in opposite directions. Where transform faults bisect continents, there are massive earthquakes. The world's most notorious transform fault is the 1,300 kilometer (800 mile) long San Andreas Fault in California (**Figure** 6.29). This is where

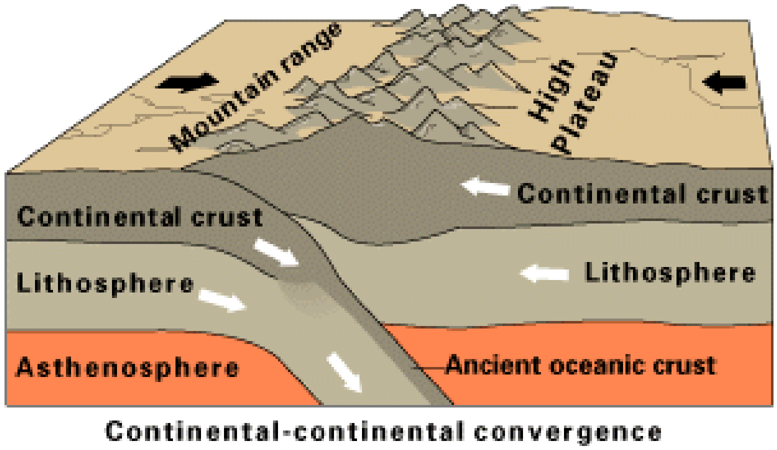

Figure 6.27: When two plates of continental crust collide, the material pushes upward forming a high mountain range. The remnants of subducted oceanic crust remain beneath the continental convergence zone. (19)

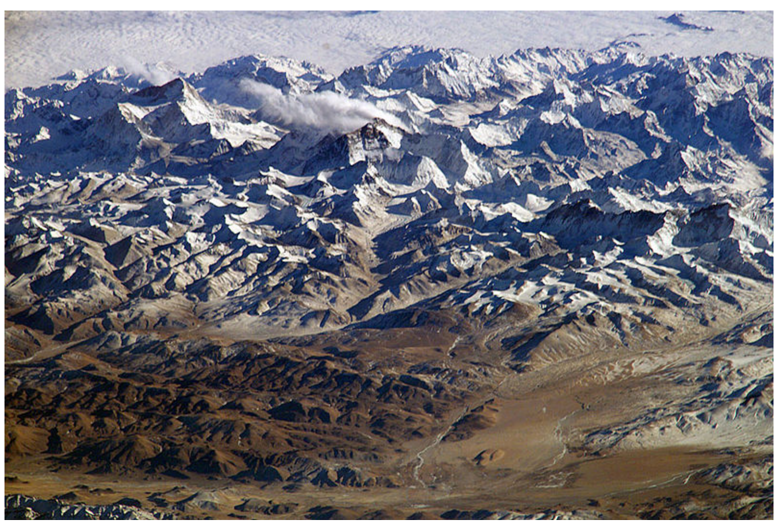

Figure 6.28: The Himalaya Mountains are the result of the collision of the Indian Plate with the Eurasian Plate, seen in this photo from the International Space Station. The high peak in the center is world's tallest mountain, Mount Everest (8,848 meters; 29,035 feet). (26)

the Pacific and North American plates grind past each other, sometimes with disastrous consequences.

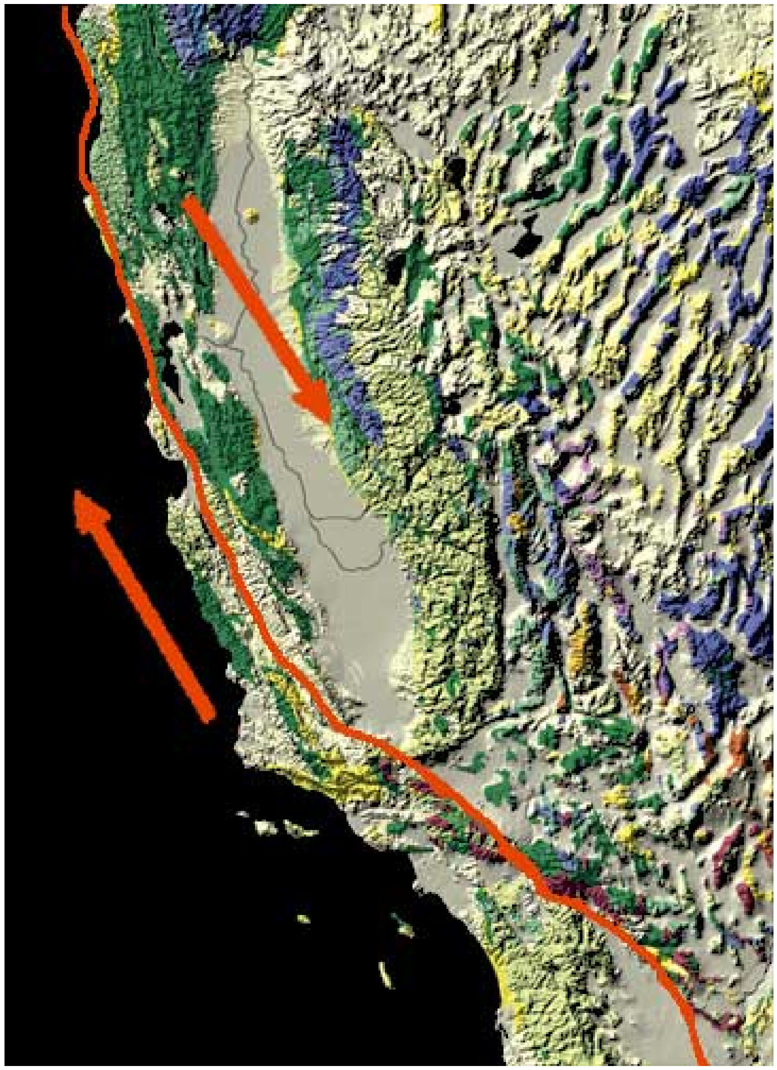

Figure 6.29: At the San Andreas Fault in California, the Pacific Plate is sliding northeast relative to the North American plate, which is moving southwest. At the northern end of the picture, the transform boundary turns into a subduction zone. (12)

California is very geologically active. A transform plate boundary creates the San Andreas Fault. A convergent plate boundary between an oceanic plate and a continental plate creates the Cascades volcanoes. Just offshore, the Juan de Fuca ridge is subducting beneath the North American plate at a divergent plate boundary.

Earth’s Changing Surface

Geologists now know that Wegener was right when he said that the continents had once been joined into the supercontinent Pangaea and are now moving apart. Most of the geologic activity that we see on the planet today is due to the interactions of the moving plates. Where plates come apart at a divergent boundary, there is volcanic activity and small earthquakes. If the plates meet at a convergent boundary, and at least one is oceanic, there is a chain of volcanoes and many earthquakes. If both plates at a convergent boundary are continental, mountain ranges grow. If the plates meet at a transform boundary, there is a transform fault. These faults do not have volcanic activity but they have massive earthquakes.

If you look at a map showing the locations of volcanoes and earthquakes in North America, you will see that the plate boundaries are now along the western edge. This geologically active area makes up part of the Pacific Ring of Fire. California, with its volcanoes and earthquakes, is an important part of this region. The eastern edge of North America is currently mostly quiet, although mountain ranges line the area. If there is no plate boundary there today, where did those mountains come from?

Remember that Wegener used the similarity of the mountains in eastern North America, on the west side of the Atlantic, and the mountains in Great Britain, on the eastern side of the Atlantic, as evidence for his continental drift hypothesis. These mountains were formed at a convergent plate boundary as the continents that made up Pangaea came together. So about 200 million years ago these mountains were similar to the Himalaya today (**Figure** 6.30)!

Figure 6.30: The Appalachian Mountains of eastern North America were probably once as high as the Himalaya, but they have aged since the breakup of Pangaea. (14)

Before the continents collided they were separated by an ocean, just as the continents rimming the Pacific are now. That ocean crust had to subduct beneath the continents just as the oceanic crust around the Pacific is being subducted today. Subduction along the eastern margin of North America produced continental arc volcanoes. Ancient lava from those volcanoes can be found in the region.

Currently, Earth's most geologically active area is around the Pacific. The Pacific is shrinking at the same time the Atlantic is growing. But hundreds of millions of years ago, that was reversed: the Atlantic was shrinking as the Pacific was growing. What we've just identified is a cycle, known as the **supercontinent cycle,** which is responsible for most of the geologic features that we see and many more that are long gone. Scientists think that the creation and breakup of a supercontinent takes place about every 500 million years.

Intraplate Activity

While it is true that most geological activity takes place along plate boundaries, some is found away from the edges of plates. This is known as **intraplate activity.** The most common intraplate volcanoes are above hotspots that lie beneath oceanic plates. Hotspot volcanoes arise because plumes of hot material that come from deep in the mantle rise through the overlying mantle and crust. When the magma reaches the plate above, it erupts, forming a volcano. Since the hotspot is stable, when the oceanic plate moves over it, and it erupts again, another volcano is created in line with the first. With time, there is a line of volcanoes; the youngest is directly above the hot spot and the oldest is furthest away. Recent research suggests that hotspots are not as stable as scientists once thought, but some larger ones still appear to be.

The Hawaiian Islands are a beautiful example of a chain of hotspot volcanoes. Kilauea volcano on the south side of the Big Island of Hawaii lies above the Hawaiian hot spot. The Big Island is on the southeastern end of the Hawaiian chain. Mauna Loa volcano, to the northwest, is older than Kilauea and is still erupting, but at a lower rate. Hawaii is the youngest island in the chain. As you follow the chain to the west, the islands get progressively older because they are further from the hotspot (**Figure** 6.31).

The chain continues into the Emperor Seamounts, which are so old they no longer reach above sea level. The oldest of the Emperor seamounts is about to subduct into the Aleutian trench off of Alaska; no one knows how many older volcanoes have already subducted. It's obvious from looking at the Emperor seamounts that the Pacific plate took a large turn. Radiometric dating has shown that turn to have taken place about 43 million years ago (**Figure** 6.32). The Hawaii hotspot may also have been moving southward during this time. Still, geologists can use some hotspot chains to tell not only the direction but the speed a plate is moving.

Hot spots are also found under the continental crust, although it is more difficult for the magma to make it through the thick crust and there are few eruptions. One exception is Yellowstone, which creates the activity at the Yellowstone hotspot. In the past, the hotspot produced enormous volcanic eruptions, but now its activity is best seen in the region's famous

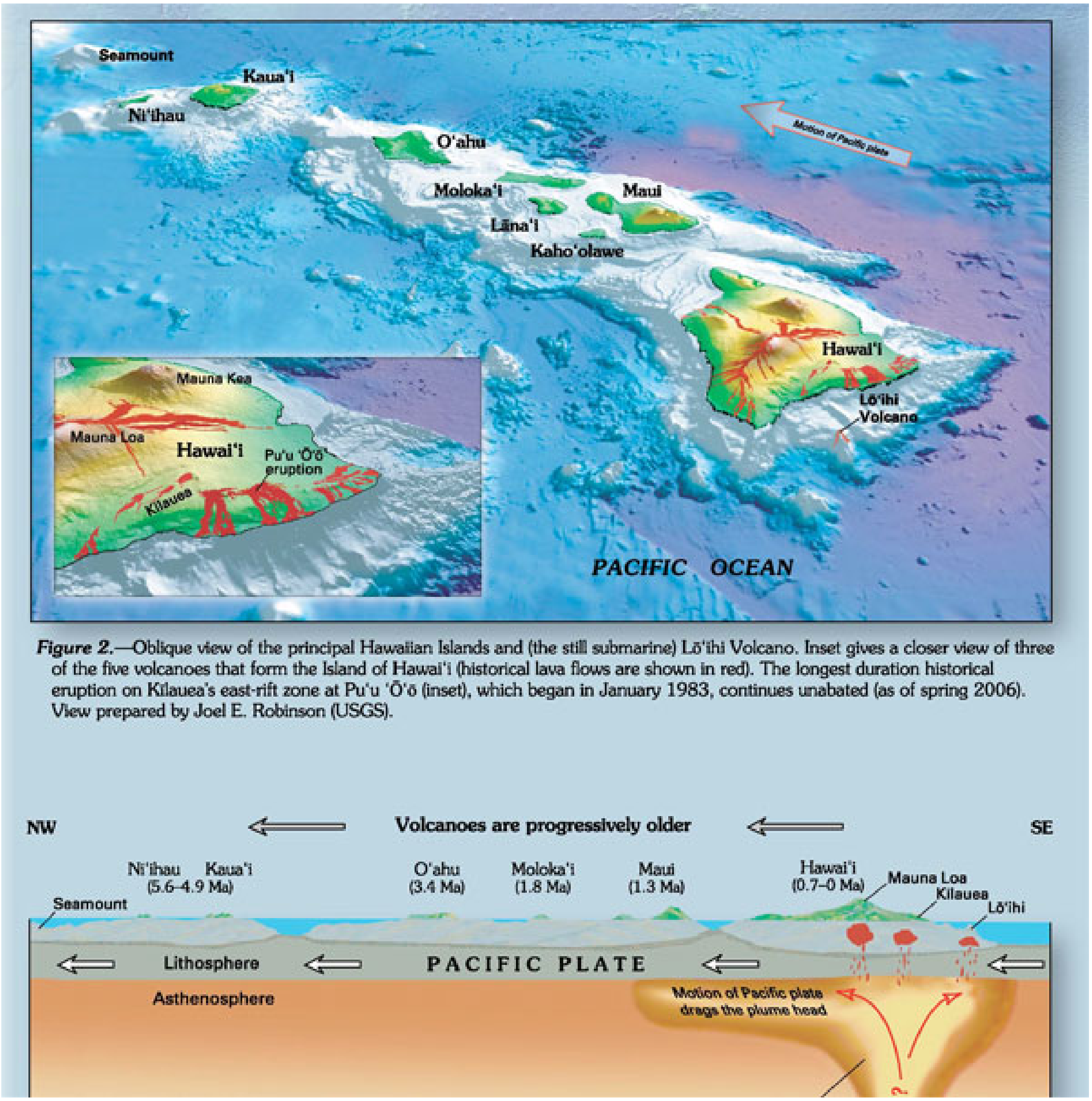

Figure 6.31: This view of the Hawaiian islands showing the youngest islands in the southeast and the oldest in the northwest. Kilauea volcano, which makes up the southeastern side of the Big Island of Hawaiian, is located above the Hawaiian hotspot. (15)

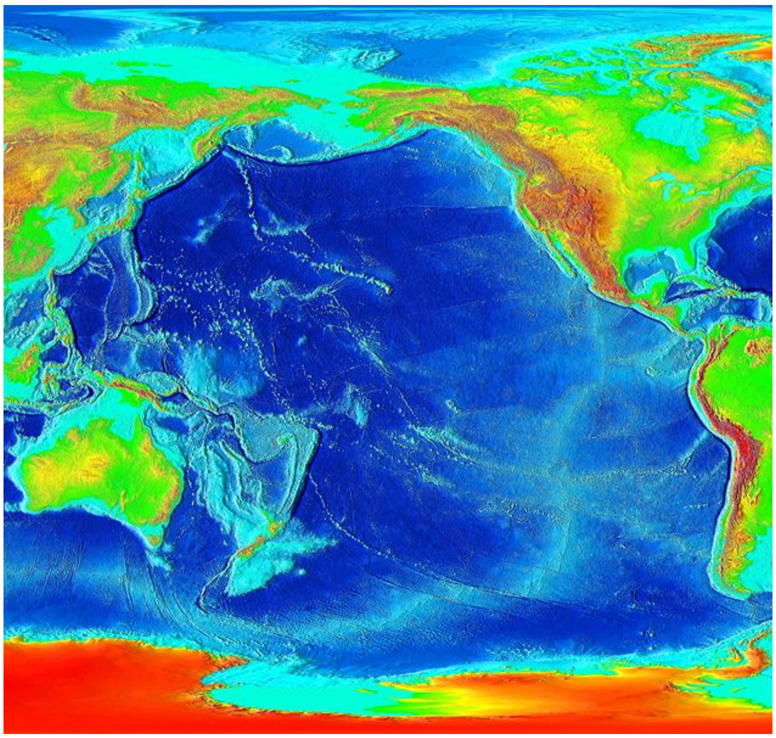

Figure 6.32: The Hawaii-Emperor chain creates a large angular gash across the Pacific basin in this satellite image. The bend in the chain is due to a change in the direction of motion of the Pacific plate 43 million years ago. (10)

geysers.

Lesson Summary

- Driven by mantle convection, the plates of lithosphere move around Earth's surface. New oceanic crust forms at the ridge and pushes the older seafloor away from the ridge horizontally.
- Plates interact at three different types of plate boundaries, divergent, convergent and transform fault boundaries, which are where most of the Earth's geologic activity takes place.
- These processes acting over long periods of time are responsible for the geographic features we see.

Review Questions

1. What are the three types of plate boundaries? For each type, what sort of geologic activity do you find?
2. As a working geologist, you come across a landscape with a massive fault zone that produces lots of large earthquakes, but has no volcanoes. What type of plate boundary have you come across? What are the movements of plates relative to each other at type of boundary? Where would you find a plate boundary of this type in California?
3. You continue on your geologic tour to a location where there is a chain of volcanoes on land, but not too far inland from the edge of the continent. The region experiences frequent large earthquakes. What type of plate boundary have you come across? What types of plates are involved? Where would you find a plate boundary of this type in California?
4. What is the driving force behind the movement of lithospheric plates on the Earth's surface? About how fast do the plates move?
5. How does the theory of plate tectonics explain the locations of volcanoes, earthquakes and mountain belts on Earth?
6. Thinking about the different types of plate boundaries, explain why continental crust is much thicker than oceanic crust.
7. Why are there few (if any) volcanoes along transform plate boundaries?

Vocabulary

batholith An enormous body of granitic rock that is formed from a large number of plutons.

continental arc A line of volcanoes sitting on a continental plate and aligned above a subducting oceanic plate near a deep sea trench.

continental rifting A divergent plate boundary that forms in the middle of a continent.

convergent plate boundary A location where two lithospheric plates come together.

divergent plate boundary A location where two lithospheric plates spread apart.

epicenter The point on the Earth's surface directly above an earthquake's focus, which is the place where the ground breaks.

fault A fracture along which there has been movement of rock on one or both sides.

intraplate activity Geologic activity such as volcanic eruptions and earthquakes that takes place away from plate boundaries.

island arc A line of volcanoes sitting on an oceanic plate above a subducting oceanic plate near a deep sea trench.

plate A slab of the earth's lithosphere that can move around on the planet's surface.

plate boundary A location where two plates come together.

plate tectonics The theory that the Earth's surface is divided into lithospheric plates that move on the planet's surface.
The driving force behind plate tectonics is mantle convection.

pluton A relatively small body of igneous intrusive rock.

subduction The sinking of one lithospheric plate beneath another.

subduction zone The area where two lithospheric plates come together and one sinks beneath the other.

supercontinent cycle The cycle in which the continents join into one supercontinent on one side of the planet and then break apart.

transform fault An earthquake fault where relative motion is sliding past.

transform plate boundary The type of plate boundary where two plates slide past one another.

Points to Consider

- On the map in Figure 3 above, the arrows show the directions that the plates are going. The Atlantic has a mid-ocean ridge, where seafloor spreading is taking place. The Pacific ocean has many deep sea trenches, where subduction is taking place. What is the future of the Atlantic plate? What is the future of the Pacific plate?
- Using your hands and words, explain to someone how plate tectonics works. Be sure you describe how continents drift and how seafloor spreading provides a mechanism for continental movement.
- Now that you know about plate tectonics, where do you think would be a safe place to live if you wanted to avoid volcanic eruptions and earthquakes?

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Chapter 7

Earthquakes

7.1 Stress in the Earth's Crust

Lesson Objectives

- List the different types of stresses that cause different types of deformation.
- Compare the different types of folds and the conditions under which they form.
- Compare fractures and faults and define how they are related to earthquakes.
- Compare how mountains form and at what types of plate boundaries.

Introduction

When you think about enormous plates of lithosphere traveling around on the planet's surface, you can probably imagine that the process is not smooth. Most geological activity takes place where two plates meet, at plate boundaries. In the Earthquakes chapter, you will learn that nearly all earthquakes, volcanic eruptions, and mountain building occur at plate boundaries. In this chapter, you will learn more about the geological activity that occurs because of plate tectonics, specifically mountain building and earthquakes.

When plates are pushed or pulled, the rock is subjected to stress. Stress can cause a rock to change shape or to break. When a rock bends without breaking, it folds. When the rock breaks, it fractures. Mountain building and earthquakes are some of the responses rocks have to stress.

Causes and Types of Stress

Stress is the force applied to an object. In geology, stress is the force per unit area that is placed on a rock. There are four types of stresses that act on materials.

- A deeply buried rock is pushed down by the weight of all the material above it. Since the rock is trapped in a single spot, it is as if the rock is being pushed in from all sides. This pushing causes the rock to become compressed, but it cannot deform because there is no place for it to move. This is called **confining stress.**
- **Compression** is the stress that squeezes rocks together. Compression causes rocks to fold or fracture (break)(**Figure** 7.1). When cars driving around a parking lot collide, compression causes the cars to crumple. Compression is the most common stress at convergent plate boundaries.

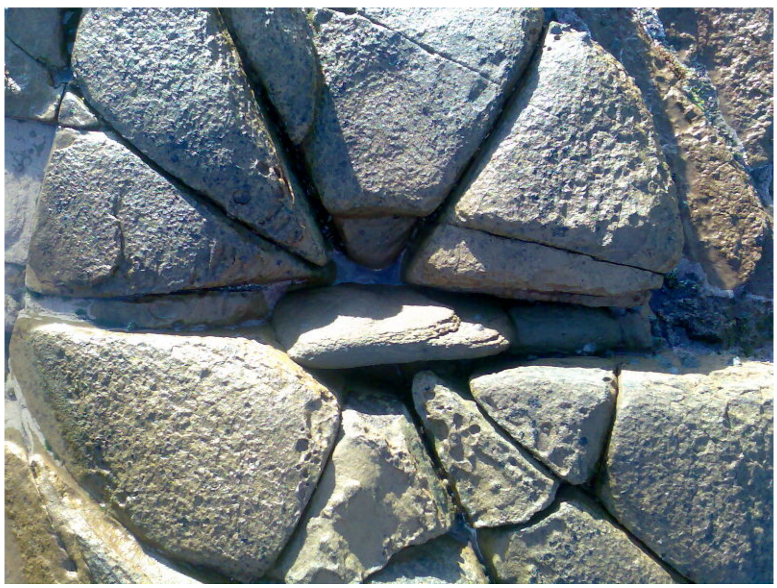

Figure 7.1: Stress caused these rocks to fracture. (27)

- Rocks that are being pulled apart are under **tension** (also called extension). Tension causes rocks to lengthen or break apart. Tension is the major type of stress found at divergent plate boundaries.
- When forces act parallel to each other but in opposite directions, the stress is called **shear** (**Figure** 7.2). Shear stress causes two planes of material to slide past each other. This is the most common stress found at transform plate boundaries.

If the amount of stress on a rock is greater than the rock's internal strength, the rock bends elastically. This type of change is called elastic because when the stress is eliminated the

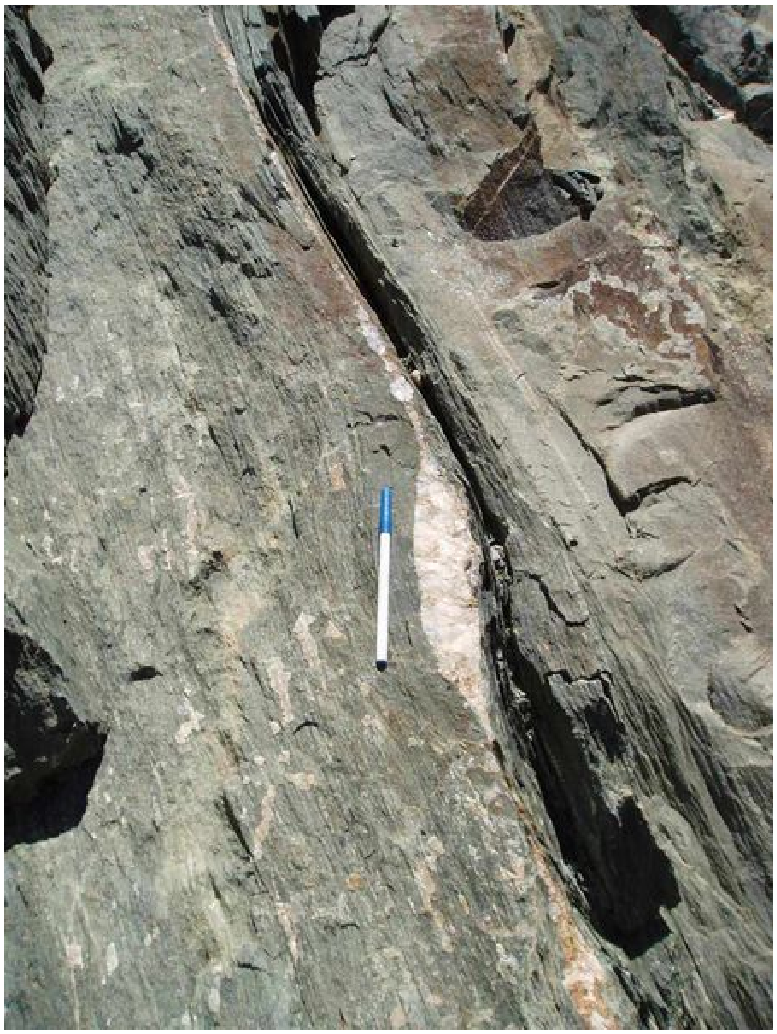

Figure 7.2: Rocks showing dextral shear. Note how the white quartz vein has been elongated by shear. (44)

rock goes back to its original shape, like a squeezed rubber ball. If more stress is applied to the rock, it will eventually bend plastically. In this instance, the rock bends, but does not return to its original shape when the stress is removed. If the stress continues, the rock will **fracture;** that is, it breaks. When a material changes shape, it has undergone **deformation.** Deformed rocks are common in geologically active areas (**Figure** 7.3).

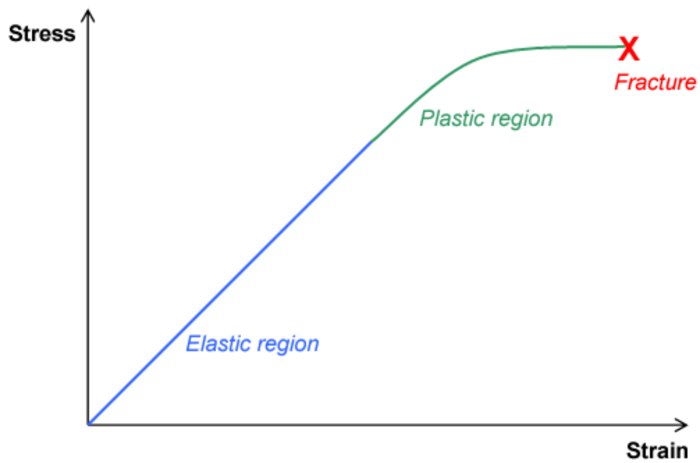

Figure 7.3: When stress is applied to a material, it initially deforms elastically. With more stress, the material deforms plastically and when the material's strength is exceeded, it fractures. The amount of stress that can be applied before the material transitions to the next type of deformation depends on the material and the conditions where it is located. (30)

What a rock does in response to stress depends on many factors: the rock type; the conditions the rock is under, primarily the surrounding temperature and pressure; the length of time the rock is under stress; and the type of stress. It seems difficult to imagine that rocks would not just simply break when exposed to stress. At the Earth's surface, rocks usually break quite quickly once stress is applied. But deeper in the crust, where temperatures and pressures are higher, rocks are more likely to deform plastically. Sudden stress, like a hit with a hammer, is more likely to make a rock break. Stress applied over time, often leads to plastic deformation.

Geologic Structures

Sedimentary rocks are often found in layers. This is most magnificently displayed at the Grand Canyon, where the rock layers are exposed like a layer cake (**Figure** 7.4). Each layer is made of sediments that were deposited (laid down) in a particular environment, perhaps a lake bed, shallow offshore region, or a sand dune. Sediments are deposited horizontally. the lowest layers are the oldest and the highest layers are the youngest. Some volcanic rocks, like ash falls, resemble sedimentary rocks because they are laid down horizontally as well.

Figure 7.4: The layered rocks of the Grand Canyon from the rim. (38)

It's important to remember that sediments are deposited horizontally when thinking about geologic structures. This is because you can trace the deformation the rock has experienced by seeing how it differs from its original horizontal, oldest-on-bottom, position (**Figure** 7.5). Geologic structures are the folds, joints and faults that are caused by stresses.

Folds

When rocks experiencing compressive stress deform plastically, the rocks crumple into **folds.** Folds are just bends in the rock. You can easily make folds by placing your hands on opposite edges of a piece of cloth and pushing the cloth together. In layered sedimentary rocks, you can trace the folding of the layers with your eyes (**Figure** 7.6).

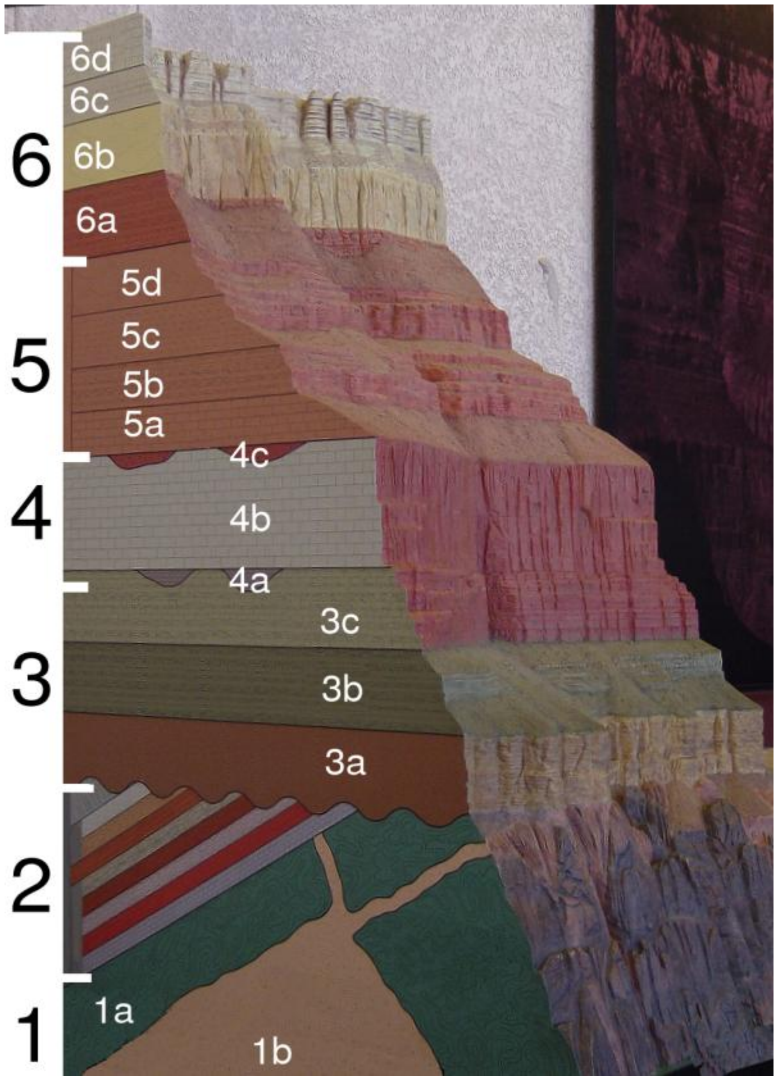

Figure 7.5: Geologic column of the Grand Canyon. The sedimentary rocks of groups 3 through 6 were deposited horizontally and remain horizontal. Group 2 rocks were deposited horizontally but have been tilted. Group 1 rocks are not sedimentary. The rock layers at the bottom of the stack are the oldest while the ones at the top are the youngest. (32)

Figure 7.6: Snow accentuates the fold exposed in these rocks in Provo Canyon, Utah. (34)

Once rocks are folded, they do not return to their original shape. If the rocks experience more stress, they may undergo more folding, or even fracture. Folds often occur in groups.

There are three types of folds: monoclines, anticlines, and synclines. A **monocline** is a simple bend in the rock layers so that they are no longer horizontal but are inclined (**Figure** 7.7). In a monocline, the oldest rocks are at the bottom and the youngest are at the top. In the Grand Canyon geologic column, the rocks in group 2 have been folded into a monocline.

An **anticline** is a fold that arches upward. The rocks dip away from the center of the fold (**Figure** 7.8).

The oldest rocks are found at the center of an anticline and the youngest ones are draped over them at the top of the structure (**Figure** 7.9).

When rocks arch upward to form a circular structure, that structure is called a **dome.** If the top of the dome is eroded off, the oldest rocks will be exposed at the center.

A **syncline** is a fold that bends downward. The rocks curve down to a center (**Figure** 7.10).

In a syncline, the youngest rocks are at the center and the oldest at the outsides (**Figure** 7.11).

When rocks bend downward in a circular structure, that structure is called a **basin.** If the rocks are exposed, the youngest rocks will be at the center. Basins can be enormous. For example, the Michigan Basin is centered on the state of Michigan, but extends into four other states and a Canadian province (**Figure** 7.12).

Folds are sometimes, but not always the cause of geographic features such as hills or valleys.

Figure 7.7: A monocline can be spotted in the photo taken at Colorado National Monument where the rocks plunge toward the ground. (28)

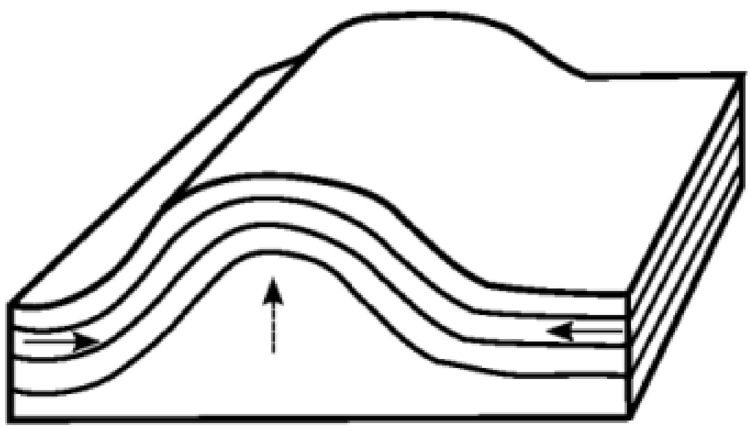

Figure 7.8: Diagram of an anticline. An anticline is a convex upward fold. (19)

Figure 7.9: An anticline exposed in a road cut in New Jersey. (12)

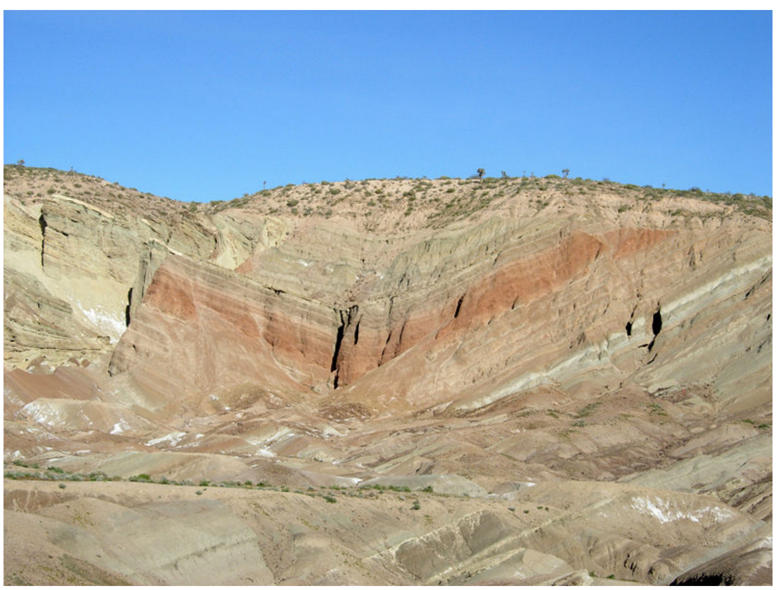

Figure 7.10: A syncline in Rainbow Basin in California. (43)

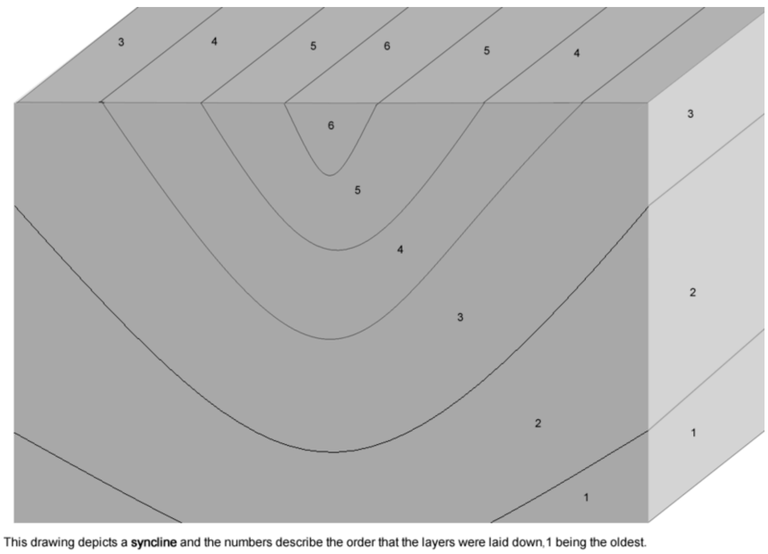

Figure 7.11: Diagram of a syncline. A syncline is a concave downward fold. (11)

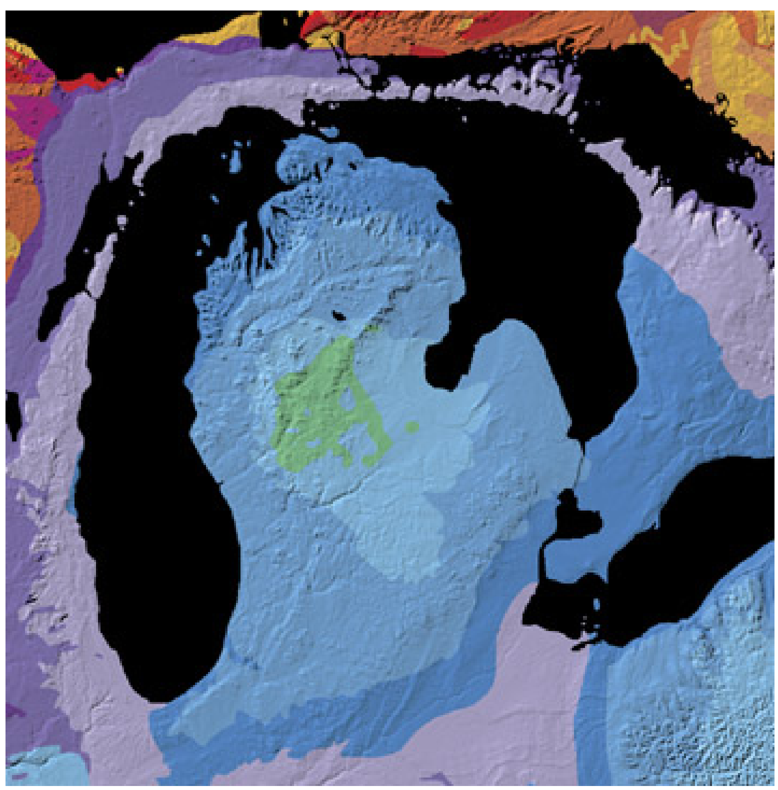

Figure 7.12: Geologic map of the Michigan Basin. (45)

Geologic processes that work at the surface, like erosion, are important in creating geographic features as well.

Faults

A rock under enough stress will fracture, or break. When there is a block of rock still standing on either side of a fracture line, as shown in **Figure** 7.13, the fracture is called a **joint.** One example of how joints form is when confining stress is removed from an underlying granite.

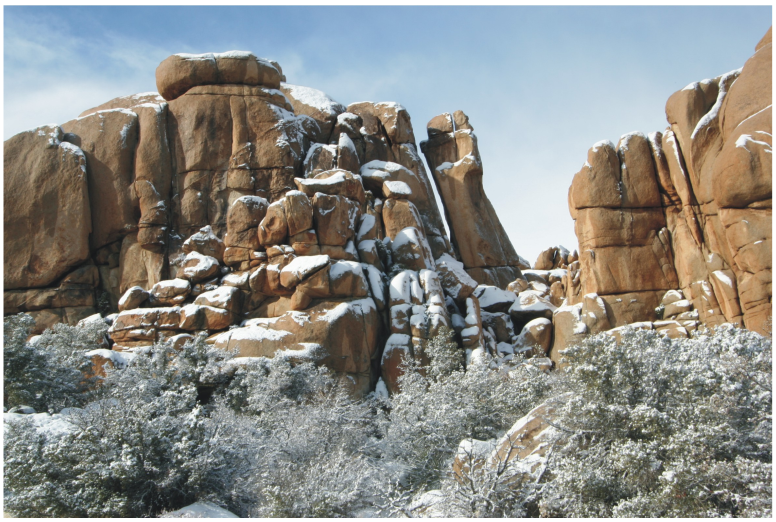

Figure 7.13: Granite rocks in Joshua Tree National Park showing horizontal and vertical jointing. Over millions of years, wind and water have broken down the granite, enlarging the joints and making the pattern of jointing more obvious. (3)

If the blocks of rock on one or both sides of a fracture move, the fracture is called a **fault** (**Figure** 7.14). Earthquakes happen when there are sudden motions along faults. When rocks break and move suddenly, the energy released causes an earthquake. Faults may occur at the Earth's surface or deeper in the crust. Faults are found alone or in clusters, creating a **fault zone.**

Slip is the distance rocks move along a fault. Slip is said to be relative, because there is usually no way to know whether both sides moved or only one. The only thing we can say for sure, is that one block of rock moved passed the other. Faults lie at an angle to the horizontal surface of the Earth. That angle is called the fault's **dip.** The dip defines which of two basic types a fault is. If the fault's dip is inclined relative to the horizontal, the fault is a **dip-slip fault.** Slip can be up or down the fault plane.

In the following images, you are looking at the fault straight on, as if you are standing on a road and the fault is exposed in the road cut. The **hanging wall** is the rock that overlies the fault, while the **footwall** is beneath the fault. You can remember which part is the hanging

Figure 7.14: Faults are easy to recognize as they cut across bedded rocks. (47)

wall and which is the footwall by imagining you are walking along a fault. The hanging wall is above you and the footwall is where your feet would be. Miners often extract mineral resources along faults. They used to hang their lanterns above their heads. That is why these layers were called the hanging wall.

In **normal faults,** the hanging wall drops down relative to the footwall. Normal faults are caused by tensional stress that pulls the crust apart, causing the hanging wall to slide down relative to the footwall. When compression squeezes the crust into a smaller space, the hanging wall pushes up relative to the footwall. This creates a **reverse fault** (**Figure** 7.15).

A type of reverse fault is called a **thrust fault.** At a thrust fault, the fault plane angle is nearly horizontal and rocks can slip many miles along thrust faults (**Figure** 7.16).

Normal faults can be huge. They can be responsible for uplifting mountain ranges in regions experiencing tensional stress (**Figure** 7.17).

Strike-Slip

A **strike-slip fault** is a dip-slip fault where the dip of the fault plane is vertical. Strike-slip faults result from shear stresses. If you stand with one foot on one side and one foot on the other side of a strike-slip fault, the block on one side will be moving toward you and the block on the other side will be moving away from you. If the block moving toward you is the

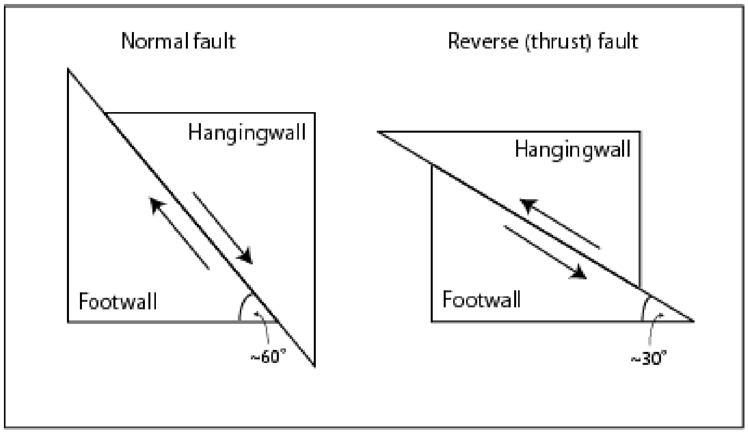

Figure 7.15: The two types of dip-slip faults. In normal faults the hanging wall drops down relative to the footwall. In reverse faults, the footwall drops down relative to the hanging wall. (17)

Figure 7.16: At Chief Mountain in Montana, stresses that raised up the Rocky Mountains caused a block of ancient Precambrian crust to be thrust more than 80 kilometers (50 miles) over much younger Cretaceous rocks. The result is that the upper rocks at the Lewis Overthrust are more than 1 billion years older than the lower rocks. (39)

Figure 7.17: The Teton Range in Wyoming rose up along a normal fault. (22)

block that your right foot is on, the fault is known as a right-lateral strike-slip fault. If the block moving toward you is the one your left foot is on, the fault is a left-lateral strike-slip fault (**Figure** 7.18).

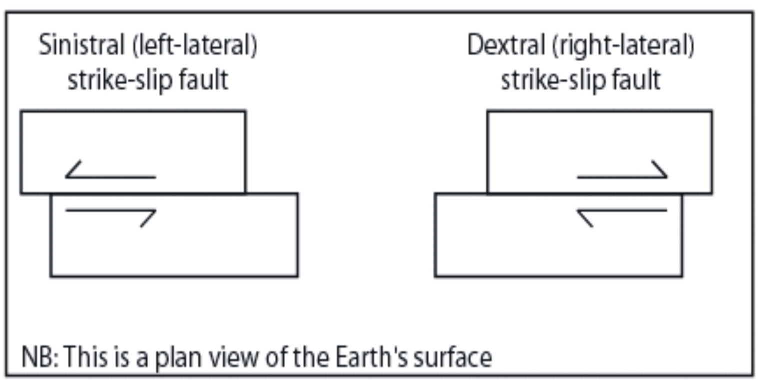

Figure 7.18: The two types of strike-slip faults. (4)

The world's most famous strike-slip fault is the San Andreas Fault in California, which is a right-lateral strike slip fault (**Figure** 7.19). Because the San Andreas is a plate boundary, it is also called a transform fault. People sometimes say that California will fall into the ocean someday, but this is a joke. The portion west of the San Andreas Fault is moving northeastward and someday Los Angeles will be a suburb of San Francisco, but the land west of the San Andreas Fault is a solid piece of continental crust that will not disappear entirely.

Figure 7.19: The San Andreas is a transform fault separating the Pacific from North American Plates. The fault creates a scar on the land as it moves across the Carizzo Plains in eastern San Luis Obispo County, California. (18)

A fault may have broken and moved only once, but most faults are active repeatedly. There are two reasons for this. One is that plate tectonic processes continue in the same locations. The other is that a fault is a zone of weakness in the crust, and it is easier for movement to take place along an existing fault than for a new fault to be created in solid crust.

Stress and Mountain Building

Mountains can stand alone or in ranges that formed at a similar time and in a similar way. Many processes can create mountains. Although most mountains form along plate boundaries, some result from intraplate activity. For example, volcanoes build upwards at hotspots within the Pacific Plate.

Most of the world's largest mountains result from compression at convergent plate boundaries. The largest mountains arise when two continental plates smash together. Continental lithosphere is too buoyant to get pushed down into the mantle or subduct, so when the plates smash together, the crust crumples upwards, causing **uplift.** The stresses cause folds, reverse faults, and thrust faults, all of which allow the crust to grow thicker and rise upwards.

The world's highest mountain range, the Himalayas, is growing from the collision between the Indian and the Eurasian plates. About 80 million years ago, the Indian plate was separated from the Eurasian plate by an ocean (**Figure** 7.20). As the Indian plate moved northward, a subduction zone formed beneath Eurasia. The seafloor was subducted and caused the formation of a set of continental arc volcanoes. When the oceanic lithosphere was completely subducted, about 40 million years ago, the Indian plate began to collide with the Eurasian plate. Some of the Indian plate was thrust beneath Asia and some of Asia was thrust onto India. Rock also folded, which thickened the crust and formed the mountains. In places, the old seafloor that was between the two slabs of continental crust have been thrust over the Asian continent and are found high in the Himalayas (**Figure** 7.21).

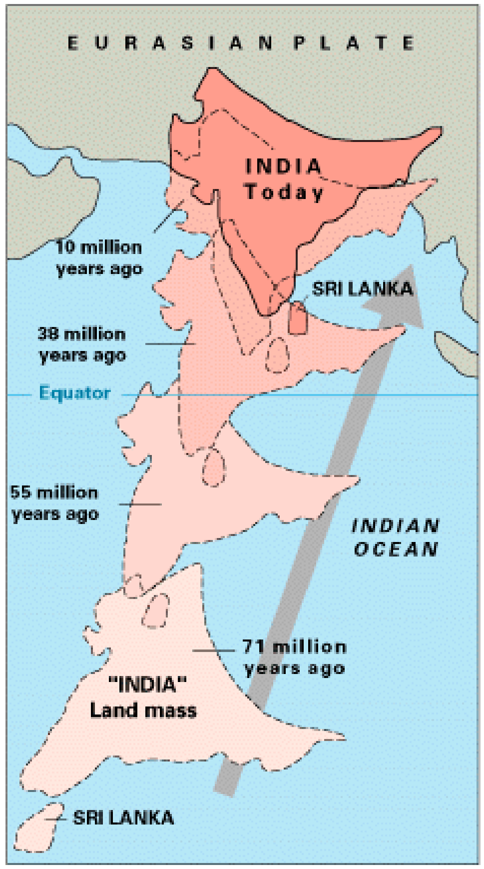

Figure 7.20: The India plate collides with the Eurasian plate to form the world's largest mountain range, the Himalayas. (23)

Figure 7.21: The Himalayas are the world's highest mountain range. (5)

Subduction of oceanic lithosphere at convergent plate boundaries also builds mountain ranges. The Andes Mountains are a chain of continental arc volcanoes that build up as the Nazca plate subducts beneath the South American plate (**Figure** 7.22).

Rifting at a divergent plate boundary can also build mountain ranges. When crust is pulled apart, it occupies more area. The crust breaks into blocks that slide up and down along the normal faults that separate them. The result is alternating mountain ranges and valleys, known as a basin-and-range (**Figure** 7.23). The state of Nevada is the center of a classic basin and range province (**Figure** 7.24).

Figure 7.22: The Andes Mountains have arisen due to the convergence of two lithospheric plates. (21)

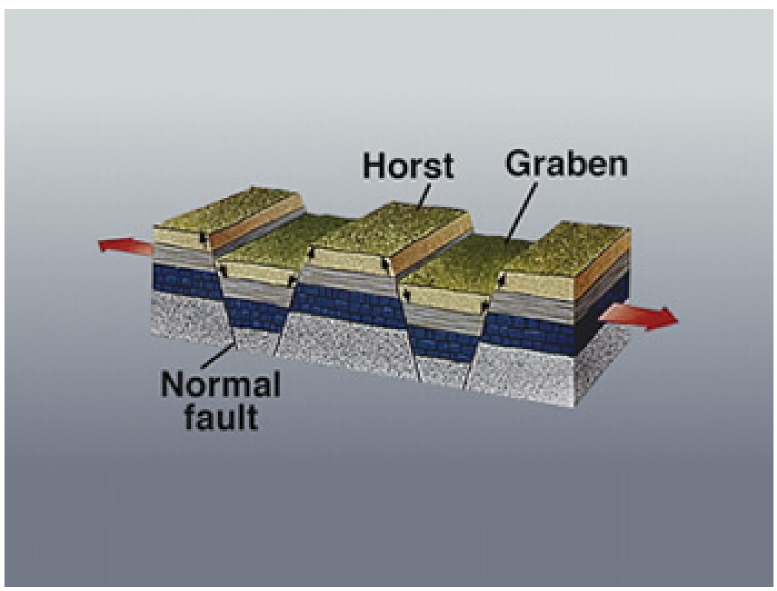

Figure 7.23: Where the crust is being pulled apart by tension, it breaks apart along normal faults. Some blocks are uplifted to form ranges, known as horsts, and some are down-dropped to form basins, known as grabens. (2)

Figure 7.24: In this photo taken in the Basin and Range province, the photographer is standing at Emigrant Pass in the Nopah Range, and looking across a basin to the Kingston Range beyond. (1)

Lesson Summary

- Stress is the force applied to a rock, which may cause deformation. The three main types of stress go along with the three types of plate boundaries: compression is common at convergent boundaries, tension at divergent boundaries, and shear at transform boundaries.
- Where rocks deform plastically, they tend to fold. Brittle deformation brings about fractures and faults. The two main types of faults are dip-slip and strike-slip.
- In dip-slip faults, the angle of the fault plane is inclined to the horizontal, in strike-slip faults the fault plane is perpendicular to the horizontal.
- The world's largest mountains grow at convergent plate boundaries, primarily by thrust faulting and folding.

Review Questions

1. Why don't rocks deform under confining stress?
2. What type of stress is compression and at what type of plate boundary is this found?
3. What type of stress is tension and at what type of plate boundary is it found?
4. What type of stress is shear and at what type of plate boundary is it found?
5. What is the difference between plastic and elastic strain?
6. A Under what conditions is a rock more likely to deform plastically than to break?
7. You are a geologist walking around in the field, when you spot a monocline. You inspect the fossils in each layer of the rock and you discover that the oldest rocks are

at the top and the youngest at the bottom. How do you explain how the rocks came to be this way?

8. Describe an anticline and name the age order of rocks.
9. Describe a syncline and name the age order of rocks.
10. What is the difference between a dome and a basin and what is the age order of rocks in each?
11. Name one similarity and one difference between a fracture and a fault?
12. What are the two types of dip-slip faults and how are they different from each other?
13. California is plagued by earthquakes along the San Andreas Fault zone. Why are there so many earthquakes and why are they so severe?
14. Volcanoes are mountains that form in two ways. Describe these two ways and how they are associated with a plate boundary.
15. Describe the plate tectonics processes and associated stresses that have led to the formation of the Himalayas, the world's largest mountain range?

Vocabulary

anticline A fold that arches upward, in which the older rocks are in the center and the younger rocks are at the outside.

basin A block of rock that has slipped downward between two normal faults.

compression Stresses that push toward each other. This causes a decrease in the space a rock takes up.

confining stress The stress due to the weight of material above a buried object. Confining stress reduces volume but causes no deformation.

deformation The change of shape that a rock undergoes when it has been altered by stresses. Also called strain.

dip-slip fault A fault in which the dip of the fault plane is inclined relative to the horizontal.

dome A circular anticline. A dome has the oldest rocks in the center and the youngest on the outside.

elastic strain Strain that alters the shape of a rock but that is not permanent. The rock goes back to its original shape when the stress is removed.

fault zone A network of related faults.

fold A bend in a set of rocks caused by compression. Folds are easiest to see in sedimentary or volcanic rocks that were deposited horizontally.

footwall The block of rock that is beneath a dip-slip fault.

fracture A break in rock caused by stresses. There may or may not be movement of the rock on either or both sides of a fracture.

hanging wall The block of rock that is above a dip-slip fault.

joint A break in rock caused by stresses along which there is no movement.

monocline A bend in a set of rocks that causes them to be inclined relative to the horizontal.

normal fault A dip-slip fault in which the hanging wall drops down relative to the footwall.

plastic strain Strain that causes deformation in which the rock deforms but does not return to its original shape when the strain is removed.

reverse fault A dip-slip fault in which the hanging wall pushes up relative to the footwall.

shear Stresses that pushed past each other in opposite directions.

slip The distance rocks move along a fault.

strain Deformation in a rock that is due to a stress that exceeds the rock's internal strength.

stress Force per unit area in a rock.

strike-slip fault A fault in which the dip of the fault plane is vertical.

syncline A fold in rocks that bends downward, in which the youngest rocks are at the center.

tension Stresses that pull material in opposite directions so that it is pulled apart.

thrust fault A reverse fault in which the dip of the fault plane is nearly horizontal.

uplift The upward rise of rock material.

Points to Consider

- Think about stresses in the ocean basins. Where in the ocean basis do you think you would find the features that indicate tensional stresses? Where would you find the features that indicate compressional stresses?
- Earthquakes are primarily the result of plate tectonic motions. List the three types of plate boundaries and what you think the stresses are that would cause earthquakes there.
- Which type of plate boundary do you think has the most dangerous earthquakes? How do earthquakes cause the greatest damage?

7.2 Nature of Earthquakes

Lesson Objectives

- Be able to identify an earthquake focus and its epicenter.
- Identify earthquake zones and what makes some regions prone to earthquakes.
- Compare the characteristics of the different types of seismic waves.
- Describe how tsunamis are caused by earthquakes, particularly using the 2004 Boxing Day Tsunami as an example.

Introduction

An **earthquake** is sudden ground movement caused by the sudden release of energy stored in rocks. The earthquake happens when so much stress builds up in the rocks that the rocks rupture. An earthquake's energy is transmitted by seismic waves. Each year there are more than 150,000 earthquakes strong enough to be felt by people and 900,000 recorded by seismometers.

Causes of Earthquakes

Almost all earthquakes occur at plate boundaries. All three boundary types—divergent, convergent and transform—are prone to earthquake activity. Plate tectonics causes the lithospheric plates to move. As you might imagine, having giant slabs of lithosphere moving about on a spherical shape is not smooth. When stresses build, they first cause the rocks to bend elastically. If the stresses persist, energy continues to build in the rocks. When the stresses are greater than the internal strength of the rocks, the rocks snap. Although they return to their original shape, the stresses cause the rocks to move to a new position. This movement releases the energy that was stored in the rocks, which creates an earthquake. During an earthquake the rocks usually move several centimeters or maybe as much as a few meters. This description of how earthquakes occur is called **elastic rebound theory** (**Figure** 7.25).

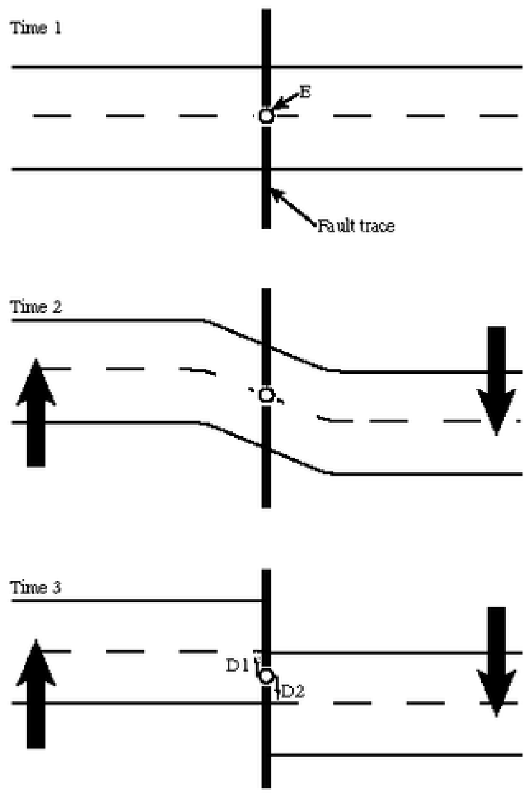

Figure 7.25: Elastic rebound theory. Stresses build on both sides of a fault, causing the rocks to deform plastically (Time 2). When the stresses become too great, the rocks return to their original shape but they move (Time 3). This motion releases the energy that creates an earthquake. (46)

The point where the rock ruptures is usually below the Earth's surface. The point of rupture is called the earthquake's **focus.** The focus of an earthquake can be shallow - less than 70 kilometers (45 miles), intermediate - 70 to 300 kilometers (45 to 200 miles), or deep - greater than 300 kilometers (200 miles). About 75% of earthquakes have a focus in the top 10 to 15 kilometers (6 to 9 miles) of the crust. Shallow earthquakes cause the most damage because the focus is near the Earth's surface where people live.

Just above the focus on the land surface, is the earthquake's **epicenter** (**Figure** 7.26). It is the epicenter of an earthquake that is reported by scientists and the media. The epicenter of the 1906 San Francisco earthquake, for example, was offshore, 1.5-3 kilometers (1-2 miles) west of Golden Gate Park.

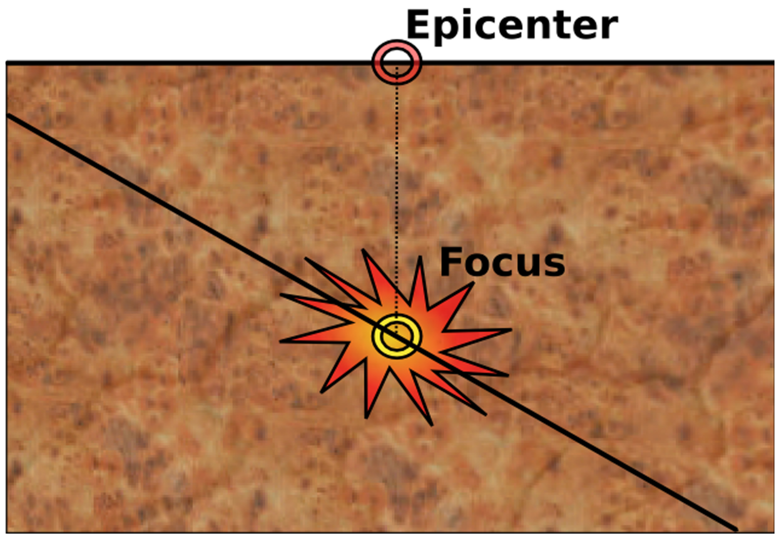

Figure 7.26: A vertical cross section through the crust shows an earthquake's focus below ground and its epicenter at the ground surface. (13)

Earthquake Zones

Some locations are prone to earthquakes and some are not. Nearly 95% of all earthquakes take place along one of the three types of plate boundaries. Scientists use the location of earthquake epicenters to draw the boundaries of the plates because earthquakes frequently occur along plate boundaries (**Figure** 7.27).

The region of the planet with the most earthquakes is the area around the Pacific Ocean. About 80% of all earthquakes strike this area. This region is called the Pacific Ring of Fire because most volcanic eruptions occur there as well. The Pacific Ocean is surrounded by convergent and transform plate boundaries (**Figure** 7.28).

About 15% of all earthquakes take place in the Mediterranean-Asiatic belt. This is where convergent plate boundaries are shrinking the Mediterranean Sea and causing the Himalayas to grow. The remaining 5% of earthquakes are scattered around the other plate boundaries with a few occurring in the middle of a plate, away from plate boundaries.

All three types of plate boundaries have earthquakes. Enormous and deadly earthquakes occur at transform plate boundaries. Because the slabs of lithosphere slide past each other without moving up or down, transform faults have shallow focus earthquakes. The most

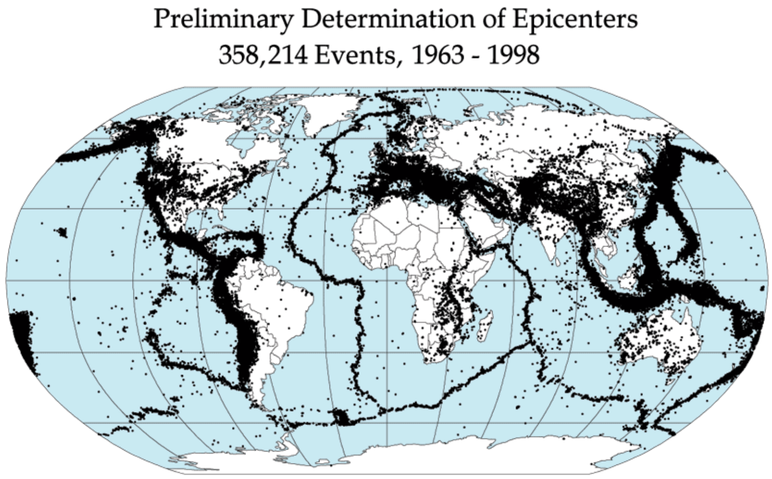

Figure 7.27: Earthquake epicenters can be used to outline the edges of the lithospheric plates. Most earthquakes occur around the Pacific Ocean basins and in the Mediterranean-Asiatic belt. (7)

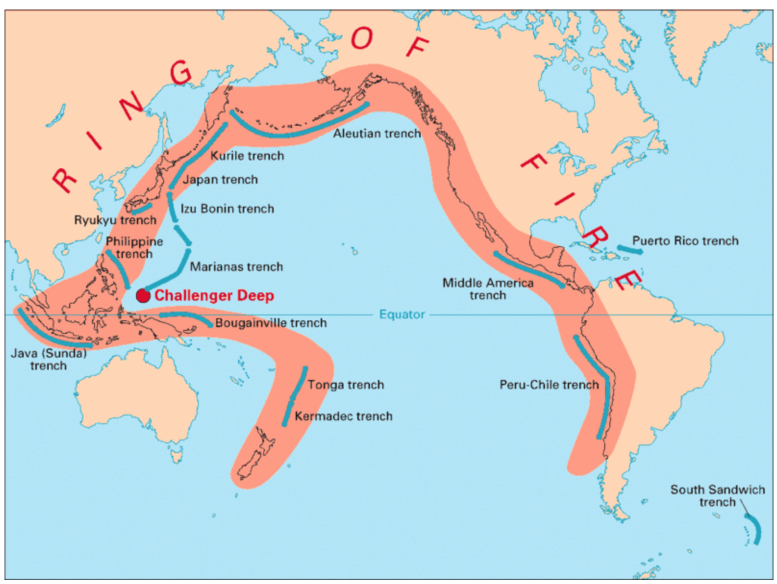

Figure 7.28: The Pacific Ring of Fire is the most geologically active region of the world. Convergent plate boundaries cause earthquakes and volcanic eruptions all around the Pacific Ocean basin. There are also transform plate boundaries along the San Andreas Fault in California and the Alpine Fault in New Zealand. (48)

notorious earthquake fault in North America is the San Andreas Fault that runs through California. The 1,300 kilometer (800 mile) long fault is the transform boundary between the northeastward-moving Pacific plate and the southwestward-moving North American plate. The San Andreas is a right-lateral strike-slip fault (**Figure** 7.29).

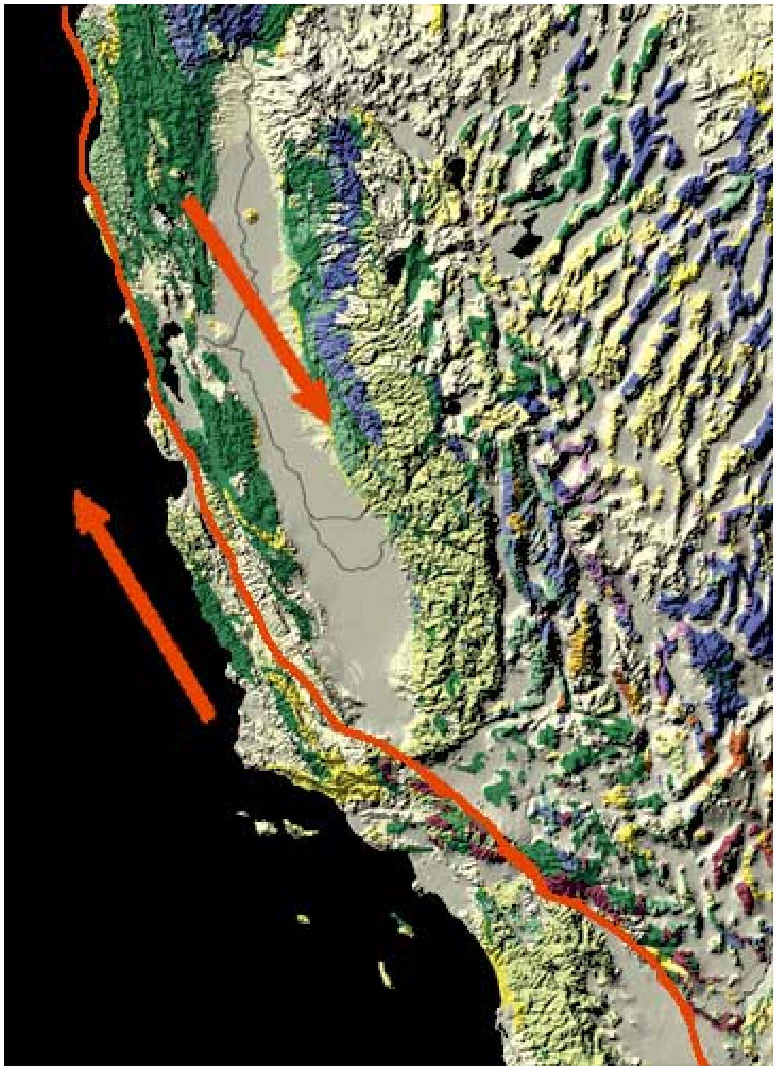

Figure 7.29: The San Andreas Fault runs up western California. It is the transform plate boundary between the northwestward moving Pacific Plate and the southeastern moving North American Plate. (10)

The largest earthquake on the San Andreas Fault in historic times occurred in 1906 in San Francisco (**Figure** 7.30). This earthquake likely measured magnitude 7.8, which is a very large earthquake. The earthquake and the subsequent fire is still the most costly natural disaster in California history. An estimated 3,000 people died and about 28,000 buildings were lost, mostly in the fire.

Figure 7.30: Damage after the 1906 San Francisco Earthquake and fire (26)

In 1989, the Loma Prieta earthquake struck near Santa Cruz, California. The magnitude 7.1 quake resulted in 63 deaths, 3,756 injuries and left more than 12,000 people homeless. The property damage was estimated at about $6 billion. In 1994, an earthquake on a blind thrust fault struck near Los Angeles, California in the neighborhood of Northridge. It registered 6.7 on the moment magnitude scale. Seventy two people died, 12,000 more were injured and damage was estimated at $12.5 billion.

There are many other faults spreading off the San Andreas, which together with the main fault produce around 10,000 earthquakes a year (**Figure** 7.31). While most of those earthquakes cannot even be felt by people nearby, occasionally one is massive. In the San Francisco Bay Area, the Hayward Fault was the site of a magnitude 7.0 earthquake in 1868.

Convergent plate boundaries also produce massive and deadly earthquakes. Earthquakes mark the motions of subducting lithosphere as it plunges through the mantle. The earthquakes can be shallow, intermediate or deep focus. Convergent plate boundaries produce earthquakes all around the Pacific Ocean basin.

The Philippine plate and the Pacific plate subduct beneath Japan creating a chain of volcanoes and as many as 1,500 annual earthquakes. The great Kanto earthquake of 1923 is thought to have killed 140,000 people, many in the subsequent fire. In Yokohama, 90% of houses were damaged or destroyed and 60% of Tokyo's population became homeless. In the Great Hanshin (Kobe) Earthquake of 1995, 6,434 people died (**Figure** 7.32).

Subduction is also taking place along the Cascades Mountains in the Pacific Northwest as part of the Pacific Ring of Fire. The Juan de Fuca plate is plunging beneath the North American plate and forming volcanoes that extend south into northern California. The

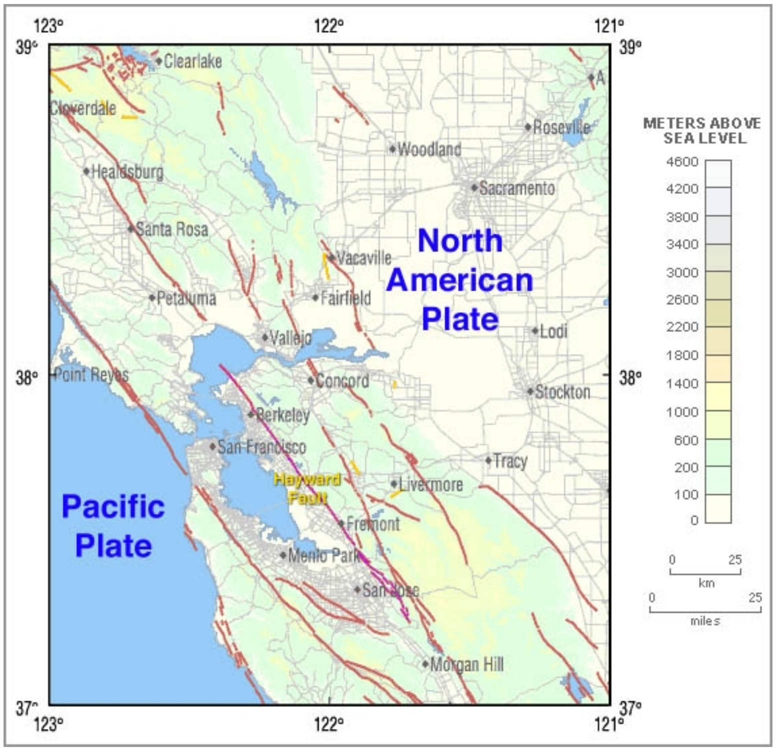

Figure 7.31: The San Andreas Fault Zone in the San Francisco Bay Area. The San Andreas Fault is seen running through San Francisco and Marin County, east of Point Reyes. The Hayward Fault lies across the East Bay and runs through Berkeley. Many other small faults are shown in the map as well. (41)

Figure 7.32: Destruction in Kobe, Japan, from the 1995 Great Hanshin Earthquake. (33)

Cascades volcanoes are active and include Mount Saint Helens, which had a large eruption in 1980. Mount Lassen, Mount Shasta, and Medicine Lake volcano in northeastern California are the three southernmost volcanoes in the Cascades chain.

Yet the Cascadia subduction zone is one of the world's quietest subduction zones, with relatively few earthquakes. Though they don't happen often, they are extremely powerful when they hit. The last major earthquake on the Juan de Fuca occurred in 1700, with a magnitude estimated at between 8.7 and 9.2. The geologic history of the area reveals that major earthquakes occur here about every 300 to 600 years. Since it has now been more than 300 years since the last earthquake in the area, the Pacific Northwest is at risk from a potentially massive earthquake that could strike any time.

The thrust faulting and folding that result from the convergence of continental plates creates massive earthquakes. The region in and around the Himalaya, for example, is the site of many earthquakes. The 2001 Gujarat, India earthquake is responsible for about 20,000 deaths with many more people injured or made homeless.

Earthquakes also occur at divergent plate boundaries. At mid-ocean ridges, these earthquakes tend to be small because the plates are young and hot. The earthquakes are shallow because the new plates are thin. Since divergent plate boundaries in the oceans are usually far from land, they have little effect on peoples' lives. On land, where continents are rifting apart, earthquakes are larger and stronger.

About 5% of earthquakes take place within a plate; that is, away from plate boundaries. A large intraplate earthquake occurred in 1812 when a magnitude 7.5 earthquake struck near New Madrid, Missouri. The earthquake was strongly felt over around 50,000 square miles, and altered the course of the Mississippi River. Because very few people lived here at the time, only 20 people died. However many more people live here today and the New Madrid Seismic Zone continues to be active (**Figure** 7.33). A similar earthquake today would undoubtedly kill many people and cause a great deal of property damage. Intraplate earthquakes are caused by stresses due to plate motions acting in solid slabs of lithosphere.

Seismic Waves

Energy is transmitted in waves. Every wave has a high point called a **crest** and a low point called a **trough.** The height of a wave from the center line to its crest is its **amplitude.** The distance between waves from crest to crest (or trough to trough) is its **wavelength** (**Figure** 7.34).

The energy from earthquakes (and also from explosions) travels in waves called **seismic waves.** Other types of waves transmit other types of energy; for example, sound waves transmit a child's laughter and other sounds. The study of seismic waves is known as **seismology.** Seismologists use seismic waves to learn about earthquakes and also about the Earth's interior.

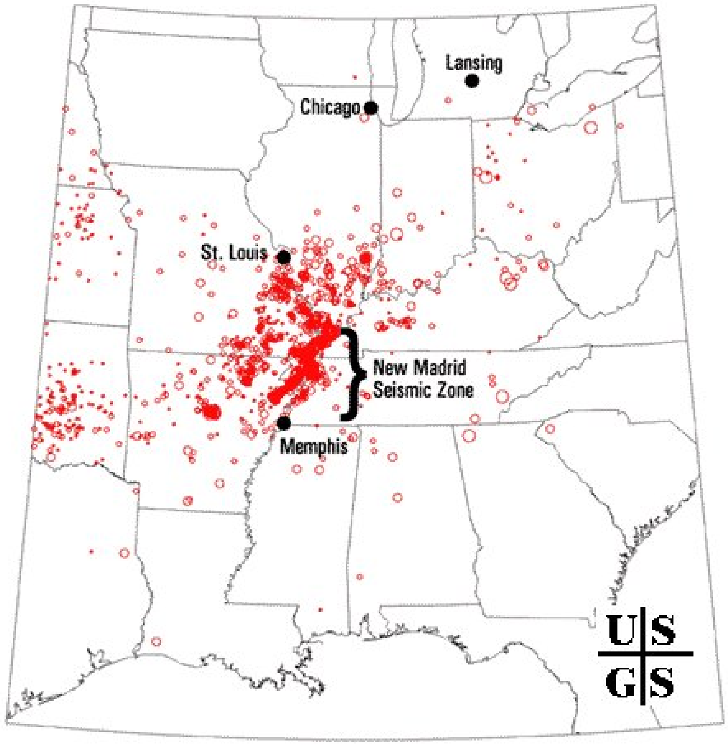

Figure 7.33: The location of the New Madrid Seismic Zone is well within the North American plate far from the nearest plate boundary. This figure shows that around 4,000 earthquakes have occurred in the region since 1974. (36)

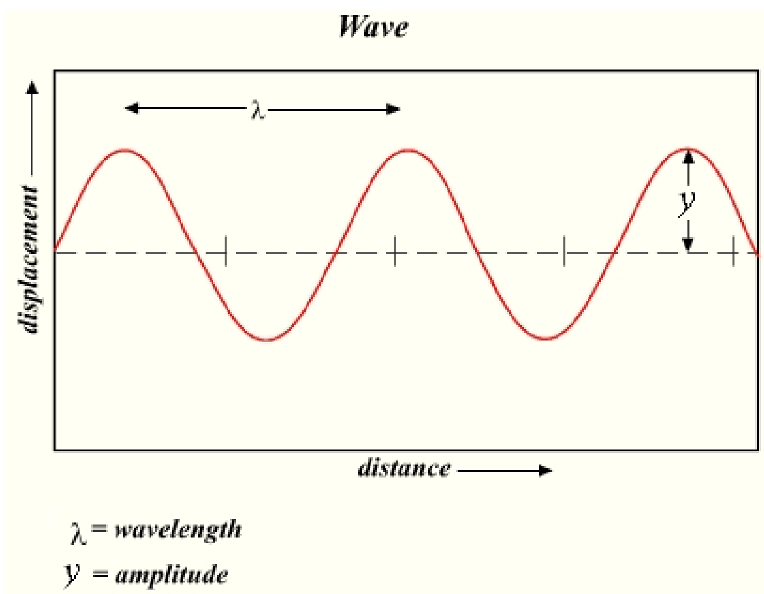

Figure 7.34: Features of a set of waves. (37)

Seismic waves move outward in all directions away from their source. There are two major types of seismic waves. **Body waves** travel through the solid body of the Earth from the earthquake's focus throughout the Earth's interior and to the surface. **Surface waves** just travel along the ground surface. The different types of seismic waves travel at different speeds in different materials. All seismic waves travel through rock, but not all travel through liquid or gas. In an earthquake, body waves are responsible for sharp jolts. Surface waves are responsible for rolling motions. Surface waves do most of the damage in an earthquake.

Body Waves

There are two types of body waves – **primary waves (P-waves)** and **secondary waves (S waves)**. These waves travel through the Earth's interior. P-waves are the fastest at about 6 to 7 kilometers (about 4 miles) per second. They are named primary waves because they are the first waves to reach a seismometer. S-waves are slower and so are the second waves to reach a seismometer. Body waves move at different speeds depending on the type of material they are passing through.

P-waves are longitudinal waves. They move material forward and backward in the same direction that they are traveling. This motion resembles a spring squeezing and unsqueezing. The material returns to its original size and shape after the P-wave goes by. For this reason, P-waves are not the most damaging earthquake waves. P waves can travel through solids, liquids and gases.

S-waves are transverse waves, that move up and down. Their oscillations are perpendicular to the direction the wave is traveling. In a rock, this motion produces shear stresses. S-waves are about half as fast as P-waves, traveling at about 3.5 km (2 miles) per second. S-waves can only move through solids because liquids and gases have no shear strength.

Surface Waves

Surface waves travel along the ground outward from an earthquake's epicenter. Surface waves are the slowest of all seismic waves, traveling at 2.5 km (1.5 miles) per second. There are two types of surface waves. **Love waves** move side-to-side much like a snake. **Rayleigh waves** move in rolls, like ocean swells (**Figure** 7.35). These waves cause objects to fall and rise, while swaying back and forth. These motions cause damage to rigid structures during an earthquake.

Tsunami

Earthquakes can cause deadly ocean waves called **tsunami,** although tsunami can be caused by any shock to ocean water, including a meteorite impact, landslide, or a nuclear explosion. When ocean water is displaced by the sharp jolt of an undersea earthquake, the seismic

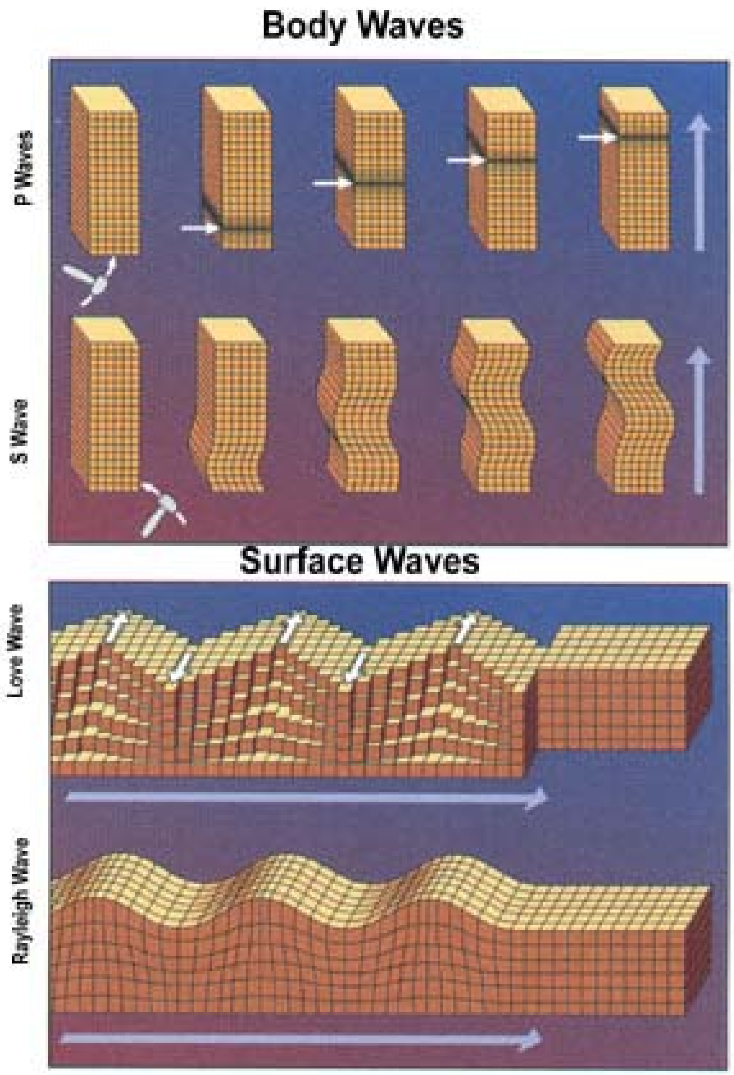

Figure 7.35: The top figure shows how body waves, including P-waves and S-waves, move through a grid. The bottom figure shows how surface waves move. The two types of surface waves are Love waves and Rayleigh waves. (14)

energy forms a set of waves. The waves travel through the sea entirely unnoticed since they have low amplitudes and long wavelengths. When these waves come onto shore, they can grow to enormous heights and cause tremendous destruction and loss of life. Fortunately, few undersea earthquakes generate tsunamis.

The Boxing Day Tsunami of December 26, 2004 was by far the deadliest of all time. The tsunami was caused by the 2004 Indian Ocean Earthquake, also called the Great Sumatra-Andaman earthquake (**Figure** 7.36). This earthquake, with a magnitude of 9.2, was the second largest earthquake ever recorded. The energy that reached the planet's surface was 1,502 times the amount released by the atomic bomb dropped on Hiroshima, but the total amount of energy released was estimated at 550 million times Hiroshima.

The Indian Ocean Earthquake struck 160 kilometers (100 miles) off of Sumatra, Indonesia. In this region the Indian plate is subducting beneath the Burma plate. Slip along the earthquake fault was an incredible 15 meters (50 feet), about two-thirds of that in a horizontal direction and one-third in a vertical direction. The fault ruptured over about 1,600 kilometers (1,000 miles). Faulting went on for up to 10 minutes, the longest duration ever witnessed.

The extreme movement of the crust displaced trillions of tons of water. Water displacement occurred along the entire length of the rupture. This means that tsunami waves formed along a great distance, which increased the area that the killer waves traveled to. Several tsunami were created, with about 30 minutes between the peaks of each one.

The water traveled rapidly across the Indian Ocean outward from the fault. As is typical for tsunami, the waves were not noticeable in open water. Satellites measured the height of the waves across the sea at just 50 centimeters (20"). The first wave hit the northern regions of Sumatra in about 15 minutes. At its worst, the waves rose to around to 10 meters (33 feet) in height. Within 1.5 to 2 hours, waves were striking Sri Lanka and the eastern coast of India. Thailand was battered two hours after the earthquake. Somalia was hit seven hours after the earthquake. The size of the waves decreased with distance from the earthquake so that the waves in Sri Lanka, Thailand, and Somalia were relatively small, about 4 meters (13 feet) in height.

Like other waves, a tsunami wave has a crest and a trough. What people see when the tsunami hits the beach depends on whether the crest or the trough hits first. In some locations, the trough of the wave hit the beach first. When this happens, water is sucked out to sea and the seafloor just offshore from the beach is exposed. Curiosity is often fatal in this instance, since people who go out to the beach to see the unusual sight are drowned when the wave crest hits.

One amazing story was that of Tilly Smith, a 10 year old British girl who was visiting Maikhao Beach in Thailand with her parents. About two weeks before the earthquake, Tilly had learned about tsunamis in school. She knew that the receding water and the frothy bubbles at the sea surface indicated an approaching tsunami. As the trough of the tsunami wave hit the beach, she pointed these features out to her parents. They told other tourists and the staff at their hotel and the beach was evacuated. No one on Maikhao Beach died

Figure 7.36: The location of the 2004 Indian Ocean earthquake and the countries that were most affected by the tsunami. (31)

and Tilly is credited with saving nearly 100 people.

On other beaches, people were not so lucky. In all, the tsunami struck eight countries, with Indonesia, Sri Lanka, India and Thailand the hardest hit (**Figure** 7.37). About 230,000 people died, with fatalities even as far away as South Africa, nearly ,000 kilometers (5,000 miles) from the earthquake epicenter. More than 1.2 million people lost their homes and many more lost their ways of making a living. For example, fishermen lost their boats, and business people lost their restaurants and shops. Many marine animals were washed inland, including dolphins, turtles, and sharks.

Only a few scientists had thought that a massive tsunami would strike the Indian Ocean so no warning system had been in place. Tsunami are much more common in the Pacific due to the enormous number of subduction zones that line the Pacific basin, and communities around the Pacific have had a tsunami warning system in operation since 1948 (**Figure** 7.38). As a result of the 2004 tsunami, an Indian Ocean warning system was put into operation in June 2006.

Warning systems are of limited use. They base their warnings on the location of earthquakes within an ocean basin. Unfortunately, communities that are very close to the earthquake do not receive the warning in time to move inland or uphill since the wave hits too fast. Still evacuation of low-lying areas could save many people in a large tsunami that is further from the earthquake.

Figure 7.37: The Boxing Day tsunami strikes a beach in Thailand. (40)

Figure 7.38: A sign indicating a tsunami hazard zone in California. (6)

Lesson Summary

- During an earthquake, the ground shakes as stored up energy is released from rocks. Nearly all earthquakes occur at plate tectonic boundaries and all types of plate boundaries have earthquakes.
- The Pacific Ocean basin and the Mediterranean-Asiatic belt are the two geographic regions most likely to experience quakes. The seismic waves that do the most damage are surface waves, which only travel along the surface of the ground.
- Body waves travel through the planet and arrive at seismograms before surface waves. Tsunamis are deadly ocean waves that can be caused by undersea earthquakes.

Review Questions

1. What is an earthquake's focus? What is its epicenter?
2. Why do most earthquakes take place along plate boundaries?
3. Using elastic rebound theory, describe what triggers an earthquake.
4. Use plate tectonics theory to describe why are there far more earthquakes around the Pacific Ocean than anywhere else on Earth?
5. Since intraplate earthquakes are not near plate boundaries, give a general idea of what you think might cause them.
6. Do the largest earthquakes cause the most deaths and the most damage to property?
7. California is famous for earthquakes along the San Andreas Fault zone but there is another type of plate boundary where large earthquakes occur. What type of plate boundary is it and where the earthquakes likely to occur?
8. Using what you know about plate tectonics and elastic rebound theory, describe what is taking place in the Cascades Mountains of the Pacific Northwest, including northern California. What is likely to occur in the future? Include earthquakes and tsunamis.
9. What type of faulting is found where two slabs of continental lithosphere are converging? Explain what this would look like on a diagram of the faults and the rocks on either side.
10. What are the characteristics of body waves? What are the two types?
11. What materials can P-waves travel through and how fast are they? Describe a P-wave's motion.
12. What materials can S-waves travel through and how fast are they? Describe an S-wave's motion.
13. How are surface waves different from body waves? In general, which type of waves is more damaging in an earthquake?
14. What did Tilly Smith notice on the beach in Thailand that caused the adults around her to evacuate the beach before the enormous tsunami hit in 2004? How were these signs evidence of a tsunami?

Further Reading / Supplemental Links

- http://earthquake.usgs.gov/
- http://www.exploratorium.edu/faultline/index.html

Vocabulary

amplitude The height of a wave from a center line to the top of the crest (or to the bottom of the trough.

body waves A type of seismic wave that travels through the body of a planet. The two types are primary waves and secondary waves.

crest The highest point of a wave.

earthquake Ground shaking caused by the release of energy stored in rocks.

elastic rebound theory The theory of how earthquakes are generated. Elastic rebound theory states that stresses cause strain to build up in rocks until they can no longer bend elastically and they break, causing an earthquake.

epicenter The point on the earth's surface that lies above an earthquake's focus.

focus The point where rocks rupture during an earthquake.

Love waves These surface waves have a side-to-side motion, much like a slithering snake.

primary waves (P-waves) P-waves are body waves that are the first to arrive at a seismometer because they are the fastest. P-waves are longitudinal waves that travel through solids, liquids, and gases.

Rayleigh waves These surface waves have a rolling motion.

secondary waves (S-waves) S-waves are body waves that are the second to arrive at a seismometer. S-waves are transverse waves that can only move through solids.

seismic wave Seismic waves transport the energy released during an earthquake. The two main types are body waves and surface waves.

seismology The study of seismic waves including earthquakes and the earth's interior.

surface waves Surface waves are seismic waves that travel along the ground surface. The two types are Love waves and Rayleigh waves. Surface waves do the most damage after an earthquake.

trough The lowest point of a wave.

tsunami A deadly set of waves that are ordinarily caused by an undersea earthquakes or another shock in which large amounts of seawater are displaced. Tsunamis rise high on a beach and can travel far inland, causing death and destruction as they go.

wavelength The distance from crest to crest or trough to trough between two waves.

Points to Consider

- The last time there was a large earthquake on the Hayward Fault in the San Francisco Bay area of California was in 1868. Use elastic rebound theory to describe what may be happening along the Hayward Fault today and what will likely happen in the future.
- Why is California so prone to earthquakes?
- How could coastal California be damaged by a tsunami? Where would the earthquake occur? How could such a tsunami be predicted?

7.3 Measuring and Predicting Earthquakes

Lesson Objectives

- List the different types of seismic waves, their different properties and describe how seismologists can use them to learn about earthquakes and the Earth's interior.
- Describe how to find an earthquake epicenter.
- Describe the different earthquake magnitude scales and what the numbers for moment magnitude mean.
- Describe how earthquakes are predicted and why the field of earthquake prediction has had little success.

Introduction

Seismograms tell seismologists how strong an earthquake is and how far away it is. At least three seismograms must be used to calculate where the epicenter is located. Over the past century, scientists have developed several ways of measuring earthquake intensity. The currently accepted method is the moment magnitude scale, which measures the total amount of energy released by the earthquake. At this time, seismologists have not found a reliable method for predicting earthquakes.

Measuring Magnitude

A **seismometer** is a machine that records seismic waves. In the past, all seismometers were **seismographs** because they produced a graph-like representation of the seismic waves they received. The paper record is called a **seismogram.** Modern seismometers record ground motions using electronic motions detectors. The data are then kept digitally on a computer.

Seismographs have a pen suspended from a stationary frame, while a drum of paper rotates beneath it. The pen is weighted so that it is suspended and not attached to the ground. The drum is attached to the ground. As the earth shakes in an earthquake, the pen remains stationary but the drum moves beneath it. This creates the squiggly lines that make up a seismogram (**Figure** 7.39).

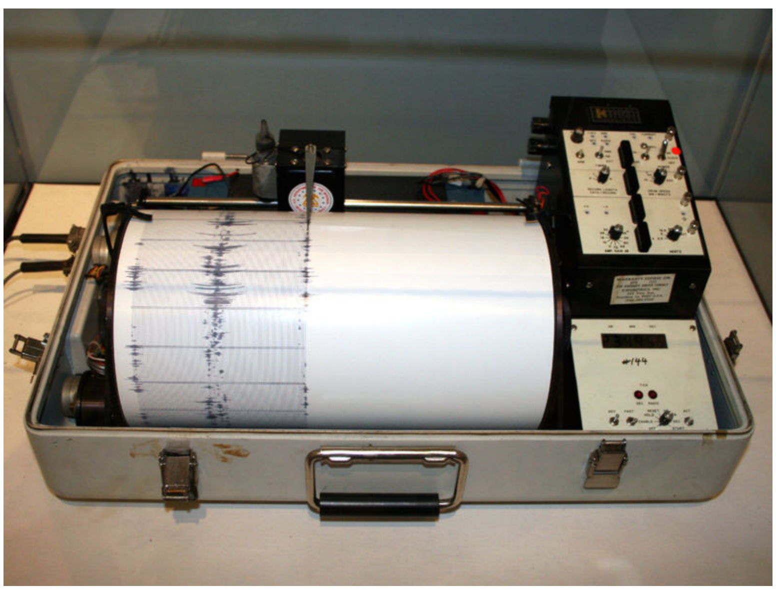

Figure 7.39: A seismograph that had recorded an earthquake is beginning to record another earthquake, likely an aftershock. (16)

Seismograms contain information on how strong an earthquake was, how long it lasted, and how far away it was. The wiggly lines that are produced in a seismogram clearly show the different arrival times of P- and S-waves (**Figure** 7.40). As with words on a page, the seismogram record goes from left to right. First, there is a flat line, where there was no ground shaking. The first waves to be recorded by the seismogram are P-waves since they are the fastest. S-waves come in next and are usually larger than P-waves. The surface waves arrive just after the S-waves. If the earthquake has a shallow focus, the surface waves will be the largest ones recorded.

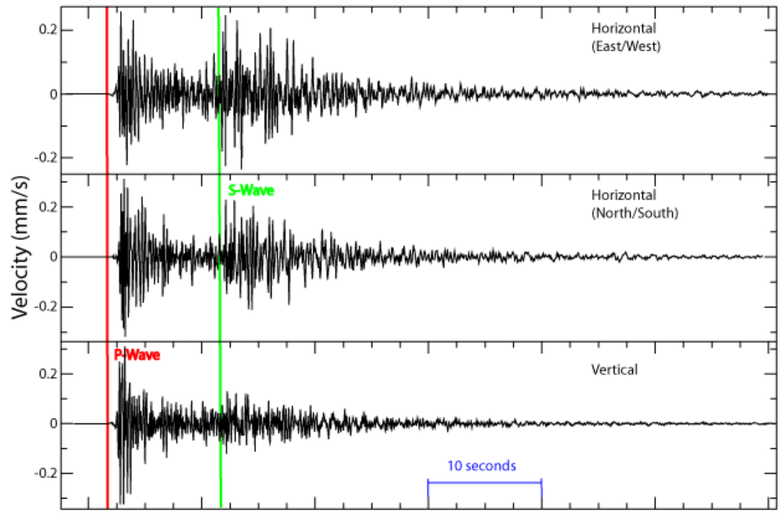

Figure 7.40: These seismograms show the arrival of P-waves and S-waves. The surface waves arrive just after the S-waves and are difficult to distinguish. Time is indicated on the horizontal portion (or x-axis) of the graph. (25)

If a seismogram has recorded P-waves and surface waves, but not S-waves, the seismograph was on the other side of the planet from the earthquake. Scientists know that the earth's outer core is liquid because S-waves cannot travel through liquid. The liquid outer core creates an S-wave shadow zone on the opposite side of the planet from the earthquake's focus where no S-waves reach. The amplitude (height) of the waves can be used to determine the magnitude of the earthquake. How magnitude is calculated will be discussed in a later section.

Finding the Epicenter

A single seismogram can tell a seismologist how far away the earthquake was but it does not provide the seismologist with enough information to locate the exact epicenter. For that, the seismologist needs at least three seismograms. Determining distance to an earthquake epicenter depends on the fact that different seismic waves travel at different speeds. P-waves always arrive at a seismometer first, but the amount of time it takes for the S-waves to arrive after the P-wave indicates distance to the epicenter. If the epicenter is near the seismometer, the P-waves, S-waves and surface waves will all arrive in rapid succession. If the epicenter is further away, the S-waves will lag further behind. In other words, the longer it is between the arrival of the P-wave and S-wave from an earthquake, the farther the epicenter is from the seismometer.

After many years of study, geologists know the speed at which the different types of waves travel through various earth materials. Based on the difference in the arrival times of the first P wave and the first S wave, seismologists determine the distance between the epicenter and a seismometer. Once the distance to the epicenter is known, scientists can identify each point that is that distance away. Let's say that they know that an earthquake's epicenter is 50 kilometers from Kansas City. When each point that is that distance away from Kansas City is marked, the marks create a circle. This circle can be drawn with a compass.

To locate the earthquake epicenter, seismologists must have data from at least three seismometers. A circle drawn at the correct distance to the epicenter from a second seismometer will intercept the first circle in two places. A third circle showing the distance to the epicenter from a third seismometer will intercept the other two circles at a single point. This point is the earthquake epicenter (**Figure** 7.41). While this method was extremely useful for locating epicenters for decades, the technique has been replaced by digital calculations.

Figure 7.41: Circles are drawn with radii representing the distance from each seismic station to the earthquake's epicenter. The intersection of these three circles is the earthquake's epicenter. (24)

Earthquake Intensity

People have always tried to quantify the size of and damage done by earthquakes. Early in the 20th century, earthquakes could only be described in terms of what nearby residents felt and the damage that was done to nearby structures. This was called the **Mercalli Intensity Scale** and was developed in 1902 by the Italian seismologist Giuseppe Mercalli. The Mercalli Scale is sometimes used today in conjunction with the more modern intensity scales described below.

Table 7.1 shows an abbreviated description of the twelve Mercalli intensity levels:

Table 7.1:

Number	Description
I	Not felt except by a very few under especially favorable conditions.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt noticeably by people indoors, especially on upper floors of buildings. Many people don't know it's an earthquake. Standing automobiles may rock lightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Felt by all, many frightened. Some heavy furniture moved; a little fallen plaster. Damage slight.
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or designed structures; some chimneys broken.
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fallen chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.

Table 7.1: (continued)

Number	Description
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI	Few if any structures still standing. Bridges destroyed. Rails bent greatly.
XII	Damage total. Lines of sight and level distorted. Objects thrown into air.

There were many problems with the Mercalli scale. What people feel and see in an earthquake is affected by how far they are from the earthquake's focus, the type of rock that lies beneath them, the construction type of the nearby buildings, and many other factors. Different observers will also perceive the experience differently. For example, one might exaggerate while the other downplays the damage done. With the Mercalli scale, comparisons between earthquakes are difficult to make.

To address these problems, in 1935 Charles Richter developed his **Richter magnitude scale.** The Richter scale measures the magnitude of the largest jolt of energy released in an earthquake. Because Richter's scale is logarithmic, the amplitude of the largest wave increases 10 times from one integer to the next. For example, the amplitude of the largest seismic wave of a magnitude 5 quake is 10 times that of a magnitude 4 quake and 100 times that of a magnitude 3 quake. One integer increase in magnitude roughly correlates with a 30-fold increase in the amount of energy released. A difference of two integers on the Richter scale equals a 1,000-fold increase in released energy.

Seismologists recognize that the Richter scale has limitations, since it measures the height of the greatest earthquake wave. A single sharp jolt will measure higher on the Richter scale than a very long intense earthquake that releases more energy. In other words, earthquakes that release more energy are likely to do more damage than those that are short, but have a larger single jolt. Using the Richter scale, a high magnitude may not necessarily reflect the amount of damage caused.

The **moment magnitude scale** is the current method of measuring earthquake magnitudes. This method measures the total energy released by an earthquake and so more accurately reflects its magnitude. Moment magnitude is calculated from the area of the fault that is ruptured and the distance the earth moved along the fault. Like the Richter scale, the moment magnitude scale is logarithmic. An increase in one integer means that 30 times more energy was released, while two integers means that 1,000 times the energy was released released. The Richter and moment magnitude scales often give very similar measurements.

In a single year, more than 900,000 earthquakes are recorded. 150,000 of them are strong enough to be felt. About 18 per year are major, with a Richter magnitude of 7.0 to 7.9. Each year, on average, one earthquake with a magnitude of 8 to 8.9 strikes. Remember that many of these earthquakes occur deep in the crust and out in the oceans and do not cause much or any damage on land.

Earthquakes with a magnitude in the 9 range are rare. The United States Geological Survey lists six such earthquakes on the moment magnitude scale in historic times (see **Figure** 7.42 and **Table** 7.2). All but one of them, the Great Indian Ocean Earthquake of 2004, occurred somewhere around the Pacific Ring of Fire.

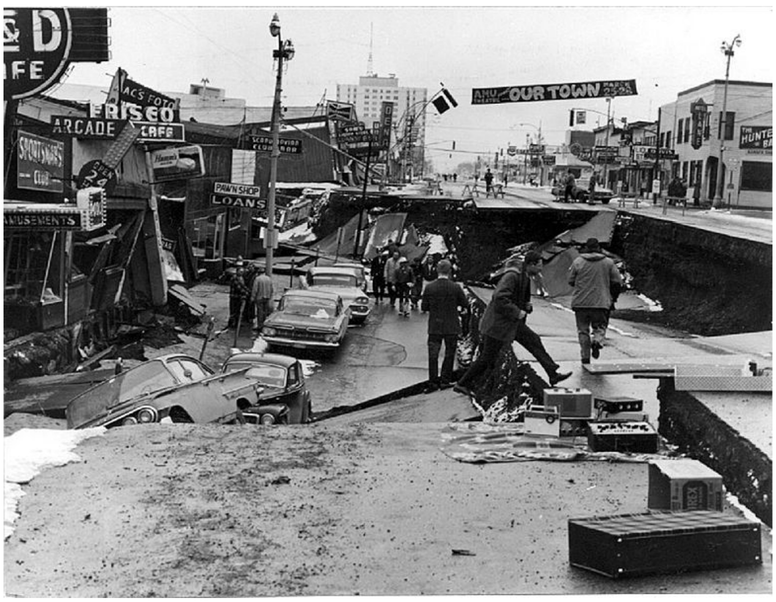

Figure 7.42: The 1964 Good Friday Earthquake centered in Prince William Sound, Alaska released the second most amount of energy of any earthquake in recorded history. (35)

Table 7.2:

Location	Year	Magnitude
Chile	1960	9.5
Prince William Sound, Alaska	1964	9.2
Great Indian Ocean Earthquake	2004	9.1
Kamchatka, Alaska	1952	9.0

Table 7.2: (continued)

Location	Year	Magnitude
Africa, Peru (now Chile)	1868	9.0
Cascadia Subduction Zone	1700	9.0

(*Data from:* United States Geological Survey)

Earthquake Prediction

To be valuable, an earthquake prediction must be accurate. A good predication would anticipate the date, location, and magnitude of the earthquake. The prediction would need to be accurate so that authorities could convince people to evacuate. An unnecessary evacuation would be very expensive and would decrease the credibility of authorities who might need to evacuate the region at a later time. Unfortunately, accurate predictions like these are not likely to be common for a long time.

The easiest thing to predict is where an earthquake will occur (**Figure** 7.43). Because nearly all earthquakes take place at plate boundaries, and because earthquakes tend to happen where they've occurred before, scientists know which locations are likely to have earthquakes. This information is useful to communities because those that are earthquake-prone can prepare for the event. For example, these communities can implement building codes to make structures earthquake safe. The added work and expense can be avoided in areas that are not at risk.

Predicting when an earthquake will occur is much more difficult. Scientists can get a general idea by looking at the historical and geological records of earthquakes in an area. If stress on a fault builds up at the same rate over time, then earthquakes should occur at regular intervals. While this is true, there is a large margin of error in these predictions. Using this method, scientists cannot even be accurate to within a few years, and evacuation is not practical.

Seismologists have also used the seismic gap theory for long-term earthquake prediction. In this theory, scientists assume that, on average, all of the rocks on the same side of a fault move at the same rate. For example, they say that rocks on the North American plate side of the San Andreas Fault in California move at the same speed over time. While this may be true, the frequency and magnitude of earthquakes along the fault is not the same: there are more quakes in the northern and southern sections, but a relatively inactive zone in the center.

Seismologists attempted to use the seismic gap theory to predict an earthquake in a seismic gap. Around Parkfield, California earthquakes occur regularly: an earthquake of magnitude 6.0 or higher occurs about every 22 years. Using this information, seismologists predicted

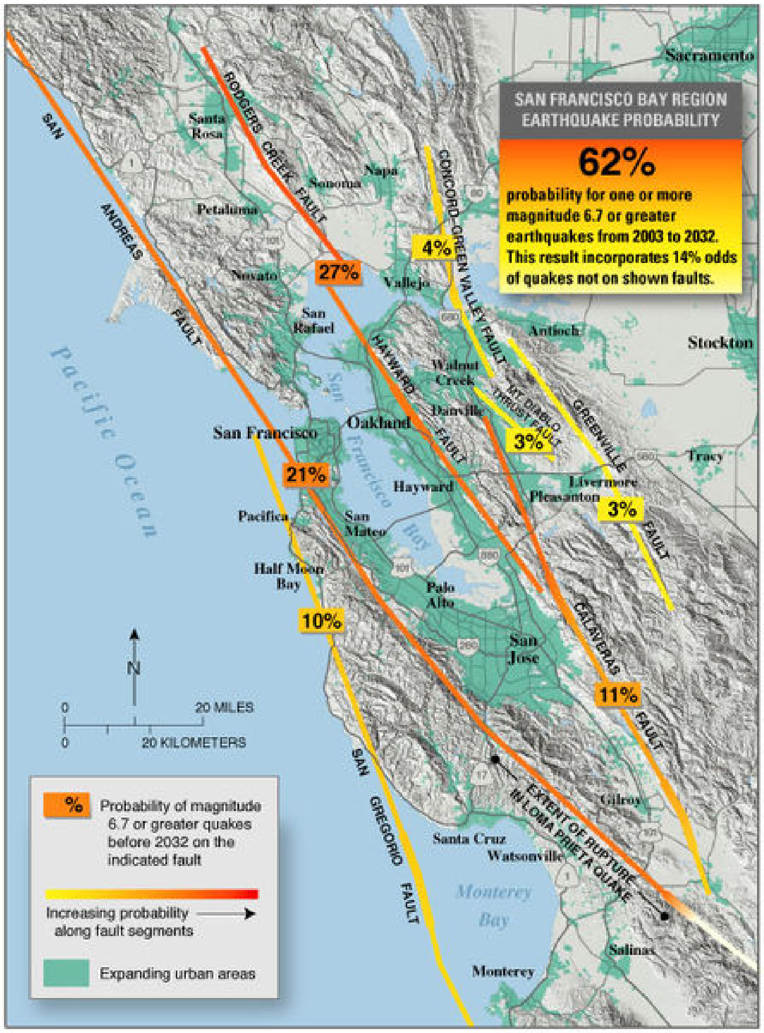

Figure 7.43: The probabilities of earthquakes striking along various faults in the San Francisco area between 2003 (when the work was done) and 2032. (15)

that a magnitude 6 or greater earthquake would strike the region in 1993. In the mid-1980s, seismologists with the United States Geological Survey set up an enormous number of instruments along the Parkfield section of the San Andreas to monitor the expected earthquake. While they were right that an earthquake was due in that segment of the fault, they were quite far off in predicting the earthquake's timing. A magnitude 6.0 quake did not strike Parkfield until 2004, 11 years late.

Scientists have recognized some indicators that allow them to recognize that a large earthquake is likely. Large earthquakes are often preceded by small tremors, called foreshocks, that occur between a few seconds and a few weeks before a major quake. However, many earthquakes are not preceded by foreshocks and clusters of small earthquakes are not necessarily followed by a large earthquake.

Large earthquakes are also often preceded by the tilting of the ground surface, which is caused by the buildup of stress in the rocks. Seismologists measure the ground tilt and use the changes to predict an impending earthquake. While this technique has been somewhat successful, it has also been a part of predictions of earthquakes that never came and has failed to predict some that did. Water levels in wells fluctuate as water moves into or out of fractures before an earthquake. This information can also be used as a possible, but uncertain, predictor of large earthquakes.

The most successful earthquake prediction was on February 4, 1975. At the recommendation of Chinese seismologists, officials evacuated many of the residents of the Manchurian province of Liaoning. Although the region was not prone to earthquakes, the seismologists made their prediction because the area experienced about 400 small foreshocks over a few days. The night of the evacuation an earthquake of magnitude 7.3 struck the town and only a few hundred people died. An estimated 150,000 people may have been saved. However, a little more than a year later, Chinese seismologists failed to predict the Tangshan earthquake, which killed more than 250,000 people. One month after that, Chinese officials evacuated residents of the Guandong Province for an earthquake that never came.

There is value in predicting the arrival of seismic waves from an earthquake that is already taking place. Seismometers can detect P-waves a few seconds before more damaging S-waves and surface waves arrive. Although a few seconds is not much, a coordinated computerized system can use that time to shut down gas mains and high tension electrical transmission lines, and initiate protective measures in chemical plants, nuclear power plants, mass transit systems, airports and on roadways.

Folklore tells of animals behaving erratically just before an earthquake. Mostly these anecdotes are told after the earthquake, when people remember back to the time before the shaking began. Memories are notoriously faulty. However, Chinese scientists actively study the behavior of animals before earthquakes to see if there is something to the anecdotes.

One interesting tale involves the number of animals killed in the 2004 Boxing Day Tsunami, which appeared to be surprisingly low. Reports abound suggesting that the animals had a "sixth sense" that warned them of the danger. In Sri Lanka's Yala National Park, for example, about 60 tourists and park employees drowned but few large animals. Three elephants were seen fleeing to higher ground. On closer inspection, the elephants with tracking collars appeared to have exhibited normal movements for the day. If indeed animals sense danger from earthquakes or tsunamis, scientists do not know what it is they could be sensing, but they would like to find out.

Lesson Summary

- Seismologists use seismograms to determine how strong an earthquake is, how far away it is, and how long it lasts.
- Epicenters can be calculated using the difference in the arrival times of P-and S-waves from three seismograms.
- The intensity of an earthquake can be determined in many ways. The Mercalli Scale identifies the damage done and what people feel, the Richter Scale measures the greatest amplitude of the earthquake, and the moment magnitude scale measures the total energy released by an earthquake.
- Despite some successes, seismologists have not come too far in their ability to predict earthquakes.

Review Questions

1. How can a seismograph measure ground shaking if all parts of it must be attached to the ground?
2. On a seismogram, which waves arrive first, second, third and which arrive last?
3. What information is needed for seismologists to calculate the distance that a seismic station is from an earthquake's epicenter?
4. If a seismogram records P-waves and surface waves but not S-waves, where was the earthquake epicenter located relative to the seismograph and why?
5. Like the Richter scale, the magnitude moment scale is logarithmic. What is the difference in the amount of energy released by an earthquake that is a 7.2 versus an 8.2 in magnitude? A 7.2 versus a 9.2?
6. Why do you need at least three seismographs to locate an earthquake epicenter?
7. While the Mercalli scale is still used for measuring earthquake magnitude, why is it not the only scale used? Where does it fall short relative to the Richter and Moment Magnitude scales?
8. Why is the moment magnitude scale thought to be more useful than the Richter scale for measuring earthquake magnitudes?
9. What is the difference in energy released between a 6 and a 7 on the Richter scale? How about a 6 and a 7 on the moment magnitude scale?
10. How do seismologists use earthquake foreshocks to predict earthquakes? Why are foreshocks not always an effective prediction tool?

11. What are the characteristics of a good earthquake prediction? Why are these features needed?
12. Why were Chinese seismologists so successful at predicting the 1975 earthquake in the Manchurian province of Liaoning? Why did they fail to predict the 1976 Tangshan earthquake and evacuate Guandong Province a month later needlessly?

Further Reading / Supplemental Links

- http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/swf_earthquake_triangulation/p_activity_eqtriangulation.html

Vocabulary

mercalli intensity scale This scale measures the effects of an earthquakes seen on the land surface and felt by humans. It measures I-XII.

moment magnitude scale This is a logarithmic scale that measures the total energy released by an earthquake. An increase of one integer indicates a 30-fold increase in energy released. An increase of two integers indicates a 1,000-fold increase in energy released.

Richter scale The Richter scale measures the largest jolt produced by an earthquake. It is a logarithmic scale.

seismogram A seismogram is the printed record of seismic activity produced by a seismometer.

seismograph An older type of seismometer in which a pen that was suspended and weighted wrote on a drum that moved with the ground.

seismometer A seismometer is a machine that measures seismic waves and other ground motions.

Points to Consider

- If you live in an earthquake prone area, how do you feel about your home now that you've read this section? Since earthquakes are unlikely to be predicted, what can you do to minimize the risk to you and your family? If you do not live in an earthquake prone area, what would it take to get you to move to one? Also, what risks from natural disasters do you face where you live?

- What do you think is the most promising set of clues that scientists might some day be able to use to predict earthquakes?
- What good does information about possible earthquake locations do for communities in those earthquake-prone regions?

7.4 Staying Safe in Earthquakes

Lesson Objectives

- Describe different types of earthquake damage.
- Describe the features that make a structure more earthquake safe.
- Describe the ways that a person and a household can protect themselves in earthquake country.

Introduction

Earthquakes are rivaled only by hurricanes in their ability to cause enormous amounts of damage. Earthquake damage comes not only from ground shaking, but also from the fires, landslides, and tsunamis that may result from the shaking. There are ways for communities to prepare for earthquakes by using earthquake-safe construction techniques or retrofitting old structures. Individuals and households can take actions such as securing heavy objects and preparing an emergency kit. Still, despite the best precautions, a massive earthquake can cause enormous numbers of fatalities and damage.

Damage from Earthquakes

Earthquakes kill people and damage property. There are a lot of falsehoods about how earthquakes do their damage and what sort of damage they do or can be expected to do. The ground shaking almost never kills or injures people; rarely, if ever, does the ground open up and swallow someone. Fatalities and injuries caused by earthquakes are due to structures falling on people. More damage is done and more people are killed by the fires that usually follow an earthquake than by the earthquake itself.

Damage to people and property depends on an earthquake's magnitude, the distance of the epicenter to population centers, and how long the ground shakes. But human factors are important too. The type of ground structures are built on is an enormous factor in the amount of damage done. Damage also depends on the quality of structures, including what materials are used.

The largest earthquakes are not necessarily the deadliest. Only about 2,000 people died in the 1960 Great Chilean earthquake, which was the largest earthquake ever recorded at magnitude 9.5. The 1556 Shaanxi earthquake in China measured a magnitude 8.0, but is estimated to have killed about 830,000 people. The Great Sumatra - Andaman earthquake of 2004 makes the list of the largest earthquakes and was also one of the deadliest. However, most of the 230,000 fatalities were due to the tsunami that followed the earthquake, not the earthquake itself.

Damage during an earthquake depends on the type of ground under the buildings. Solid bedrock vibrates much less than soft sediments. Buildings on bedrock will only fail if the earthquake is extremely violent. Soft ground, such as sand, silt, or clay, settles when it is shaken and so buildings tilt or fall over, and pipelines, roadways, and other structures break. Sediments that are saturated with water undergo **liquefaction** during an earthquake and become like quicksand. Soil on a hillside that is shaken loose can become a landslide, which takes houses downhill with it or buries structures at the hill's base.

In earthquake-prone areas, city planners spend a lot of time understanding which locations are the most vulnerable and trying to reduce the hazards. For example, in the San Francisco Bay Area, planners study maps that show how much shaking is expected in various areas for different magnitudes and locations of earthquakes (**Figure** 7.44). Using this information can allow them to understand and prepare for the hazards. For example, when faced with two possible locations for a new hospital, planners must build on bedrock rather than silt and clay.

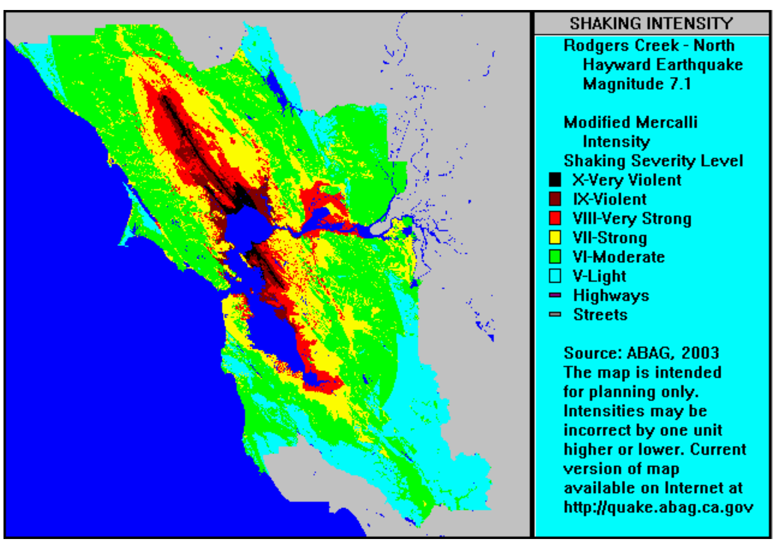

Figure 7.44: This map shows the amount of shaking on the Modified Mercalli Intensity Scale that would be expected for an earthquake of magnitude 7.1 on the northern portion of the Hayward Fault. Much of the land near the bay, where shaking is predicted to be most violent is loose mud & soil, called fill. The hills around the bay, which are mostly colored green, are bedrock. The outline of the Hayward Fault can be seen in black, since it is where the most violent shaking is predicted to be. (8)

Mexico City provides an example of how soft ground can magnify earthquake damage. In 1985, a magnitude 8.1 earthquake struck about 350 kilometers west of the city. The earthquake was caused by subduction of the Cocos Plate beneath the North American Plate. Mexican government records show that the earthquake killed at least 9,000 people, injured 30,000 more, left 100,000 people homeless, destroyed 416 buildings, and seriously damaged 3,000 other buildings. The reason for so much destruction so far from the earthquake's epicenter is that Mexico City is built on a drained lakebed. Beneath the capital city, the ground is soft silt and clay in a basin made of solid rock. When the earthquake struck, seismic waves bounced back-and-forth off the sides and bottom of the rock basin amplifying the shaking. In addition, the wet clay experienced liquefaction (**Figure** 7.45). The buildings were not anchored to bedrock as they should have been and so they settled into the muck, causing enormous damage.

Figure 7.45: Liquefaction of sediments in Mexico City caused the collapse of many buildings in the 1985 earthquake. (9)

Water, sewer and electrical systems were destroyed, resulting in fires. Acapulco, which was much closer to the epicenter but built on bedrock suffered little damage. To prevent Mexico City from being taken by surprise again, the government built an alert system. The next time there is an earthquake in the subduction zone, a signal will be activated and sirens will sound in the city. This will give residents about one minute to prepare for the inevitable earthquake. At the least, this is enough time for most people to get in a secure location.

The population density of a region is also important to the number of casualties and the amount of damage. The 1964 Great Alaska Earthquake, near Anchorage, was the largest earthquake ever recorded in North America and the second largest globally, with a magnitude of 9.2. The earthquake lasted for several minutes, resulted in slip of up to 11.5 meters (38 feet), and affected an area of 100,000 square miles (250,000 square km). Ground liquefaction caused landslides (**Figure** 7.46).

Figure 7.46: A landslide in a neighborhood in Anchorage Alaska after the 1964 Great Alaska earthquake. (29)

Because the earthquake occurred at a subduction zone offshore, large tsunami (up to 70 meters (20 feet)) were created. Despite the intensity of the earthquake, only 131 people died, mostly due to the tsunami and property damage was relatively modest, at just over $300 million ($1.8 billion in 2007 U.S. dollars). The reason there was such a small amount of damage for such a large earthquake is that very few people lived in the area at that time (Alaska had only been a state for five years!). A similar earthquake today would cause immeasurably more casualties. The number of people that an earthquake kills or injures is often related to the time of day that it strikes and where it strikes. The most lethal earthquakes strike densely populated cities when people are at work and school. Being at home in bed is usually safer.

Earthquake-Safe Structures

The way a building is built—its construction—is a large factor in what happens during an earthquake. Building construction is the reason many more people died in the 1988 Armenia earthquake than the 1989 Loma Prieta, California earthquake. Although the Armenian earthquake was only slightly lower in magnitude, the mud houses that are found throughout the area collapsed. Most buildings in California's earthquake country are designed to be earthquake safe. However even earthquake safe buildings can be damaged by a large earthquake.

Engineers who design earthquake safe buildings must understand seismic waves and how they affect different types of ground. Skyscrapers and other large structures built on soft ground must be anchored to bedrock, even if it is lies hundreds of meters below the ground surface.

The materials used to construct a structure affect its ability to weather an earthquake. The type of material that is best depends on the size of the building. Small structures, like houses, do better if they are constructed of materials that bend and sway such as wood and steel rather than brick, stone, and adobe, which are brittle and will break. Brittle materials are less likely to break if they are reinforced by steel or wood. Larger buildings must sway, but not so much that they touch nearby buildings. Counterweights and diagonal steel beams are used to hold down sway. A completely different approach for large buildings is to place them on rollers so that they move with the ground but do not collapse. Buildings may also be placed on layers of steel and rubber, which absorb the shock of the passing seismic waves. Structures that fail usually do so because they are weak at the connections, such as where the walls meet the foundation. Earthquake safe buildings are well connected. In a multi-story building, the first story must be supported or the structure may collapse (**Figure** 7.47).

Figure 7.47: The first floor of this San Francisco building is collapsing after the 1989 Loma Prieta earthquake. The building is being held up by the two walls that are not in the photograph and the strength of the upper floors. The two walls that are in view are not strong because they had doors in them. (42)

Older structures can be retrofitted to be more earthquake safe. Retrofitting includes adding steel or wood to reinforce a buildings structure and its connections (**Figure** 7.48). Elevated freeways and bridges can also be retrofitted so that they do not collapse. The goal of retrofitting is different depending on the type of structure being altered. Most structures are retrofit only to a strength that protects human life. More important structures, like bridges, are made to survive intact, but may need extensive repair after the earthquake. Structures that need to be used in an emergency, like hospitals, are retrofit to higher standards so that they will need only superficial repairs after an earthquake. The highest level of protection is a retrofit that will allow a building to survive unaffected. This is very expensive and is only done for buildings that are of great historical or cultural significance.

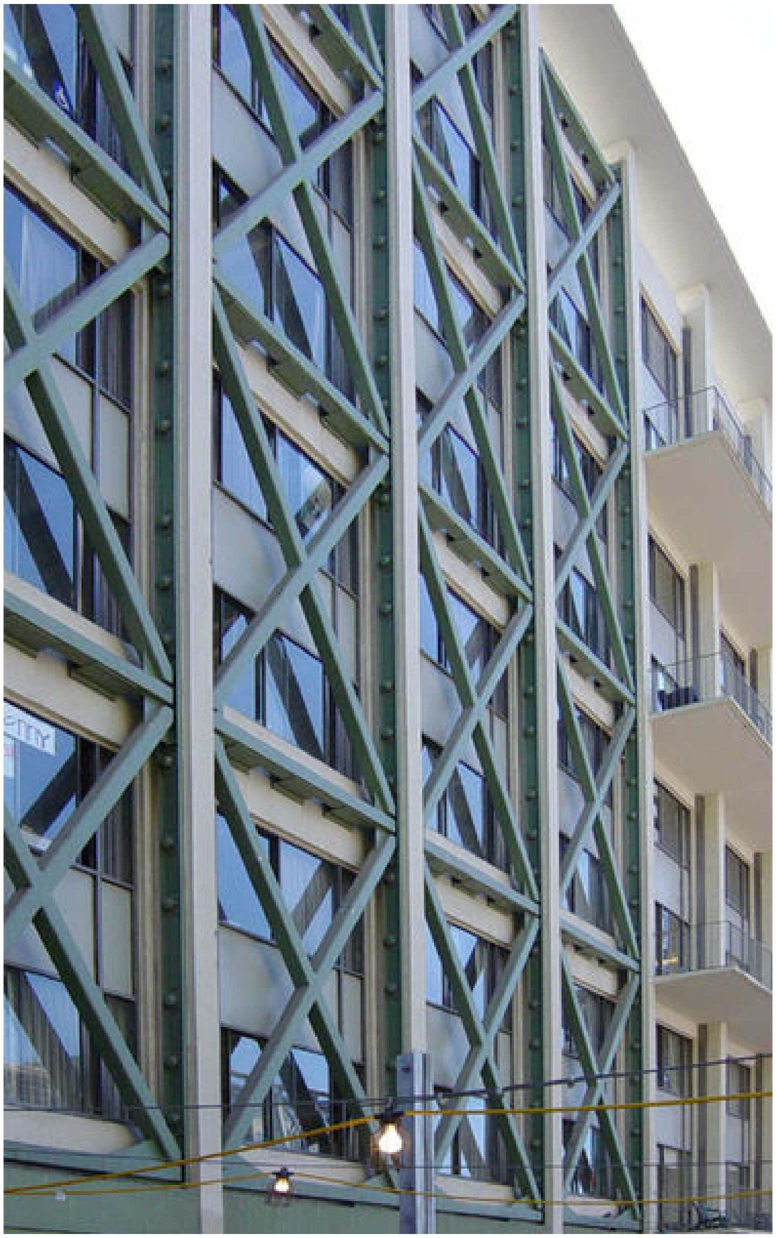

Figure 7.48: Steel trusses were built in an x-pattern to retrofit a dormitory at the University of California, Berkeley. The building is very near the Hayward Fault. (20)

Of course, one of the biggest problems stemming from earthquakes is fire. Fires start because earthquakes rupture gas and electrical lines. Breaks in water mains compound the problem by making it difficult to fight those fires. One effective way of dealing with this is to zigzag pipes so that they bend and flex when the ground shakes. Straight pipes will break in a quake. In San Francisco, water and gas pipelines are separated by valves so that areas can be isolated if one segment breaks.

Since engineers know what sorts of structures do best in earthquakes, why aren't all structures in earthquakes zones constructed for maximum safety? Of course, the reason is cost. More sturdy structures are much more expensive to build. Since no one knows which structures will be exposed to a large earthquake during their effective lifetimes, communities must decide how safe to make their buildings. They must weigh how great the hazard is, what different building strategies will cost, and how much risk they are willing to take. In poor communities, the choice may come down to spending money on earthquake-safe buildings or funding other priorities, such as a water sanitation project. The choice often comes down to protecting against a known risk versus unknown one; for example, many people in developing nations die each year from drinking and bathing in unclean water.

Protecting Yourself in an Earthquake

If you live in an earthquake zone, there are many things you can do to protect yourself before, during and after an earthquake. The two goals are to make sure that the house and its contents are not a hazard and for the household to be ready to live independently for a few days until emergency services are available in full force.

Before the Earthquake:

- Have an engineer evaluate your house for structural integrity. Make sure the separate pieces—floor, walls, roof and foundation—are all well attached to each other.
- Bracket or brace brick chimneys to the roof.
- Be sure that heavy objects are not stored in high places. Move them to low places so that they do not fall.
- Secure water heaters all around and at the top and bottom.
- Bolt heavy furniture onto walls with bolts, screws, or strap hinges.
- Replace halogen and incandescent light bulbs with fluorescent bulbs to lessen fire risk.
- Check to see that gas lines are made of flexible material so that they do not rupture. Any equipment that uses gas should be well secured.
- Everyone in the household should know how to shut off the gas line. A wrench should be placed nearby for doing so.
- Prepare an earthquake kit with at least three days supply of water and food. Include a radio and batteries.
- Place flashlights all over the house so that there is always one available. Place one in the glove box of your car.

- Keep several fire extinguishers around the house to fight the small fires that might break out.
- Be sure to have a first aid kit. Everyone in the household who is capable should know basic first aid and CPR.
- Plan in advance how you will evacuate your property and where you will go. Do not plan on driving as roadways will likely be damaged.

During the Earthquake:

- If you are in a building, drop to the ground, get beneath a sturdy table or desk, cover your head, and hold on.
- Stay away from windows and mirrors since glass can break and fall on you. Stay away from large furniture that may fall on you.
- If the building is structurally unsound, get outside as fast as possible. Run into an open area away from buildings and power lines that may fall on you.
- If you are in a car, stay in the car and stay away from structures that might collapse like overpasses, bridges, or buildings.

After the Earthquake:

- Be aware that aftershocks are likely.
- Avoid dangerous areas like hillsides that may experience a landslide.
- Turn off water and power to your home.
- Use your phone only if there is an emergency. Many people with urgent needs will be trying to get through to emergency services.
- Be prepared to wait for help or instructions. Assist others as necessary.

Lesson Summary

- A person standing in an open field in an earthquake will almost certainly be safe. Nearly all earthquake danger is from buildings falling, roadways collapsing, or from the fires and tsunamis that come after the shaking stops.
- Communities can prepare for earthquakes by requiring that buildings be earthquake safe and by educating citizens on how to prepare for an earthquake.
- Individuals and households can prepare in two ways: by making sure that their house and its contents are not a hazard and by being ready to live independently for a few days while emergency services regroup and get to all parts of the region.

Review Questions

1. What usually kills or injures people in an earthquake?

2. In two earthquakes of the same size, what reasons are there that more people would be killed in a location further from the epicenter than in one nearer the epicenter?
3. Describe why Mexico City was so devastated by the far away 8.1 earthquake that struck in 1985. Why did Acapulco, which is located much closer to the quake site, fare so much better?
4. What is liquefaction and how does it cause damage in an earthquake?
5. Pretend that you live in an old home in an earthquake-prone region. No work has ever been done to prepare your home for an earthquake. What should you do to minimize the harm that will come to yourself and your home?
6. What can an architect do to make a skyscraper earthquake safe?
7. Which types of buildings deserve the greatest protection from earthquake hazards?
8. Using what you know about elastic strength, will a building better withstand an earthquake if it is built absolutely solid or if it is able to sway? Why?
9. Why do wealthy communities (such as those in California) tend to have greater earthquake protection than poorer communities (such as those in developing nations)?
10. What are the two goals of earthquake preparation?
11. What should you include in an earthquake kit?
12. Under what circumstances should you run outside in an earthquake?

Vocabulary

liquefaction Clay, silt, and sand saturated with water become like quicksand, lose their strength and behave more like a liquid than a solid.

Points to Consider

- Many people think that in a large earthquake California will fall into the ocean and that Arizona and Nevada will be beachfront property. Why is this not true?
- If you were the mayor of a small city in an earthquake-prone area, what would you like to know before choosing the building site of a new hospital?
- How are decisions made for determining how much money to spend preparing people and structures for earthquakes?

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(4) *The two types of strike-slip faults.*. GNU-FDL.

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(6) *A sign indicating a tsunami hazard zone in California.*. GNU-FDL.

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(42) http://en.wikipedia.org/wiki/Image:007srFromUSGS.jpg. GNU-FDL.

(43) *A syncline in Rainbow Basin in California.*. GNU-FDL.

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(45) *Geologic map of the Michigan Basin.*. GNU-FDL.

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Chapter 8

Volcanoes

8.1 Volcanic Activity

Lesson Objectives

- Explain how volcanoes form.
- Describe places where volcanoes occur.
- Describe what volcanic hot spots are and where they occur.

Introduction

Everybody has heard of volcanoes—the angry Earth spewing up its wrath, the sudden explosion of a distant mountain top, and lava that slithers ominously toward villages. Volcanoes are fantastic displays of the power of the Earth. But what actually is a volcano? How and where are they formed? Why do some places have a history of volcanic activity? Volcanoes explain a key piece of the Earth's geologic puzzle (**Figure** 8.1).

How Volcanoes Form

You have already learned about tectonic plates. Beneath the Earth's surface, powerful forces are at work. These forces move lithospheric plates and produce huge chambers of **magma**, molten rock beneath the Earth's crust. Like water that bursts from a tiny hole in a water pipe, the liquid magma seeks cracks or **fissures** in the Earth's crust through which it could flow. This is a volcano — an opening in the earth's crust through which magma or gases can erupt onto the surface.

When molten rock escapes from beneath the Earth's surface, it changes from magma to **lava,**

Figure 8.1: Mount Merapi, Indonesia. (5)

molten rock above the Earth's surface. Because the temperatures at the Earth's surface are much lower than in the magma chambers, the lava does not take long to solidify back into rock. As layer upon layer of lava solidifies, a mountain is formed (**Figure** 8.2).

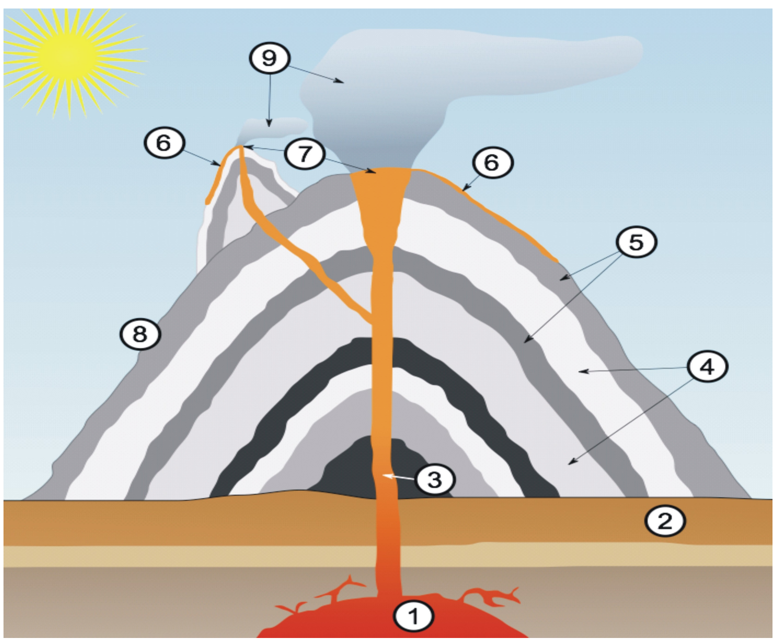

Figure 8.2: A volcano is a vent through which molten rock and gas from beneath the Earth's surface escape. (**1**) Large magma chamber (**2**) Bedrock (**3**) Pipe (conduit) (**4**) Layers of ash (**5**) Layers of lava (**6**) Lava flow (**7**) Vent (**8**) Lava (**9**) Ash cloud (26)

As you can see in **Figure 2**, magma begins in the lava chamber and comes to the surface through the throat of the volcano. The volcano is constructed layer by layer, as ash and lava solidify, one upon the other. However, other types of volcanoes exist, and will be discussed later in this chapter.

Where Volcanoes Occur

Because volcanoes are vents for magma, it makes sense that volcanoes would be formed above underground magma chambers. If you recall, magma is molten rock that has been heated because of high temperatures and pressures beneath the Earth's crust. This pressure mostly occurs where the tectonic plates meet and subduct. Look at the map of tectonic plates in **Figure** 8.3.

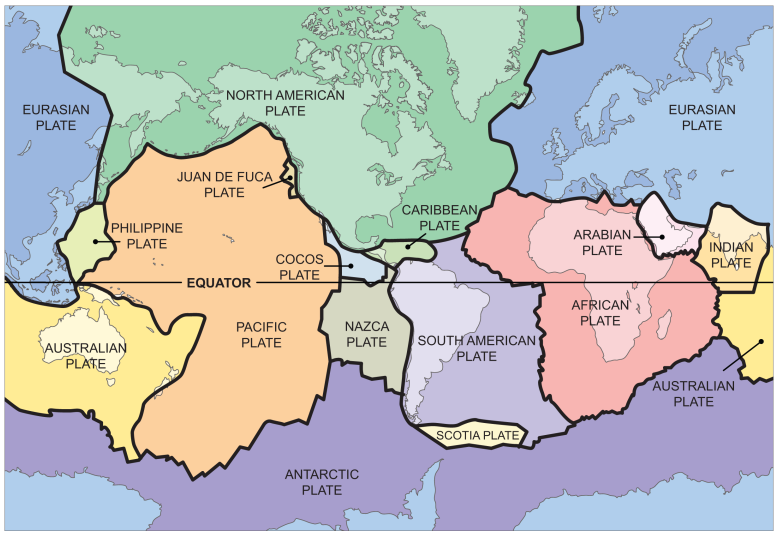

Figure 8.3: Tectonic plates. Some of the largest tectonic plates meet along the coasts of Asia and North America. Compare this map to the map in **Figure 4**. (23)

So, volcanic activity tends to occur along subduction plate boundaries, where one plate slides underneath another. The edges of the Pacific Plate make up a long subduction boundary. There are a huge number of earthquakes along these boundaries, because these are regions where the plates are colliding. For the same reason, the majority of the volcanic activity on the Earth also occurs along these convergent boundaries. This is called the *Pacific Ring of Fire* where over 75% of the world's volcanoes are found. The Cascade Range of volcanoes runs through southwestern Canada and the Pacific Northwest of the United States. These volcanoes are the result of subduction of the Juan de Fuca plate beneath the North American plate. (**Figure** 8.4).

Of course, this is not the only area where volcanoes occur. Beneath the ocean, there are also divergent boundaries, where tectonic plates are pulling away from each other. As the plates pull away from each other, they create a deep canyon or fissure on the sea floor through which molten rock escapes. Mid-ocean ridges, like the Mid-Atlantic ridge, form here as lava flows out through the fissure (**Figure** 8.5). Submarine volcanoes can also form on the ocean floor. At times these volcanoes can grow to create islands above the water's surface. This explains how Surtsey, a small island near Iceland formed (**Figure** 8.6).

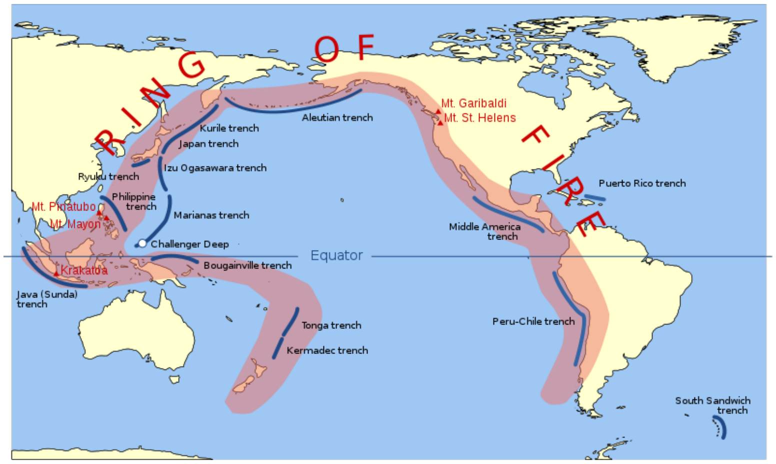

Figure 8.4: The Pacific Ring of Fire is where the majority of the volcanic activity on the Earth occurs. (27)

Volcanic Hot Spots

Although most volcanic activity on Earth occurs at plate boundaries, there are some volcanically active spots that are in the middle of a tectonic plate. These areas are called **hot spots**. The islands of Hawaii formed over a hot spot and are not located on the Pacific Ring of Fire (**Figure** 8.7). The Hawaiian islands are the exposed peaks of a great chain of volcanoes that were formed over millions of years. The islands are thought to lie directly above a column of hot rock called a **mantle plume**. Mantle plumes are more or less fixed in place and continuously bring magma up form the mantle towards the crust. As the tectonic plates move above them, they leave a trail of volcanic activity, which forms island chains like Hawaii. Scientists believe there are about 50 hot spots on the Earth. Other hot spots include Yellowstone and the Galapagos Islands.

Don't confuse hot spot volcanoes with islands that are formed by plate tectonics like the Aleutian island chain in Alaska. These long lines of volcanoes form as the edge of a subducted plate melts, producing magma which rises to the surface along the edge of the plate. These volcanic mountains will all be about the same age. When islands form over a hot spot, the youngest island is over the hot spot. As you move along the island chain, each island further from the hot spot will be older than the one before it.

Lesson Summary

- Volcanoes form when magma reaches the Earth's surface.
- Volcanoes occur most often along plate boundaries.
- Convergent plate boundaries where oceanic crust is subducted form many of the volcanoes found on Earth.

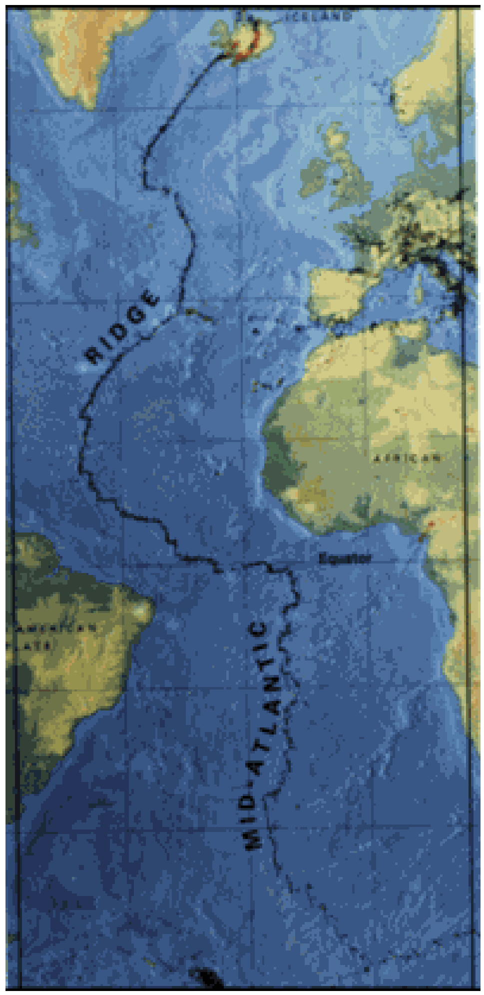

Figure 8.5: The Mid-Atlantic Ridge is formed by divergent tectonic plates. (9)

Figure 8.6: A volcanic eruption in Iceland. (22)

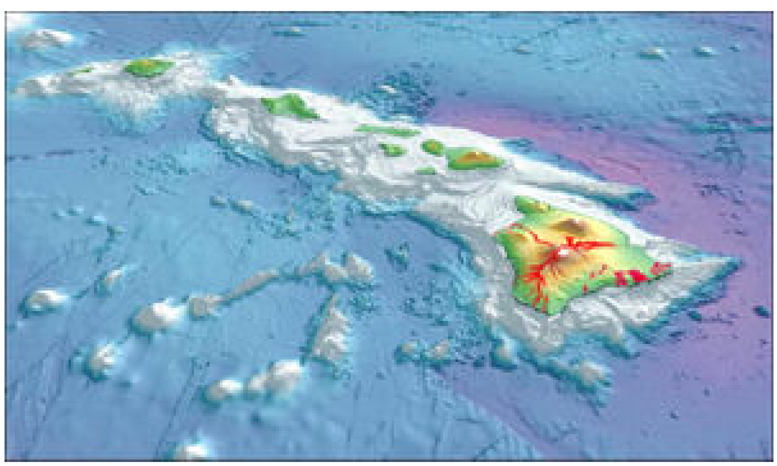

Figure 8.7: Hawaii is a volcanic hot spot. It was formed by volcanic activity fed by mantle plumes. (16)

- Divergent plate boundaries produce huge mountain ranges under water in every ocean basin.
- Volcanoes like those that form the islands of Hawaii, form over areas called hot spots.

Review Questions

1. What is the difference between magma and lava?
2. Explain how volcanoes are formed.
3. Why are there volcanoes along the west coast of the United States?
4. Why do volcanoes occur where tectonic plates pull apart or diverge?
5. Explain how the Pacific Ring of Fire got its name.
6. What is a mantle plume?
7. Suppose a new volcano suddenly formed in the middle of the United States. How might you explain what caused this volcano?
8. Volcanoes have been found on Venus, Mars, and even Jupiter's moon Io. What do you think this indicates to planetary geologists?

Vocabulary

fissures A long crack into the Earth's surface, from which lava erupts onto the surface.

hot spot A fixed region of hot magma that rises through the mantle and creates volcanoes on the Earth's surface. A hot spot is above a mantle plume.

lava Molten rock that has been erupted onto the Earth's surface. Magma becomes lava once it emerges on the surface.

magma Molten rock found under the Earth's surface.

mantle plume A column of very hot rock that rises up through the mantle. Mantle plumes will form hot spots if they make it all the way up to the surface of the Earth's crust.

Points to Consider

- When you look at the map of tectonic plates (Figure 3), what areas besides the Pacific Ring of Fire would you expect to have volcanic activity?
- Some volcanoes are extinct; they are no longer active and will probably never be again. What do you think causes a volcano to become extinct?
- Hot spots are still poorly understood by earth scientists. Given your understanding of the Earth's interior, why do you think it's hard to study hot spots?

8.2 Volcanic Eruptions

Lesson Objectives

- Explain how volcanoes erupt.
- Describe and compare the types of volcanic eruptions.
- Distinguish between different types of lava and understand the difference between magma and lava.
- Describe a method for predicting volcanic eruptions.

Introduction

In 1980, Mount St. Helens erupted in one of the most deadly and costly volcanic eruptions in the United States ever. The eruption was particularly deadly since Mount St. Helens, one of the Cascade Range, is in a populated area between Portland, Oregon and Seattle, Washington. The eruption killed 57 people, destroyed 250 homes, and swept away 47 bridges. The elevation of the volcano dropped by over 400 meters (1,300 feet) because of the immense explosion created by the eruption. Today Mt. St. Helens is still active (**Figure** 8.8). The volcano now has a horseshoe-shaped crater that is 1.5 km (nearly one mile) across. Within the crater, a new lava dome has formed. How did this eruption occur? Why aren't all volcanoes explosive like Mt. St. Helens? Why did so many people perish if we knew that it was going to erupt? The study of volcanoes has many questions still unanswered. However, scientists have studied volcanoes for many years and are piecing together evidence that explains these powerful geologic phenomena.

Figure 8.8: Mount St. Helens, Washington, two years after its eruption. (4)

How Volcanoes Erupt

All volcanoes share the same basic features. The magma collects in magma chambers that can be 160 kilometers (100 miles) beneath the surface. As the rock heats, it expands, which creates even more pressure. As a result, the magma seeks a way out pushing toward the surface, the magma seeps through cracks in the Earth's crust called vents. Eventually, the magma reaches the surface; when it comes out, we call it an eruption. The word **eruption** is used in other contexts, as well. An eruption can be an outburst or explosion, a violent and sudden occurrence, like when a crowd erupts in anger. But an eruption can also be a spreading of something like a rash on your skin, gradual and relatively calm. These two definitions are similar to the two kinds of eruptions that we see in volcanoes.

Types of Eruptions

Every geological formation is unique. Their composition and construction depend on so many factors, that it would be impossible for two formations to be exactly alike. In the same way, each volcano and its eruptions are unique. However, we tend to see two major kinds of eruptions. We talked about eruption to mean both a violent explosion or a sort of silent spreading. These are the two types of volcanic eruptions that we see–explosive and non-explosive eruptions. When we think of volcanic eruptions, we often think of huge clouds of volcanic ash ejected high into the atmosphere and then thick rivers of red lava snaking down the mountainside. In reality, these two phenomena rarely occur in the same volcano. Volcanic eruptions tend to be one or the other.

Explosive Eruptions

Figure 8.9: An explosive eruption from the Mayon Volcano in the Philippines in 1984. (25)

Imagine the devastation and force caused by the atom bomb dropped on Nagasaki at the end of World War II in which over 40,000 people died. Now imagine an explosion 10,000 times as powerful. Explosive volcanic eruptions can be that powerful (**Figure** 8.9). As hot magma beneath the surface interacts with water, gases accumulate and the magma pressure builds up. This pressure grows and grows until these dissolved gases cause it to burst in an enormous explosion.

This great explosion takes with it the magma and volcanic gases, which can shoot many kilometers into the sky and forms a mushroom cloud, similar to that formed by a nuclear explosion (**Figure** 8.10). The debris travels up into the air at very high speeds and cools in the atmosphere to form solid particles called **pyroclasts.** Some of these particles can stay in the atmosphere for years, which can disrupt weather patterns and affect the temperature of the Earth. The rest of the debris comes falling back to Earth where it rains down for kilometers and kilometers around.

Figure 8.10: Explosive eruption of Mt. Redoubt in Alaska, 1989. This huge mushroom cloud reached 45,000 feet and caught a Boeing 747 in its plume. (1)

Sometimes secondary explosions occur that are even greater than the first. Additionally, volcanic gases like water vapor, carbon dioxide, sulfur dioxide, hydrogen sulfide, and hydrogen chloride can form poisonous and invisible clouds that roam about the atmosphere. These gases contribute to environmental problems like acid rain and ozone destruction, and can actually cool the Earth's atmosphere.

In the Cascade Range, the explosive eruption of Mount St. Helens was preceded by the eruption of Lassen Peak, one of the three Cascade Volcanoes in northern California. On May 22, 1915, an explosive eruption sent a column of ash and gas 30,000 feet into the air and triggered a high-speed pyroclastic flow, which melted snow and created a lahar. Lassen continues to have geothermal activity and could erupt explosively again. Mt. Shasta erupts every 600 to 800 years. An eruption would most likely to create a large pyroclastic flow, and perhaps a lahar. However, the volcano could explode like Mt. Mazama, which blew itself in an eruption about 42 times more powerful than Mount St. Helens in 1980, to create Crater Lake.

Non-explosive Eruptions

Figure 8.11: In effusive eruptions, lava flows more readily, producing rivers of molten rock. (6)

A second type of volcanic eruption is a non-explosive or **effusive eruption** (**Figures** 8.11 and 8.11). Because the composition of magma is different in different volcanoes, the properties of the lava are different. In effusive eruptions, lava flows are relatively calm and do not explode out of the volcano. As a result, people generally have a great deal of warning before lava reaches them, so non-explosive eruptions are much less deadly. That does not keep them from being destructive, however. Even when we know that a lava flow is approaching, there are few ways of stopping it, given the huge quantity and temperature of lava.

Magma and Lava

Volcanoes wouldn't be nearly as interesting without the great explosions they create and the glowing red rivers of lava. All igneous rock comes from magma or lava. The next time you

Figure 8.12: When lava flows readily, pressure does not build up so great explosions do not occur. (31)

go hiking near a volcanic zone, you might try to identify the types of lava that the volcano erupted, based on the types of igneous rocks you find.

Magma

Deep beneath the Earth, magma forms as the first stage in creating a volcano. This occurs because rock below the surface is subjected to great amounts of pressure from gravity. The decay of radioactive materials generates additional heat. The substantial heat and pressure melt the rock below the surface to form a taffy-like substance. You may have seen a candle that has been left out in the hot sun too long. It becomes softer and more like a liquid. As the molecules absorb heat, they begin to slide past one another becoming more fluid. A similar process occurs with magma. However, different substances melt at different temperatures. For that reason, the temperature at which rocks melt depends on the specific types of rocks. The Earth's crust and mantle are made of many substances so the temperature required to create magma varies. Most magmas are formed between 600°C and 1300°C (**Figure** 8.13).

Melted rock or magma can be found in **magma chambers** beneath the Earth. Since the magma chambers are so far beneath the Earth's surface, it is difficult for scientists to study them. Scientists know that magma chambers are created where the heat and pressure are greatest. When tectonic plates collide and rub against each other, magma is formed there. That is how the Pacific Ring of Fire was created. We also know there are volcanoes far away from plate boundaries, so we know there are magma chambers in these areas as well. Magma chambers can be found where there are mantle plumes or hot spots.

Just how or why these hot spots are created isn't exactly known. However, because dif-

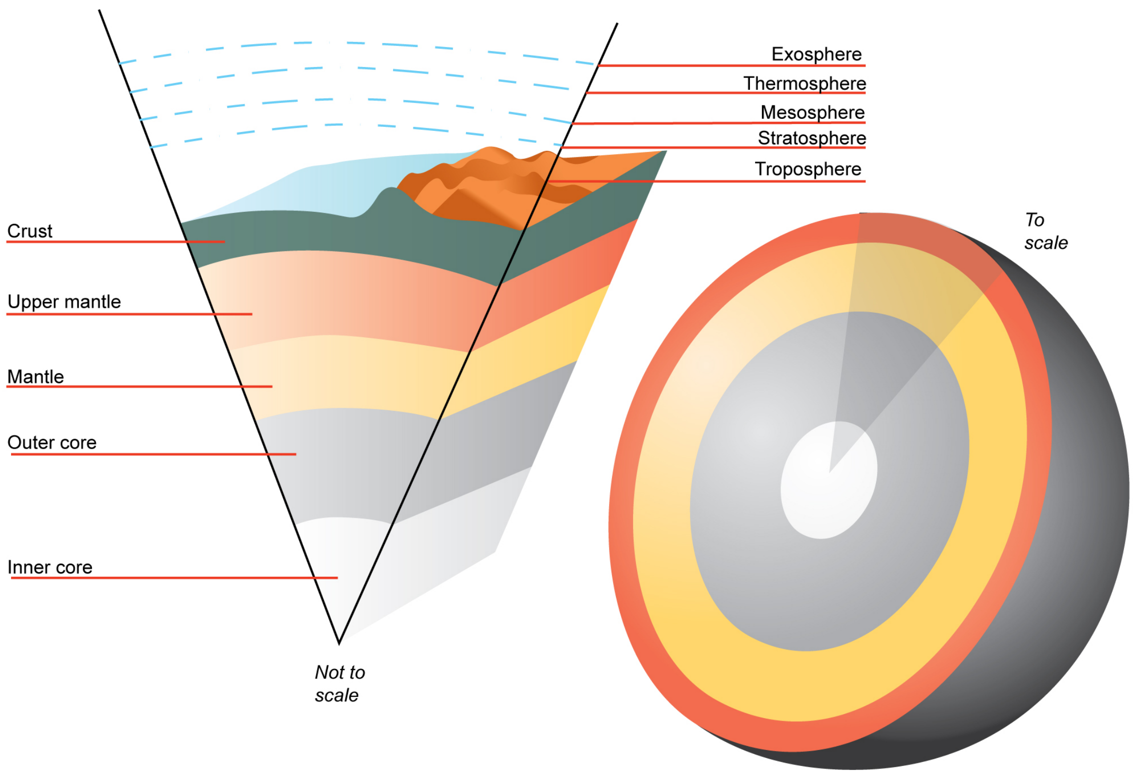

Figure 8.13: Cutaway of the Earth. The melting of rock in the crust and upper mantle create magma. (32)

ferent substances melt at different temperatures, the creation of magma depends on what substances make it up—its composition. Just like the flavor of a cake depends on the ingredients that you put in it, the behavior of magma and lava depends on its composition. Certain melted rocks act in certain ways. So when the magma becomes lava, not all lava acts the same.

Lava

Once magma reaches the surface, it becomes lava. Consider different liquids that you might see in your house—honey and a bottle of cola, for example. You might agree that the two liquids are different in many regards. They taste different, have different colors, have different gases in them, and they flow differently. In fact, honey is a liquid that resists flowing, whereas cola flows easily. Honey has a higher **viscosity** than the cola; it resists flowing (**Figure** 8.14). Cola has a low viscosity because it flows easily. One of the major differences in different types of lava is their viscosity.

Figure 8.14: Honey flows slowly; it is more viscous than water. (30)

A highly viscous lava is one that doesn't tend to flow easily. It tends to stay in place. Lavas with high silica contents tend to be more viscous. Since it is so resistant to moving, it clogs the vents in a volcano. The pressure becomes greater and greater until the volcano finally explodes. This type of lava is found in explosive eruptions. It also tends to trap a lot of gas. When the gas is released, it makes the eruption more explosive. Most of this lava is shot up into the air where it hardens and becomes solid rock. This molten rock that solidifies in the air is known as **pyroclastic material.** In an igneous rock like pumice, small holes in the solid rock show where gas bubbles were when the rock was still liquid lava.

Low-viscosity lava slides or flows down mountainsides. There is more than one type of low-viscosity lava. The differences between them come from the lavas' different composition and different spots where they come to the surface. The type of igneous formations formed depends on which type of lava it is. The three major categories are a'a, pahoehoe, and pillow lava.

A'a Lava

A'a lava is the more viscous of the non-explosive lavas (**Figure** 8.15). This lava forms a thick and brittle crust which is torn into rough and jagged pieces. The solidified surface is jagged and sharp. It can spread over large areas as the lava continues to flow underneath.

Figure 8.15: A'a lava flow. (13)

Pāhoehoe Lava

Pāhoehoe lava is less viscous than a'a lava, and flows more readily. Its surface looks more wrinkly and smooth than the jagged a'a lava. Pāhoehoe lava flows in a series of lobes or rounded areas that form strange twisted shapes and natural rock sculptures (**Figure** 8.16). Pāhoehoe lava can also form lava tubes beneath the ground (**Figure** 8.17).

Figure 8.16: Pāhoehoe lava (11)

Figure 8.17: The Thurston Lava Tube in Hawai i Volcanoes National Park. (24)

Pillow Lava

Pillow lava is lava that comes out from volcanic vents underwater (**Figure** 8.18). When it comes out underwater, it cools down very quickly and forms roughly spherical rocks that resemble pillows, from which more lava leaks and creates more pillows. Pillow lava is particularly common along underwater spreading centers.

Figure 8.18: Pillow lava. (3)

Predicting Volcanic Eruptions

Volcanic eruptions can be devastating, particularly to the people who are closer to volcanoes. As meteorologists attempt to predict, or forecast, hurricanes and tornados, so too do volcanologists attempt to forecast volcanic eruptions. Although predicting volcanic eruptions is far from perfect, many pieces of evidence can indicate that a volcano is about to erupt. Some of those factors are hard to measure, contributing to the difficulty in predicting eruptions.

History of Volcanic Activities

One important factor in predicting eruptions is a volcano's history. That is, we consider how long since it has erupted and the time span between its previous eruptions. Volcanoes are categorized into three subdivisions—active, dormant, and extinct. An **active** volcano is one that is currently erupting or shows signs of erupting in the near future. A **dormant** volcano no longer shows signs of activity, but has erupted in recent history (**Figure** 8.19). Finally, an **extinct** volcano is one that has not erupted in recent history and will probably not erupt again in the future. Both active and dormant volcanoes are heavily monitored because even dormant volcanoes could suddenly show signs of activity.

Figure 8.19: Vesuvius is a dormant volcano near the city of Naples. Although it shows no current signs of eruption, it could one day become active. (19)

Earthquakes

As magma beneath a volcano pushes upward, it shakes the ground and causes earthquakes. Although earthquakes probably occur every day near a volcano, the quantity and size of the earthquakes increases before an eruption. In fact, a volcano that is about to erupt may produce a continuous string of earthquakes, as magma moving underground creates stress on the neighboring rocks. In order to measure these earthquakes, scientists use seismographs that record the length and strength of each earthquake.

Slope Deformation

All that magma and gas pushing upwards can make the ground or the volcano's slope begin to swell. Sometimes, ground swelling reveals huge changes in the shape of a volcano. Most cases of ground deformation are subtle, though, and can only be detected by tiltmeters, which are instruments that measure the angle of the slope of a volcano. Additionally, ground swelling may cause increased rock falls and landslides.

Gas Emissions

Oftentimes, gases are able to escape a volcano before magma reaches the surface in an eruption. So, scientists can measure gas output, or gas emissions, in vents on or around the volcano. Gases, like sulfur dioxide (SO_2), carbon dioxide (CO_2), hydrochloric acid (HCl) and even water vapor can be measured at the site or, in some cases, at a distance with satellites.

The amounts of gases and their ratios are calculated to help predict eruptions.

Remote Monitoring

As mentioned, some gases can be monitored using satellite technology (**Figure** 8.20). Satellites are able to measure other factors, too, like temperature readings of particularly warm spots at a volcano site or areas where the volcano surface is changing. As our technology continues to improve, scientists are better able to detect changes accurately and safely.

Figure 8.20: An Earth-Observation Satellite before launch. (8)

Although monitoring methods are getting better and better, it is still difficult to predict a volcanic eruption with certainty. No scientist or government agency wants to be considered alarmist by announcing that an eruption is going to occur and then it really doesn't. The cost and disruption to society of a large-scale evacuation would leave many people displeased and the scientists embarrassed. However, the possibility of saving lives and property most certainly makes the pursuit of eruption prediction a worthy cause.

Lesson Summary

- Volcanoes are produced when magma rises towards the Earth's surface because it is less dense than the surrounding rock.
- Volcanic eruptions can be non-explosive or explosive depending on the viscosity of the magma.
- Explosive type eruptions happen along the edges of continents and produce tremendous amounts of material ejected into the air.
- Non-explosive type eruptions mostly produce various types of lava, such as a'a, pahoehoe and pillow lavas.
- Some signs that a volcano may soon erupt include earthquakes, surface bulging, gases emitted as well as other changes that can be monitored by scientists.

Review Questions

1. What are the two basic types of volcanic eruptions?
2. Several hundred years ago, a volcano erupted near the city of Pompeii. Archaeologists have found the remains of people embracing each other, suffocated by ash and rock that covered everything. What type of eruption must have this been?
3. 
4. What is pyroclastic material?
5. Name three liquids that have low viscosity and three that have high viscosity.
6. What is the difference between a magma chamber and a mantle plume?
7. The boiling point of water is 100°C. Why might water make an eruption more explosive?

8. What are three names for non-explosive lava?
9. What factors are considered in predicting volcanic eruptions?
10. Why is predicting volcanoes so important?
11. Given that astronomers are far away from the subjects they study, what evidence might they look for to determine the composition of a planet on which a volcano is found?

Further Reading / Supplemental Links

- http://www.usgs.gov/
- http://www.learner.org/channel/courses/essential/earthspace/session4/closer1.html
- http://www.wikipedia.org/

Vocabulary

active volcano A volcano that is currently erupting or just about to erupt.

dormant volcano A volcano that is not currently erupting, but that has erupted in the recorded past.

effusive eruption A relatively gentle, non-explosive volcanic eruption.

eruption The release of magma onto the Earth's surface. Usually an eruption is accompanied by the release of gases as well.

explosive eruption A volcanic eruption that releases large amounts of gas, so that magma is violently thrown up into the air.

extinct volcano A volcano that has not erupted in recorded history, and is considered unlikely to erupt again.

magma chamber A region within Earth surrounded by solid rock and containing magma.

pyroclast A rock made up of fragments of volcanic rock thrown into the air by volcanic eruptions.

viscosity The "thickness" or "stickiness" of a liquid. The more viscous a liquid is, the harder it will be for the liquid to flow.

Points to Consider

- What types of evidence do you think would tell scientists whether an ancient volcanic eruption was explosive or non-explosive?
- Are all volcanoes shaped like tall mountains with a crater on the peak?
- What do you think is the origin of the names A'a and Pāhoehoe?
- Earthquakes do not always indicate that a volcano is going to erupt. What factors about an earthquake might indicate a relationship to a volcanic eruption?

8.3 Types of Volcanoes

Lesson Objectives

- Describe the basic shapes of volcanoes.
- Compare the features of volcanoes.
- Describe the stages in the formation of volcanoes.

Introduction

When most people think of volcanoes, they think of a tall mountain with a crater on the top, maybe a little snow at the summit and some trees scattered around the base. There are many volcanoes like this, but volcanoes exist in many other forms as well. Each type of volcano has characteristic features that distinguish it from other types. Volcanoes differ in appearance because of the composition of their magma and the processes that originally created them.

Types of Volcanoes

The tall cone shape you usually think of when you think of a volcano describes a composite volcano, one common form of volcanoes. Other types of volcanoes include the shield volcano, the cinder cone, and the supervolcano.

Composite Volcanoes

The picture above shows Mt. Fuji, a classic example of the composite volcano (**Figure** 8.21). This is the type of volcano many people think of when they imagine volcanoes. Composite volcanoes have broad bases and sides that get steeper and steeper as you get closer to the top. These volcanoes frequently have a large crater at the top created during its last eruption.

Figure 8.21: Mt. Fuji is a dormant composite volcano that is the highest mountain in Japan. (10)

Composite volcanoes are also called stratovolcanoes because of the alternating layers, or **strata,** of which they are made (**Figure** 8.22). The magma that creates stratovolcanoes tends to be more viscous, or thick. Viscous lava creates greater pressure which, in turn, tends to create explosive eruptions. In addition, the viscous lava cannot travel far down the sides of the volcano before it solidifies. This viscous lava thus creates steep sides on stratovolcanoes.

When a stratovolcano erupts, it ejects a great deal of pyroclastic material into the air, which then settles back down on the Earth. After an initial explosion, lava then flows from the volcano creating a second layer of material. As these layers solidify, they create alternating levels, or strata, of material. Ash from the volcanic eruption is also present between the lava layers along the edge of the volcano. Composite volcanoes are common along the Pacific Ring of Fire and other major tectonic plate boundaries where the presence of water in the magma chamber creates explosive eruptions.

Shield Volcanoes

Shield volcanoes get their name from their shape—a huge shield laid on its side. **Figure** 8.23 shows the Mauna Loa Volcano. You can see that shield volcanoes do not have the steep mountainous sides of composite volcanoes. They have a very wide base and are much flatter on the top than composite volcano. Although they are not steep, they may be very large. The Mauna Loa Volcano has a diameter of over 112 kilometers (70 miles) and forms a significant part of the island of Hawaii. The Mauna Kea Volcano, also in Hawaii, is another

Figure 8.22: A composite or stratovolcano is created by many levels of alternating materials. (15)

Figure 8.23: The Mauna Loa Volcano in Hawaii is the largest shield volcano on Earth. (21)

shield volcano that is over ten kilometers (6 miles) high from its base below sea level to its peak.

Shield volcanoes are more common at spreading centers or volcanic hot spots in the middle of tectonic plates (**Figure** 8.24). The magma that creates shield volcanoes is less viscous, so it flows much more easily. For this reason, the eruptions of shield volcanoes are non-explosive. In addition, the less viscous lava spreads out more, which makes shield volcanoes much larger and flatter than stratovolcanoes. Although shield volcanoes are built by many layers over time, the composition of the layers do not alternate between ash and lava, as they do in stratovolcanoes.

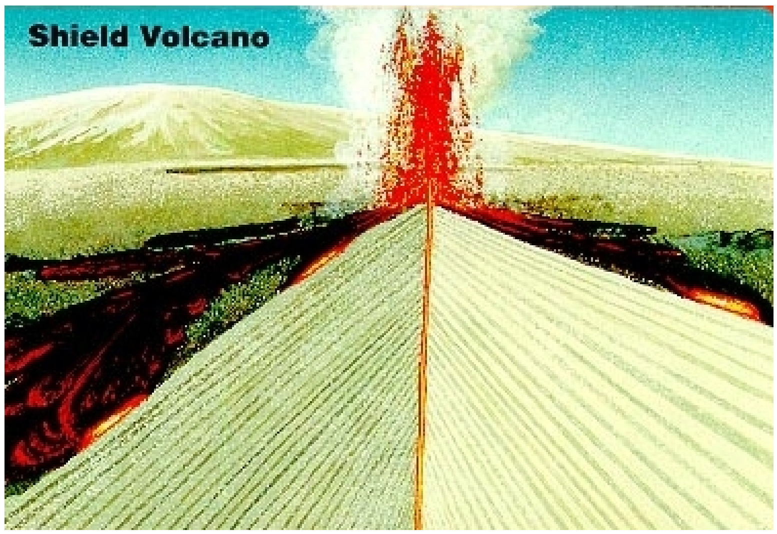

Figure 8.24: A shield volcano is built by layers of more fluid lava that spreads out over broad areas. (2)

Cinder Cones

Cinder cones are both the most common type of volcano and also the smallest. The cinder cone resembles a composite volcano but on a much smaller scale. They rarely reach even 300 meters in height but have even steeper sides than a composite volcano. They usually have a crater at the summit. Cinder cones are composed of small fragments of rock piled on top of one another. These volcanoes usually do not produce streams of lava.

In 1943, a farmer in Mexico witnessed the first eruption of a cinder cone in his field (**Figure** 8.25). Within a year, the cinder cone Paricutín grew to 336 meters high. By 1952, it grew to a peak of 424 meters tall, and then stopped erupting. This rapid growth and single eruption cycle is characteristic of cinder cones. For this reason, cinder cones do not reach the sizes of stratovolcanoes or shield volcanoes. Oftentimes, cinder cones appear near larger volcanoes, but they also may be found away from all other volcanoes, as was the case with Paricutín.

The exact composition of a cinder cone depends on the composition of the lava ejected from the Earth.

Figure 8.25: Paricutín erupting in 1943, when it first formed. Cinder cones like this one rarely reach even 300 meters high. (14)

Supervolcanoes

In certain areas of the world, huge **calderas** have been found to be the remains of volcanic eruptions of enormous scale (**Figure** 8.26). These calderas are volcanic features that are formed by the collapse of a huge amount of land due to the powerful eruptions. Caldera

Figure 8.26: The caldera at Santorini in Greece is so large that its circular shape can only be seen by satellite. (20)

comes from Latin word, meaning cauldron. Calderas are generally circular shaped geographic formations like the picture in figure 6. These are not singular mountains but entire geographical areas. Yellowstone National Park in Wyoming is another caldera that has blown about a hundred times in the last 16 million years.

Supervolcanoes represent the most dangerous type of volcano. An eruption from a supervolcano could change life on Earth as we know it for many years. Supervolcanoes were not even accepted in volcanology until this millennium. Many supervolcano eruptions are thought to have occurred, the most recent in New Zealand less than 2000 years ago. That explosion was thought to have ejected about 100 cubic kilometers of material. A supervolcano eruption near what is now Colorado was thought to have let loose over 5,000 cubic kilometers of material millions of years ago. In comparison, the Mt. Saint Helens eruption ejected about 1 cubic kilometer of material.

The eruptions from supervolcanoes can be so large that the ash ejected into the air blocks the Sun and lowers the temperature on the entire planet. The lowered temperatures caused by these eruptions is called a volcanic winter. A supervolcano eruption at Lake Toba in northern Sumatra may have annihilated about 60% of the world's human population about 75,000 years ago. One can only imagine how such a huge eruption would change the world in modern times.

The largest supervolcano in North America is Yellowstone, which had three super eruptions at 2.1 million, 1.3 million and 640,000 years ago, and much more recent smaller (but still enormous) eruptions. Long Valley caldera, south of Mono Lake in California, is the second largest supervolcano in North America, erupting extremely hot and explosive rhyolite around 700,000 years ago. An earthquake swarm in 1980 alerted geologists to the possibility of another eruption in the future, but the timing of such an event is unknown.

Supervolcanoes are a fairly new idea so the exact cause of supervolcano eruptions is still debated. However, scientists believe that an entire and very large magma chamber erupts in a catastrophic explosion. This enormous eruption creates a huge hole or caldera where the surface area collapses.

Lesson Summary

- Composite cones, shield volcanoes, cinder cones and supervolcanoes are some of the types of volcanoes formed.
- Composite cones are tall, cone shaped volcanoes that produce explosive eruptions.
- Shield volcanoes form very large, gently sloped volcanoes with a wide base.
- Cinder cones are the smallest volcanic landform. They are formed from accumulation of many small fragments of ejected material.
- A caldera forms when an explosive eruption leaves a large crater when the mountain blows apart.
- Supervolcanoes are tremendously devastating types of volcanoes that could destroy

large areas when they erupt.

Review Questions

1. Rank the four types of volcanoes in order from smallest to largest in diameter.
2. What factor is most important in determining the type of volcano formed in a given area?
3. Which type of volcano is most common?
4. Why is it that pahoehoe and a'a lava are more frequent in shield volcanoes than in composite volcanoes?
5. Why do you think that cinder cones are short-lived?
6. If supervolcanoes are so big, why do you think it took so long for scientists to discover them?

Vocabulary

caldera Circular-shaped geographic features formed from a massive eruption of an ancient volcano, and the subsequent collapse of the volcano back into the ground.

cinder cone A smaller volcano that grows rapidly but only erupts over a short period of the time. Cinder cones are composed of small rock fragments piled on top of one another. They rarely are more than 300 m in height.

composite volcano A volcano with a broad base, steep sides, and often a crater at the top. The volcano is composed of alternating layers of ash and lava flows. Also called a stratovolcano.

strata Layers of rock that are similar in composition to one another.

supervolcano A massive volcanic eruption that is rare but incredibly powerful. Thousands of cubic kilometers of matter can be ejected, and the dust and ash from their eruption can cool the world's climate for years.

Points to Consider

- Composite volcanoes and volcanic cones usually have craters on the top. Why are the craters not always circular, but sometimes "U" or horseshoe-shaped?
- A shield volcano is relatively flat, and a composite volcano is relatively steep because of the type of magma that creates them. What process might create a volcano that is more steep than a shield volcano but not as steep as a composite volcano?

- Some people have theorized that if a huge asteroid hits the Earth, the results would be catastrophic. How might an asteroid impact and a supervolcano eruption be similar?

8.4 Volcanic Landforms and Geothermal Activity

Lesson Objectives

- List and describe landforms created by lava.
- Explain how magma creates different landforms.
- Describe the processes that create hot springs and geysers.

Introduction

As you know, magma is molten rock found beneath the Earth's surface. Sometimes, it appears at the surface of the Earth as lava after moving through a volcano. At other times, magma does not come to the surface, but stays underground. In both cases, the magma eventually solidifies and the resulting rocks and formations are igneous. The rocks that solidify beneath the ground are called **intrusive** rocks, while those that solidify above the surface are called **extrusive** rocks. Extrusive rocks are sometimes small rocks that you can hold in your hand. At other times, entire landforms are created when lava flows onto the surface. Intrusive rocks do not always remain hidden below the surface. They can appear on the surface when rocks that once covered them are eroded away, exposing the intrusive igneous rock. Hot springs and geysers are some more examples of surface features related to igneous rock.

Landforms from Lava

The most obvious landforms created by lava are volcanoes. Volcanoes, of course, are the places where lava comes to the surface. As already discussed, volcanoes come in many forms, most commonly as cinder cones, stratovolcanoes, and shield volcanoes. However, lava can create other notable landforms, as described below.

Lava Domes

When lava is fairly viscous, it is thick and flows slowly. Although it might not be so viscous that it causes an explosive eruption, it can create a large sort of round "blob" or a **lava dome.** Because it is so thick, it does not flow far from the vent from which it came. In fact, lava flows often make mounds right in the middle of craters at the top of volcanoes (**Figure** 8.27 and **Figure** 8.28).

Figure 8.27: Lava domes are large, round landforms created by thick lava that does not travel far from the vent. (12)

Figure 8.28: Sometimes lava domes are formed in the crater of composite volcanoes. This lava dome is forming in the crater of Mt. St. Helens in Washington State. (28)

Plateaus

A **lava plateau** is caused by a large amount of less viscous lava that flows over a large area. When it solidifies, it creates a large, flat surface of igneous rock. Some plateaus are huge, like the Columbia Plateau in Washington, Oregon, and Idaho that covers over 161,000 square kilometers (63,000 square miles).

Land Area

Another important land formation created by lava is islands. The Hawaiian Islands are formed from solidified lava from shield volcanoes that have grown over the last 5 million years (**Figure** 8.29). The land area grows as lava continues to solidify on the coast or emerges from beneath the water.

Figure 8.29: Solidified lava flows created the island of Hawaii. (18)

Landforms from Magma

Of course, not all magma reaches the surface. Sometimes magma stays beneath the ground where it solidifies. These formations are called **intrusions** (**Figure** 8.30). Because they form underground, they only become land formations if they arrive at the surface of the Earth. This occurs because of weathering, erosion and plate tectonics. In other words, when tectonic plates collide, they create mountain ranges where one plate is lifted in a subduction zone. This lifting (which occurs at a rate of centimeters per year) and subsequent erosion can eventually uncover intrusive rock formations. As erosion removes the topmost rocks and soil, solidified magma is exposed in the same form in which it cooled and solidified many years before.

Figure 8.30: Devil's Tower in Wyoming is a huge rock formation that was once magma that cooled within a volcano. It rises to nearly 400 meters from its base. (29)

Hot Springs and Geysers

Beneath the surface of the Earth, water works its way through porous rocks or soil. Most caves, for example, are results of water's erosion of the ground. At times, that water crosses paths with volcanic activity. The same heat that melts rock into lava heats the water beneath the surface. If the water makes its way to the surface, it may emerge as either a hot spring or a geyser.

Hot Springs

When that water comes to the surface under regular pressure, it creates a **hot spring** (**Figure** 8.31). A hot spring is a crack in the Earth through which water reaches the surface, after being heated below the ground. Many people disagree on the exact definition of a hot spring. However, everyone agrees that the water's temperature is higher than normal. The water in hot springs can even reach temperatures in the hundreds of degrees Celsius beneath the surface. Most hot springs do not reach those great temperatures. In fact, many hot springs are used by people as natural hot tubs. Many people believe that hot springs hold curative properties. Hot springs are found all over the world, even in Antarctica!

Geysers

Like hot springs, geysers are created by water that is heated beneath the Earth's surface. When water is both superheated by magma and flows through a narrow passageway un-

Figure 8.31: Even some animals enjoy relaxing in nature's hot tubs. (7)

derground, the environment becomes ideal for a geyser. The narrow passageway traps the heated water underground, where heat and pressure continue to build. Sooner or later, the pressure grows so great that the superheated water bursts out onto the surface. This explosion is called a **geyser**. There are only a few areas in the world where the conditions are right for the formation of geysers. About 1,000 geysers exist worldwide and about half of those are found in the United States of America. Perhaps the most famous geyser is Old Faithful, which erupts every 60 to 70 minutes in a plume of hot water nearly 60 meters in the air. It is rare for a geyser to erupt regularly, which contributes to Old Faithful's fame (**Figure** 8.32).

Lesson Summary

- Very thick lava that doesn't travel very far can produce lava domes at or near the Earth's surface or even within a volcano.
- Lava plateaus form from large lava flows that spread out over large areas.
- Many islands are formed from volcanoes.
- Magma can also cool and crystallize below the Earth's surface forming igneous intrusions.
- When magma heats groundwater, it can form hot springs and geysers.

Review Questions

1. What is the difference between intrusive and extrusive rocks?

Figure 8.32: Old Faithful Geyser in Yellowstone National Park during an eruption. (17)

2. What are four different landforms created by lava?
3. What is the major difference between hot springs and geysers?
4. The geyser called Old Faithful has been erupting for perhaps hundreds of years. One day, it could stop. Why might geysers completely stop erupting?
5. After earthquakes, hot springs sometimes stop bubbling, and new hot springs form. Why might this be?

Vocabulary

intrusive Describing a volcanic rock that cooled underground. Intrusive rocks contain large mineral crystals that are visible to the naked eye.

extrusive Describing a volcanic rock that cooled at the earth's surface. Extrusive rocks have small crystals, and may contain air bubbles.

lava dome A dome-shaped plug of viscous lava that cools near the vent of a volcano.

intrusion A rock mass formed by magma solidifying underground.

hot spring A stream of hot water that flows out of the ground continuously.

geyser A fountain of hot water and steam that shoots into the air at either regular or random intervals. The water in a geyser encounters some sort of constriction underground, which forces pressure to build up in the water, eventually causing the geyser to erupt.

Points to Consider

- What might the Earth look like if there were no tectonic plates? Can you think of any planets or satellites (moons) that may not have tectonic plates? How is their surface different from that of the Earth?
- What kind of land formations have you seen that may have been created by volcanic activity? Were the formations made of extrusive or intrusive rock?
- Water is not the only material that can be ejected from geysers and hot springs. Consider the composition of the Earth's crust. What other materials might be ejected from geysers and hot springs?

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Chapter 9

Weathering and Formation of Soil

9.1 Weathering

Lesson Objectives

- Define mechanical and chemical weathering.
- Discuss agents of weathering.
- Give examples of each type of weathering.

What is Weathering?

Weathering is the process that changes solid rock into **sediments.** Geologists use the word sediment to describe all different sizes of rock particles. Sediment includes really large pieces of rock, like boulders or gravel, but it also includes sand and much smaller particles, called silt and clay. In the process of weathering, rock is disintegrated and decomposed. Disintegration of rock happens as rock is broken into pieces. Once the pieces are separated from the rocks, **erosion** is the process that moves those pieces. Gravity is one way that pieces of rock move, as broken pieces of rock fall or tumble from high places to lower ones. Gravity causes large and small pieces to fall from cliffs, as well as moving water in rivers and streams from mountaintops to the ocean. Wind and glaciers also move pieces of rock from one place to another. Wind moves sand sized and smaller pieces of rock through the air. Glaciers can move all sizes of particles, from extremely large boulders to the tiniest fragments.

Weathering happens at the Earth's surface. When most rocks form, they are forming at very high temperatures and pressures. This is a very different environment than the low temperatures and pressures at Earth's surface. When rocks reach Earth's surface, weathering causes them to change form. The new form will include minerals that are stable at the low temperatures and pressures of Earth's surface. So while powerful forces on Earth, such as those resulting from plate tectonics, work to build huge mountains like the Himalayas or majestic volcanoes like Mt Fuji, the forces of weathering gradually wear away rocks, changing once tall mountains into hills and even plains. The Appalachian Mountains along the east coast of North America were once as tall as the Himalayas! So what happened?

No human being can watch for millions of years as mountains are slowly built, nor can we watch as those same mountains gradually wear away. However you probably have been able to ride your bike or walk along a brand new sidewalk or road. What do you experience? The new road or sidewalk is smooth and even. If it was made well, there won't be any cracks or bumps. Does that smooth surface stay that way? Certainly over millions of years, it will completely disappear, but we don't have to wait that long. If you live in a part of the world that has cold winters, you may only have to wait one year to start seeing changes. We will talk next about what types of weathering change that brand new, smooth and even sidewalk into areas that are rough or cracked, chipped or buckled (**Figure** 9.1).

Figure 9.1: You can see the once smooth road surface has cracks and fractures, plus a large pothole. (11)

Mechanical Weathering

Mechanical weathering (also called physical weathering) is the breaking of rock into smaller pieces. These smaller pieces will be just like the bigger rock, the pieces will just be smaller. That means the rock has been changed mechanically (or physically) without changing its composition. The smaller pieces will have the same minerals, in just the same proportions as the original rock. You could actually use the expression, 'A chip off the old block' to describe mechanical weathering! The main agents of mechanical weathering are water, wind, ice, and gravity. You will see how each of these works to break rock into smaller pieces.

There are two main ways that rocks can break apart into smaller pieces. The way that is most common in cold climates is called **ice wedging.** Ice wedging is the main form of mechanical weathering in any climate that regularly cycles above and below the freezing point (**Figure** 9.2). Some places where this happens include Earth's polar regions and mid latitudes. It also happens in the colder climates of higher elevations, like mountainous regions.

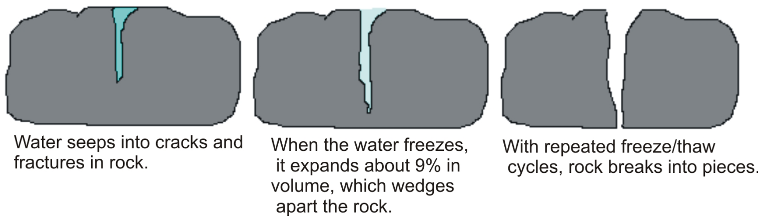

Figure 9.2: Water seeps into cracks and fractures in rock. As it freezes, it expands which wedges the rock apart. (1)

This is how it works. When water changes from a liquid into a solid (ice), it increases in volume. This is a very unusual property. Most substances contract (get smaller) as they change from a liquid to a solid, but water does just the opposite. You may have already experienced this if you ever filled an ice cube tray all the way to the top with water and then put it into the freezer. The ice cubes will be much larger than the amount of water you first put in. You may have also made the mistake of putting your favorite soda into the freezer to cool it down quickly. If you leave your drink in the freezer too long, it will expand so much that it bends or pops the can. Ice wedging happens for the same reason. Water works its way into cracks and fractures in rock, and then expands as that water freezes. The ice takes up more space than the water did, which wedges the rock apart, physically breaking the rock into pieces. Ice wedging breaks apart so much rock that you will find large piles of broken rock at the base of a cliff or mountain, as broken pieces separate and tumble down its sides. Ice wedging will work quickly, breaking apart lots of rock in areas that go above and below the freezing point every night and day, and also in areas that cycle with the seasons.

Abrasion is another form of mechanical weathering. Abrasion can happen anywhere. All that is needed is one rock bumping against another rock. Gravity can cause abrasion as a rock tumbles down a mountainside or cliff. Moving water causes abrasion as particles carried in the water collide and bump against one another. Strong winds can pick up pieces of sand and blast surfaces with those sand grains. Finally, the ice in glaciers carries many bits and pieces of rock. As the glacier moves, pieces of rock embedded in the ice scrape against the rocks below. Broken pieces of rock tumbling down a mountain stream or tossed about by waves crashing onto the shore, will become smooth and rounded as abrasions smooth and round the sharp or jagged edges. If you have ever collected beach glass or cobbles from a stream, you have benefited from the work of abrasion.

Scientists talk about a few other types of mechanical weathering but ice wedging and abrasion are the two most important types. Without these two types of mechanical weathering, very little rock would break apart and that would slow down the rate of chemical weathering as well. Sometimes biological elements can do the work of mechanical weathering. This could happen slowly as a plant's roots grow into a crack or fracture in rock and gradually grow larger, wedging open the crack. Burrowing animals can also break apart rock as they dig for food or to make living spaces for themselves. Today, of course, human beings do quite a bit of mechanical weathering, whenever we dig or blast into rock to build homes, roads, subways, or to quarry stone for construction or other uses.

Actually whenever there is mechanical weathering, it increases the rate of chemical weathering. This happens because as rock breaks into smaller pieces, the surface area of the pieces increases (**Figure** 9.3). With more surfaces exposed, there are more places for chemical weathering to occur. Let's say you wanted to make some hot chocolate on a cold day. You can imagine how hard it would be to get a big chunk of chocolate to dissolve in your milk or hot water. Maybe you could make hot chocolate from some smaller pieces like chocolate chips, but it is much easier to add a powder to your milk. This is because the smaller the pieces are, the more surface area they have and the easier it is to dissolve in the milk.

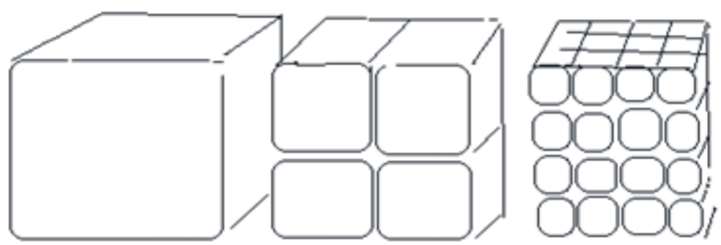

Figure 9.3: As rock breaks into smaller pieces, overall surface area increases. (7)

Salt weathering of building stone on the island of Gozo, Malta.

Chemical Weathering

Another important type of weathering that happens on the Earth's surface is **chemical weathering**. Chemical weathering is different than mechanical weathering because with this type of weathering, rock is changed, not just in size of pieces, but changed in composition. This means that one type of mineral changes into a different mineral. The reason chemical weathering happens is that most minerals form at high pressure or high temperatures, deep within the Earth. When rocks reach the Earth's surface, they are now at very low temperatures and pressures. This is a very different environment from the one in which they formed. The environment at Earth's surface is so different that these minerals are no longer stable. That's where chemical weathering begins. Minerals formed deep within the Earth must change to minerals that are stable at Earth's surface. Chemical weathering is important because it starts the process of changing solid rock into the soil we need to grow food and for the plants we need for our clothing and medicine. The way that chemical weathering works is through chemical reactions that cause changes in the rock.

There are many types of chemical weathering because there are many agents of chemical weathering. You probably remember that mechanical weathering is caused by several agents, such as water, wind, ice,and gravity. Well, water is also an agent of chemical weathering, so that makes it a double agent! Two other important agents of chemical weathering are carbon dioxide and oxygen. We will talk about each of these one at a time.

The minerals that make up most of the Earth's crust are called silicate minerals. These minerals are mostly made of just eight elements; oxygen (O), silicon (Si), aluminum (Al), iron (Fe), magnesium (Mg), calcium (Ca), potassium (K) and sodium (Na). When chemical weathering occurs, the elements that make up the minerals react to form new minerals. The minerals that form at the lowest temperatures and pressures (closest to the situation at the Earth's surface) are the most stable while minerals that form from very hot magmas or at very high pressures are the least stable. The elements sodium, calcium, potassium and magnesium actually dissolve easily in water. Iron reacts with oxygen, which leaves atoms of silicon, oxygen and aluminum to combine to form new minerals, like clay minerals.

Water is an amazing molecule. It has a very simple chemical formula, H_2O, which means it is made of just two hydrogen atoms bonded to one oxygen atom. Even though it is simple to remember, water is pretty remarkable in terms of all the things it can do. Water is an excellent solvent. The way that a water molecule joins together allows water to attract lots of other elements, separate them from their compounds and dissolve them. Water is such a good solvent that some types of rock can actually completely dissolve in water. Other minerals change by adding water into their structure.

Hydrolysis is a chemical reaction between a mineral and water. When this reaction takes place, water itself separates into ions. These ions grab onto other ions, dissolving them in water. As the dissolved elements are carried away, we say that these elements have been **leached.** Through hydrolysis, a mineral like potassium feldspar is changed into a clay mineral. Once clay minerals have formed, they are stable at the Earth's surface.

Carbon dioxide (CO_2) combines with water as raindrops fall through the air in our atmosphere. This makes a weak acid, called carbonic acid. This happens so often that carbonic acid is a very common, weak acid found in nature. This acid works to dissolve rock. It also slowly changes the paint on a new car or eats away at sculptures and monuments. The normal situation can be made worse when we add pollutants to the air. Any time we burn any fossil fuel, it adds nitrous oxide to the air. When we burn coal rich in sulfur, it adds sulfur dioxide to the air. As nitrous oxide and sulfur dioxide react with water, it forms nitric acid and sulfuric acid. These are the two main components of acid rain. Acid rain accelerates chemical weathering.

Oxidation is the type of chemical reaction that happens when oxygen reacts with elements at the Earth's surface. Oxygen is very strongly chemically reactive. The type of oxidation that you are probably most familiar with produces rust when iron reacts with oxygen (**Figure** 9.4). Many minerals are rich in iron. They break down as the iron oxidizes, forming new compounds. Iron oxide produces the red color in soils. Chemical weathering can also be contributed to by plants and animals. As plant roots take in soluble ions as nutrients, certain elements are exchanged. Plant roots and bacterial decay use carbon dioxide in the process of respiration.

Differential Weathering

Rates of weathering depend on several factors. Different types of rocks weather at different rates. Certain types of rock, like granite, are very resistant to weathering. Igneous rocks tend to weather slowly because it is hard for water to penetrate them. Other types of rock, like limestone and marble are easily weathered because they dissolve easily in weak acids. More resistant rocks remain at the surface and form ridges or hills. Devil's Tower in Wyoming is an interesting example of how different types of rock weather at different rates (**Figure** 9.5). As the softer materials of the surrounding rocks were worn away, the resistant center of the volcano remained behind. Different minerals also weather at different rates. Some minerals completely dissolve in water. As less resistant minerals dissolve away, a rock's

Figure 9.4: When iron rich minerals oxidize, they produce the familiar red color found in rust. (8)

surface becomes pitted and rough. When a less resistant mineral dissolves, more resistant mineral grains are released from the rock.

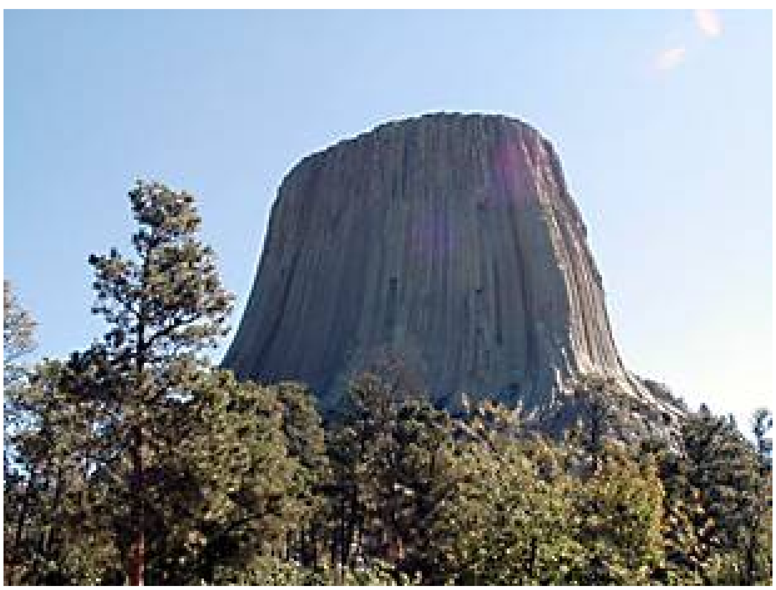

Figure 9.5: Devil's Tower is an amazing example of differential weathering. All that remains of the volcano today is this central plug of resistant lava that forms the tower. (10)

Most importantly, the climate of a region influences weathering. Climate is determined by the temperature of a region plus the amount of rainfall it receives. As the amount of precipitation increases, so does the rate of solution and the number of chemical reactions. In general, as the amount of rainfall increases, so does the degree of weathering. Remember that water is an agent of both mechanical and chemical weathering, so when water is not available, the rate of weathering slows tremendously. Two amazing examples of preservation include mummification and freezing. Both of these situations occur in the absence of liquid water. Therefore a dry climate will produce the lowest rate of weathering, followed by a very cold climate, regardless of the amount of rainfall it receives. The rates of highest weathering would occur in a wet climate that is also warm or hot. As the temperature of a region increases, so does the rate of chemical reactions. For each 10°C increase in average temperature, the rate of chemical reactions doubles. The warmer a climate is, the more types of vegetation it will have and the greater the rate of biological weathering. This happens because plants and bacteria grow and multiply faster in warmer temperatures. If you want an easy way to remember these examples, think about where you would put your sandwich if you want it to stay fresh for a while. How quickly does it go bad in your lunch box? Where would you put food from the grocery store if you wanted to save it for a week or more?

Some resources are actually concentrated for us by the actions of weathering. In tropical climates, intense chemical weathering carries away all soluble minerals, leaving behind just the least soluble components. The aluminum oxide, bauxite forms this way and is our main source of ore for producing aluminum. The actions of moving water can also concentrate heavier minerals, like gold. This process fueled the gold rush out west in North America in the 1800's.

Lesson Summary

- Mechanical weathering breaks existing rock into smaller pieces without changing the composition of the rock.
- Ice wedging and abrasion are two important processes of mechanical weathering.
- The main agents of mechanical weathering are moving water, wind, glacial ice and gravity.
- Chemical weathering decomposes or breaks down existing rock, forming new minerals that are stable at the Earth's surface.
- Water, carbon dioxide and oxygen are important agents of chemical weathering.
- Different types of rocks weather at different rates. More resistant types of rocks will remain longer.

Review Questions

1. Name two types of mechanical weathering. Explain how each works to break apart rock.
2. What are three agents of chemical weathering? Give an example of each.

3. What type of climate would likely produce the greatest degree of weathering? Explain.
4. Would a smooth even surface weather faster than an uneven, broken surface?
5. What type of rocks would be best suited to making monuments?

Vocabulary

abrasion A form of mechanical weathering that occurs whenever one rock hits another.

chemical weathering The form of weathering which decomposes rock; minerals that form at high temperatures and pressures change to minerals that are stable at the Earth's surface.

erosion The transport of weathered materials by water, wind, ice or gravity.

hydrolysis Chemical reactions between minerals and water in which hydrogen or hydroxide ions replace the cations in the mineral.

ice wedging The form of mechanical weathering that occurs as water expands as it freezes, wedging apart rock.

leaching The process of removing dissolved minerals as they are carried to lower layers in soil.

mechanical weathering The form of weathering which disintegrates rock; bigger pieces of rock are broken into smaller pieces of the same composition as the original rock.

oxidation A form of chemical weathering in which oxygen reacts with elements; happens when an atom or ion loses an electron.

sediments Bits and pieces of weathered rock; the largest pieces would be gravel or pebbles, then sand, silt, and clay sized particles.

Points to Consider

- What other types of surfaces are affected by weathering other than rock?
- What might the surface of the Earth look like if weathering did not occur on Earth?
- Do you think that you would be alive today if water did not dissolve elements?
- Would the same composition of rock weather the same way in three very different climates?

9.2 Soils

Lesson Objectives

- Discuss why soil is an important resource.
- Describe how soil forms from existing rocks.
- Describe the different textures and components of soil.
- Draw and describe a soil profile.
- Define the three climate related soils: a pedalfer, pedocal and laterite soil.

Characteristics and Importance of Soil

Thank goodness for mechanical and chemical weathering, because without these forces working to breakdown rock we would not have any soil on Earth. It is unlikely that humans would have been able to live on Earth without soil! Your life and the lives of many organisms depend on soil. We get wood, paper, cotton, medicines and even pure water from soil. So soil is a very important resource. Even though it is actually only a very thin layer on Earth's surface over the solid rocks below, it is the place where our atmosphere, hydrosphere, biosphere and the rocks of the Earth meet. Within our soil layer, reactions between solid rock, liquid water and air take place. It is a mistake on our part to disregard this important resource, yet we say things like "soiled" or "dirty" when we talk about ruining something. Our precious soil resource needs to be carefully managed and cared for. If we neglect or abuse the soil we have, it will not remain the renewable resource that we have relied on throughout human existence.

We can think about soil as a living resource or an ecosystem all by itself. Within soil, there are many elements. It is a complex mixture of different materials. Some of them are **inorganic,** like the products of weathered rock, including pebbles, sand, silt and clay particles. There are also bits of **organic materials,** formed from the partial breakdown and decomposition of plants and animals. In general, the pieces of rock and minerals make up about half of the soil, with the other half made of organic materials. In between, in the spaces of soil, there are thousands or even millions of living organisms. Those organisms could be earthworms, ants, bacteria, or fungi, as well as many other types of organisms. In between the solid pieces, there are tiny spaces filled with air and water. In some soils, the organic portion could be entirely missing, such as desert sand. At the other extreme, a soil could be completely organic, such as the materials that make up peat in a bog or swamp. The organic materials are necessary for a soil to be fertile. The organic portion provides the nutrients, like nitrogen, needed for strong plant growth. We will learn about that organic portion in just a bit.

Soil Formation

How well soil forms and what type of soil forms depends on several different factors. Some of these factors are the climate, the original rock the soil formed from, the slope, the amount of time and biological activity. Climate is ultimately the most important factor and will determine the type of soil that forms in a particular region. The climate of a region is principally determined by temperature and the amount of precipitation. This also influences the type of vegetation that grows in the region. We can identify different climates by the types of plants that grow there. Depending on how closely you look, we can divide land areas into many different climate regions (**Figure** 9.6).

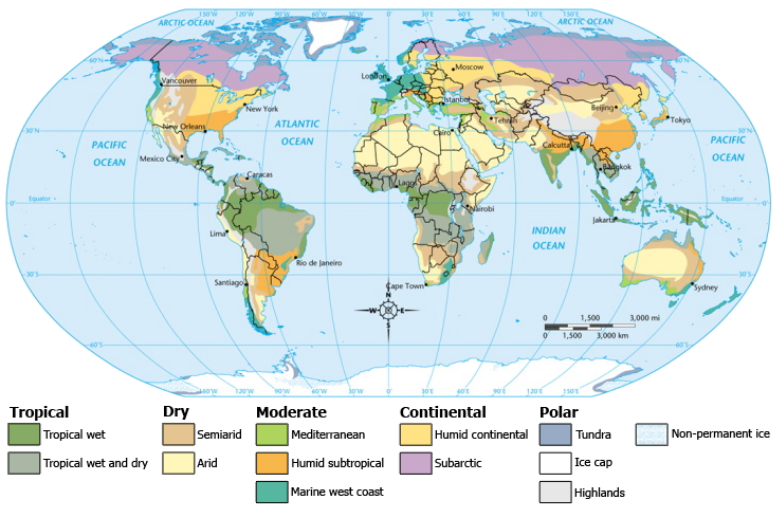

Figure 9.6: Climate is the most important factor in determining the type of soil that will form in a particular area. (13)

Given enough time, even different rock types will produce a similar climate related soil. Climate is such an important factor that even the same type of rock in different climates will produce a different climate related soil. This is true because the rocks on Earth are predominantly composed of eight elements and as rock breaks down, there will mostly be just these eight elements. Surely, if an element is not present in the original rock, then it will also not be present in the soil that forms from it. The amount of precipitation in an area is important because it influences the rate of weathering. The more it rains, the more rainwater passes through the soil and the more it reacts chemically with the particles. Those reactions are most efficient in the top layers of the soil and become less effective as the water continues to percolate through lower layers of soil. The top layers of soil in contact with the freshest water react most. Increased rainfall in a region increases the amount of rock that is dissolved as well as the amount of material carried away by moving water. As materials are carried away, new surfaces are exposed and this also increases the rate of weathering.

The temperature for a region is important too. The rate of chemical reactions increases with higher temperatures. For every 10° C increase in temperature, the rate of chemical reactions doubles. Warmer regions also have more vegetation because plants and bacteria grow and multiply faster. This means that in tropical regions, where temperatures and amounts of rainfall are consistently high, thick soils form with no unstable minerals and therefore no nutrients. Conversely, arid regions produce thin soils, rich in unstable minerals. The rate of soil formation increases with greater amounts of time. The longer the amount of time that soil remains in a particular area, the greater the degree of alteration.

The original rock is the source of the inorganic portion of the soil. Chemical reactions from weathering break down the rock's original minerals into sand, silt and clays. A soil is called a **residual soil** when it forms in place, with the underlying rock breaking down to form the layers of soil that reside above it. Only about one third of the soils in the United States form this way. The rest of the soils form from materials that have been transported in from somewhere else. These soils are called **transported soils.** Glaciers bring bits of rock from far away, depositing the materials they carried as the ice of the glacier melts. Wind and rivers also transport materials from their places of origin. These soils form from the loose particles that have been transported in to a new location and deposited. For transported materials, the rate of soil formation is faster because the transported materials have already been weathered. The closer the materials are to their place of origin, the greater the influence of the original materials. The further those materials move from their origin, the greater the degree of weathering and the influence of the original materials becomes obscured.

Soils thicken as the amount of time available for weathering increases. The warmer the temperatures, the more rainfall and greater amount of time, the thicker the soils will become. Biological activity produces the organic material and nutrients in soil. The partial decay of plant material and animal remains also forms organic acids which in turn increase the rate of soil formation and the rate of weathering. The organic material increases the ability of the soil to hold water, create a soil's structure and enhance its fertility and ability to be cultivated.

The decayed remains of plant and animal life are called **humus.** Humus is an extremely important part of the soil. It coats the mineral grains, binding them together into clumps that then hold the soil together. The humus in soil also increases the porosity and water holding capacity of a soil. Humus helps to buffer rapid changes in soil acidity and helps the soil to hold its nutrients. Decomposing organisms in the soil breakdown the complex organic molecules of plant matter and animal remains to form simpler inorganic molecules that are soluble in water. Bacteria in the soil change atmospheric nitrogen into nitrates.

One indicator of a soil's fertility is its color. Soils that are rich in nitrogen and contain a high percentage of organic materials are usually black or dark brown in color. Soils that are nitrogen poor and low in organic material might be gray or yellow or even red in color.

Soil Texture and Composition

The inorganic portion of soil is made of many different size particles. In addition to many particle sizes, there can be different proportions of each particle size. The combination of these two factors determines some of the properties of the soil. A soil will be very **permeable,** which means that water will flow through it easily, if the spaces between the inorganic particles are large enough and are well connected. Soils that have lots of very small spaces tend to be water holding soils. Clays are an example of a type of soil that holds water. When clay is present in a soil, the soil is heavier and holds together more tightly. Sandy or silty soils are considered 'light' soils because they are permeable, water draining types of soils. When a soil contains a mixture of grain sizes, the soil is called a **loam.** When soil scientists want to precisely determine the soil type, they measure the percentage of sand, silt and clay and plot this information on a triangular diagram, with each type of soil at one corner (**Figure** 9.7).

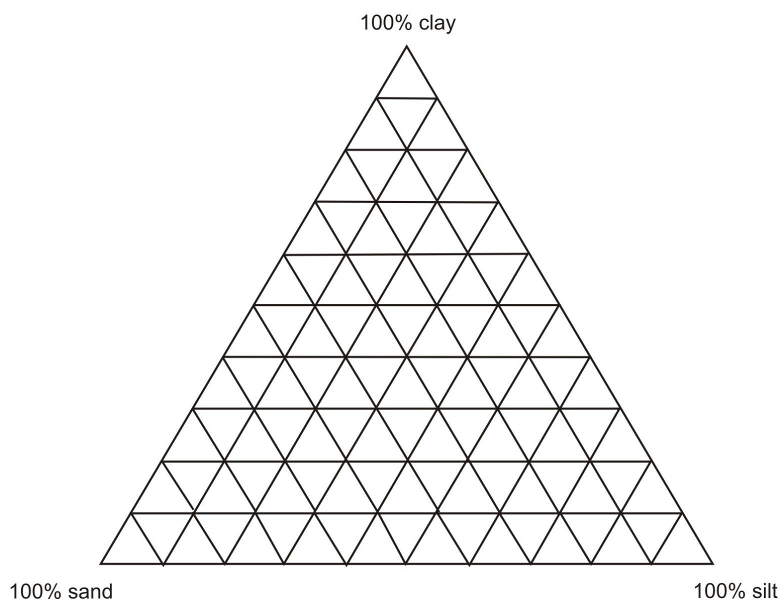

Figure 9.7: Soil texture triangular plot diagram. (4)

Soil scientists use a diagram like this to plot the percentages of sand, silt & clay in a soil. The soil type can then be determined from the location on the diagram. At the top, a soil would be a clay; at the left corner, it would be a sand and at the right corner it would be a silt. Regions in the lower middle with less than 50% clay are called loams.

Soil Horizons and Profiles

A residual soil forms from the underlying bedrock. This happens over many years, as mechanical and chemical weathering slowly change solid rock into soil. The more time available, the greater the degree of alteration that will occur. Perhaps the first changes to bare rock would be cracks or fractures due to mechanical weathering from ice wedging. Then plants like lichens or grasses become established. As more and more layers of material weather, the soil develops **soil horizons,** as each layer becomes progressively altered. The place where the greatest degree of weathering occurs is the top layer. Each successive, lower layer is altered just a little bit less. This is because the first place where water and air come in contact with the soil is at the top. As water moves down through the layers, it is able to do less work to change the soil. If you were able to dig a deep hole into the ground, you could see each of the different layers of soil. All together, these are called a **soil profile.** Each horizon has its own particular set of characteristics (**Figure** 9.8).

Figure 9.8: Soil is an important resource. Each soil horizon is distinctly visible in this photograph. (2)

In the simplest soil profile, a soil is considered to have three horizons. The first horizon is the **top soil,** which is called the A horizon. The topsoil will usually be the darkest layer of the soil, because this is the layer with the highest proportion of organic material. Remember that humus forms from all the plant and animal debris that falls to the ground. This includes branches and twigs, acorns and pine needles as well as waste from animals and fungi. The top soil is the region of most intense biological activity. Many living organisms live within this layer and plants stretch their roots down into this layer. In fact, plant roots are very important to this layer because vegetation helps to hold this layer of soil in place. The top soil layer is usually a layer where minerals that can dissolve and very small particles like clay are absent. This is because clay sized particles get carried to lower layers as water seeps down into the ground. Soluble minerals are missing because they readily dissolve in the fresh water that moves through this layer and are carried down to lower layers of the soil.

The next soil horizon is the **subsoil,** which is called the B horizon. This is the region where soluble minerals and clays accumulate. This layer will be lighter brown in color and more water holding than the top soil, due to the presence of iron and clay minerals. There will be less organic material in this layer. The next layer down, called the C horizon will be a layer of partially altered bedrock. There will be some evidence of weathering in this layer, but pieces of the original rock can still be seen and it would be possible to identify the original type of rock from which this soil formed (**Figure** 9.9).

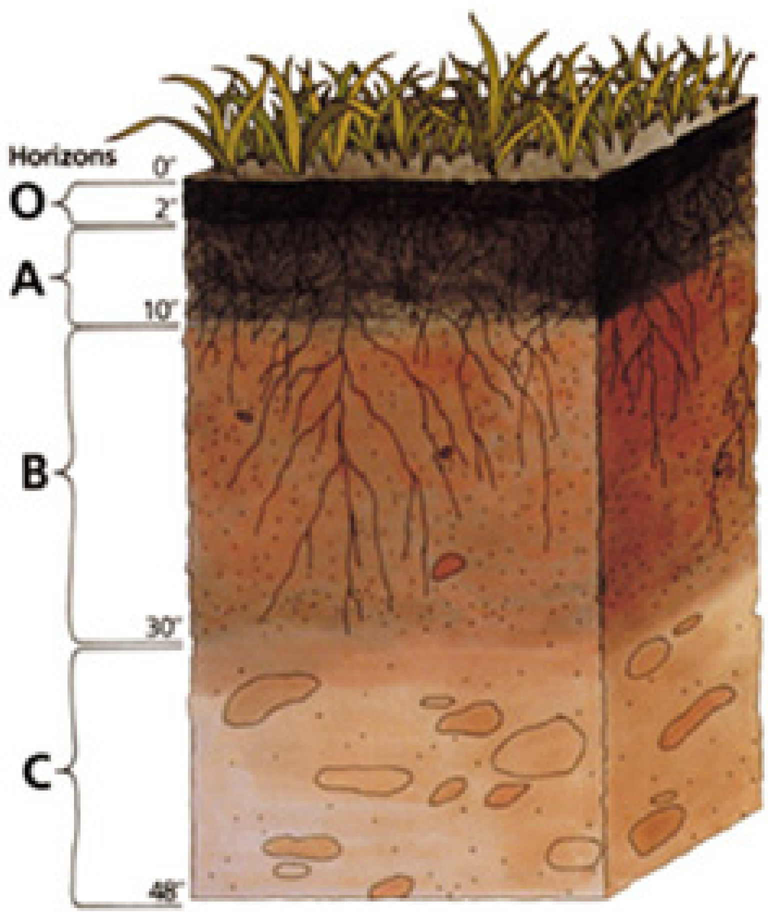

Figure 9.9: A soil profile is the complete set of soil layers. Each layer is called a horizon. (12)

Not all climate regions develop soils, and not all regions develop the same horizons. Some areas develop as many as five or six distinct layers, while others develop only very thin soils or perhaps soil doesn't form well at all.

Types of Soils

If we were to talk to soil scientists, you would learn that there are thousands of types of soil. Soil scientists study each of the many different characteristics of each soil and put them into very specific groups and have many different names for soils. Let's consider a much simpler model that considers just three types of soil. This will help you to understand some of the basic ideas about how the particular climate of an area produces a certain type of soil, but there are many exceptions to what we will learn right now.

Let's consider the type of soil that would form in a region of the world where there are forests of trees that lose their leaves each winter, called **deciduous trees.** In order for trees to grow here, there needs to be lots of rain, at least 65 cm of rainfall per year. Wherever there are trees, there is enough rain to help them grow! The type of soil that forms in a forested area is called a **pedalfer** and this type of soil is common in many areas of the temperate, eastern part of the United States (**Figure** 9.10). The word pedalfer comes from some of the elements that are commonly found in the soil. The element aluminum has the chemical symbol Al and the element iron has the chemical symbol Fe. These two symbols are combined '-al' and '-fe' to make the word ped $-al-fe\ r$. This type of soil is usually a very fertile, dark brown or black soil. It is rich in aluminum clays and iron oxides. Because it rains often in this type of climate, most of the soluble minerals dissolve and are carried away, leaving the less soluble clays and iron oxides behind.

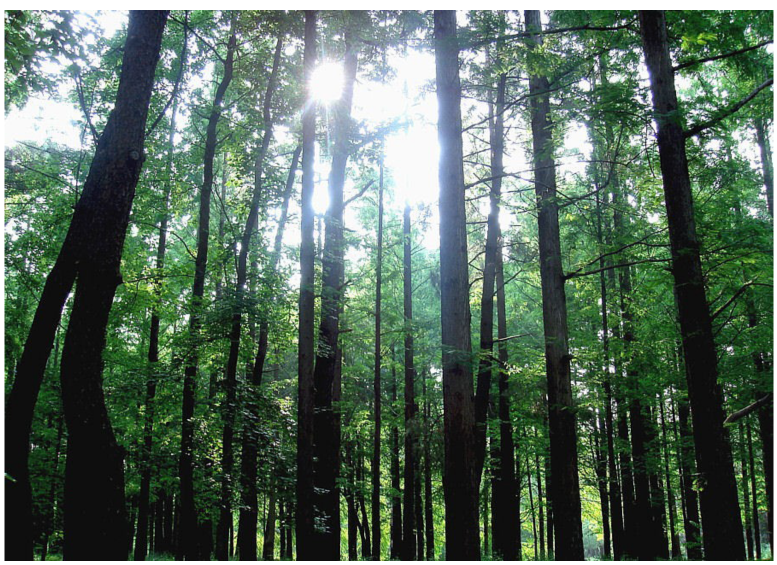

Figure 9.10: A pedalfer is the dark, fertile type of soil that will form in a forested region. (9)

Another type of climate related soil, called a **pedocal,** forms in drier temperate areas where grasslands and brush are the usual types of vegetation (**Figure** 9.11). It rains less than 65 cm per year in these areas, so there is less chemical weathering for these soils. With lower amounts of rainfall, there is less water to dissolve away soluble minerals, so more soluble minerals are present here but fewer clay minerals are produced. With lower rainfall, there is also less vegetation here, so the soils have lower amounts of organic material, making them slightly less fertile types of soils than a pedalfer. A pedo*cal* is named for the calcite enriched layer that forms. Some water begins to move down through the soil layers, but before it gets very far, it begins to evaporate away. Soluble minerals, like calcium carbonate, concentrate in a layer that marks the lowest place that water was able to reach before it evaporated away. This layer is called caliche.

Figure 9.11: A pedocal is the alkaline type of soil that forms in grassland regions (6)

A third type of soil called a **laterite** forms in tropical areas, where rainfall is so intense that it literally rains every day. The tropical rainforest is an example of this type of region (**Figure** 9.12). In these hot, wet tropical regions nutrient poor soils form due to intense chemical weathering. So much weathering happens here that there is practically no humus. All soluble minerals are removed from the soil and all plant nutrients get leached or carried away. What are left behind are the least soluble materials like aluminum and iron oxides. These soils are often red in color from the iron oxides. These soils bake as hard as a brick if they are set out in the sun to dry.

You can probably very quickly name many climates that have not been mentioned here. Each climate will produce a distinctive soil that forms in the particular circumstances found there. Where there is less weathering, soils are thinner but soluble minerals may be present. Where there is intense weathering, soils may be thick but nutrient poor. In any case, soil development takes a very long time. It may take hundreds or even thousands of years to form a good fertile top soil. Soil scientists estimate that in the very best soil forming conditions, soil forms at a rate of about 1mm/year. In poor conditions it may take thousands of years!

Figure 9.12: A laterite is the type of thick, nutrient poor soil that forms in the rainforest. (3)

Soil Conservation

Soil is only a renewable resource if we carefully manage the ways in which we use soil. There are natural cycles of unfortunate events like drought or insect plagues or outbreaks of disease that negatively impact ecosystems and also harm the soil. But there are also many ways in which humans neglect or abuse this important resource. One harmful practice is removing the vegetation that helps to hold soil in place. Sometimes just walking or riding your bike over the same place, will kill the grass that normally grows there. Other times land is deliberately cleared to make way for some other use. The 'lost' soils may be carried away by wind or running water. In many areas of the world, the rate of soil erosion is many times greater than the rate at which it is forming. Soils can also be contaminated if too much salt accumulates in the soil or where pollutants sink into the ground.

Figure 9.13: Organic material can be added to soil to help increase its fertility. (5)

There are many ways that we can protect and preserve our precious resources of soil. There are many ways to help to keep soil in good condition. Adding organic material to the soil in the form of plant or animal waste, like manure or compost, increases the fertility of the soil as well as improving its ability to hold onto water and nutrients (**Figure** 9.13). Inorganic fertilizer can also temporarily increase the fertility of a soil and may be less expensive or time consuming, but won't provide the same long term improvements as organic materials. Agricultural practices like rotating crops, alternating the types of crops planted in each row and planting nutrient rich cover crops all help to keep soil more fertile as it is used season after season. Planting trees as windbreaks, plowing along contours of the field or building terraces into steeper slopes will all help to hold soil in place (**Figure** 9.14). No till or low tillage farming helps to keep soil in place by disturbing the ground as little as possible when planting.

Figure 9.14: Steep slopes can be terraced to make level planting areas and decrease surface water runoff and erosion. (14)

Lesson Summary

- Soil is an important resource. Life on Earth could not exist as it does today without soil.
- The type of soil that forms depends mostly on climate but to a lesser extent on original parent rock material.
- Soil texture and composition plus the amount of organic material in a soil determine a soil's qualities and fertility.
- Given enough time, existing rock will produce layers within the soil, called a soil profile.
- Ultimately, the climate of a particular region will produce a unique type of soil for that climate.

Review Questions

1. Describe at least two ways in which soil is a living resource.
2. Name two factors that influence soil formation.
3. Which region of a soil profiles reacts the most?
4. Is the soil in your back yard most likely a residual soil or a transported soil? How could you check?
5. Name several advantages to adding humus to the soil.
6. What are three soil horizons? Describe the characteristics of each.
7. Name three climate related soils. Describe the climate and vegetation that occurs in the area where each forms.
8. Where would you choose to buy land for a farm if you wanted fertile soil and did not want to have to irrigate your crops?

Vocabulary

deciduous trees Trees that lose their leaves once a year.

humus The partially decayed remains of plants and animals; forms the organic portion of soil.

inorganic Parts of the soil which do not come from living organisms; the rock and mineral portion of the soil.

laterite Nutrient poor, red, tropical soil which forms in a region with rainforest vegetation.

loam Soil texture which forms from a roughly equal combination of sand, silt and clay.

organic Generally considered to mean components of the soil which come from living organisms.

pedalfer Fertile, dark soil which forms in mid latitude, forested regions.

pedocal Slightly less fertile soils which forms in drier, grassland regions.

permeable Describes a type of soil which allows water to move through it easily.

residual soil Soil that forms from the bedrock upon which it resides or lies.

soil horizon An individual layer of a complete soil profile; examples include A, B & C horizons.

soil profile The entire set of soil layers or horizons for a particular soil.

subsoil The B horizon of a soil; the zone where iron oxides and clay minerals accumulate.

topsoil The A horizon of a soil; most fertile layer of soil where humus, plant roots & living organisms are found.

transported soil A soil formed from weathered components transported by water, wind or ice to a different area.

Points to Consider

- Why is soil such an important resource?
- Do you think a mature soil would form faster from unaltered bedrock or from transported materials?
- If soil erosion is happening at a greater rate than new soil can form, what will eventually happen to the soil in that region?
- Do you think there are pollutants that could not easily be removed from soil?

Image Sources

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Chapter 10

Erosion and Deposition

10.1 Water Erosion and Deposition

Lesson Objectives

- Describe how surface rivers and streams produce erosion.
- Describe the types of deposits left behind by rivers and streams.
- Describe landforms that are produced as groundwater flows.

Introduction

Rivers and streams complete the hydrologic cycle by returning precipitation that falls on land to the oceans (**Figure** 10.1). Ultimately, gravity is the driving force, as water moves from mountainous regions to sea level. Some of this water moves over the surface and some moves through the ground as **groundwater.** As this water flows it does the work of both erosion and deposition. You will learn about the erosional effects and the deposits that form as a result of this moving water.

Erosion and Deposition by Rivers and Streams

Erosion from Runoff

As streams move over the ground, they transport weathered materials. Streams continually erode material away from their banks, especially along the outside curves of meanders. Some of these materials are carried in solution. Many minerals are ionic compounds that dissolve easily in water, so water moves these elements to the sea as part of the **dissolved load**

Figure 10.1: As rivers and streams move towards the ocean, they carry weathered materials. (29)

that the stream carries. As groundwater leaches through layers of soil and rock, minerals dissolve and are carried away. Groundwater contributes most of the dissolved components that streams carry. Once an element has completely dissolved, it will likely be carried to the ocean, regardless of the velocity of the stream. In some circumstances, the stream water could become saturated with dissolved materials, in which case elements of those minerals might precipitate out of the water before they reach the ocean.

Another way that rivers and streams move weathered materials is as the **suspended load.** These are pieces of rock that are carried as solids as the river flows. Unlike dissolved load, the size of the particle that can be carried as suspended load is determined by the velocity of the stream. As a stream flows faster, it can carry larger and larger particles. The larger the size particle that can be carried by a stream, the greater the stream's **competence.** If a stream has a steep slope or **gradient,** it will have a faster velocity, which means it will be able to carry larger materials in suspension. At flood stage, rivers flow much faster and do more erosion because the added water increases the stream's velocity. Sand, silt and clay size particles generally make up the suspended load for a stream (**Figure** 10.2). As a stream slows down, either because the stream's slope decreases or because the stream overflows its banks and broadens its channel, the stream will deposit the largest particles it has been carrying first.

Figure 10.2: Rivers carry sand, silt and clay as suspended load. During flood stage, the suspended load greatly increases as stream velocity increases. (30)

The last way that rivers and streams move weathered materials is as **bed load.** This means that although the water in the stream is capable of bumping and pushing these particles along, it is not able to pick them up and carry them continuously. Bed load is named for the fact that these particles get nudged and rolled along the stream bed as the water flows. Occasionally a larger size particle will get knocked into the main part of the stream flow, but then it settles back down to the stream bed because it is too heavy to remain suspended in the water. This is called **saltation,** which we will learn about later in this chapter with transport of particles by wind. Streams with high velocities and steep gradients do a great deal of downcutting into the stream bed, which is primarily accomplished by movement of particles that make up the bed load. Particles that move along as the bed load of a stream do not move continuously along, but rather in small steps or jumps with periods of remaining stationary in between.

Stream and River Erosion – Stages of Streams

As a stream moves water from high elevations, like mountains, towards low elevations, like the ocean, which is at sea level, the work of the stream changes. At high elevations, streams are just beginning streams that have small channels and steep gradients. This means that the stream will have a high velocity and will do lots of work eroding its stream bed. The higher the elevation, the farther the stream is from where it eventually meets the sea. **Base level** is the term for where a stream meets sea level or standing water, like a lake or the ocean. Streams will work to downcut their stream beds until they reach base level.

As a stream moves out of high mountainous areas into lower areas closer to sea level, the stream is closer to its base level and does more work eroding the edges of its banks than downcutting into its stream bed. At some point in most streams, there are curves or bends in the stream channel called **meanders** (**Figure** 10.3). The stream erodes material along its outer banks and deposits material along the inside curves of a meander as it flows to the ocean (**Figure** 10.4). This causes these meanders to migrate laterally over time. The erosion of the outside edge of the stream's banks begins the work of carving a **floodplain,** which is a flat level area surrounding the stream channel.

Stream and River Deposition

Once a stream nears the ocean, it is very close to its **base level** and now deposits more materials than it erodes. As you just learned, one place where a river deposits material is along the inside edges of meanders. If you ever decide to pan for gold or look for artifacts from an older town or civilization, you will sift through these deposits. Gold is one of the densest elements on Earth. Streams are lazy and never want to carry more materials than absolutely necessary. It will drop off the heaviest and largest particles first, that is why you might find gold in a stream deposit. Imagine that you had to carry all that you would need for a week as you walked many kilometers. At first you might not mind the weight of what you are carrying at all, but as you get tired, you will look to drop off the heaviest things you are carrying first!

When a river floods or overflows its channel, the area where the stream flows is suddenly much broader and shallower than it was when it was in its channel. This slows down the

Figure 10.3: Here a stream can be seen actively eroding its outer banks along a meander. (48)

Figure 10.4: This stream has deposited larger materials like gravel and pebbles along the inside curve of a meander. (6)

velocity of the stream's flow and causes the stream to drop off much of its load. The farmers who use the floodplain areas around the Nile River rely on these deposits to supply nutrients to their fields each year as the river floods its banks. At flood stage, a river will also build **natural levees** as the largest size particles build a higher area around the edges of the stream channel (**Figure** 10.5).

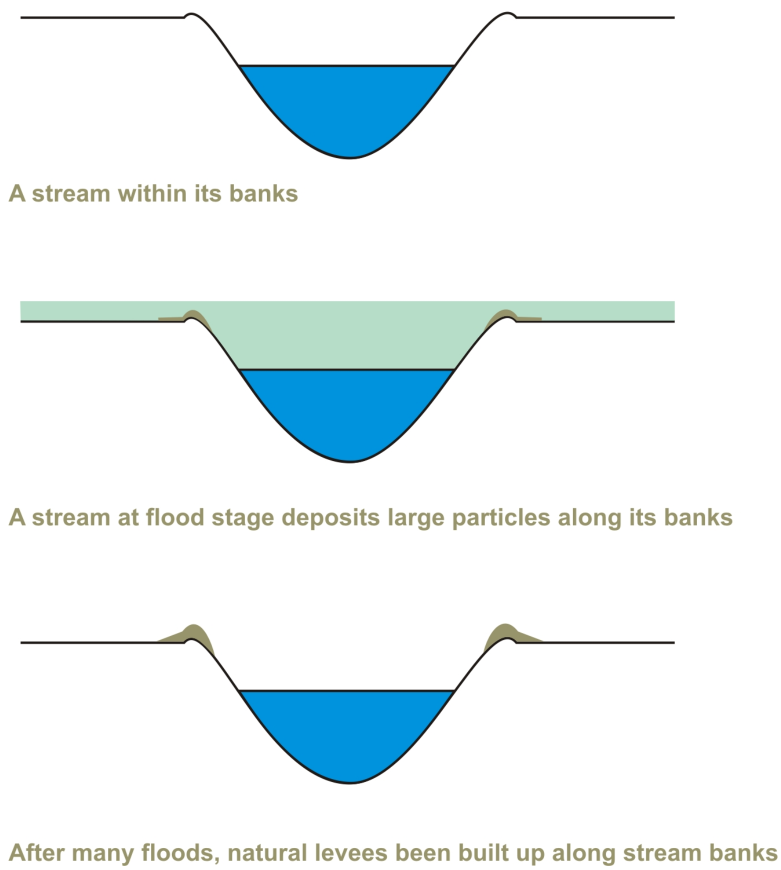


Figure 10.5: After many floods, a stream builds natural levees along its banks. (11)

When a river meets either standing water or nearly flat lying ground, it will deposit its load. If this happens in water, a river may form a **delta**. From its headwaters in the mountains, along a journey of many kilometers, rivers carry the eroded materials that form their stream load. Suddenly the river slows down tremendously in velocity, and drops the tremendous load of sediments it has been carrying. Deltas are relatively flat topped, often triangular shaped deposits of sediments that form where a large river meets the ocean. The name delta comes from the capital Greek letter delta, which is a triangle, even though not all deltas have this shape. A triangular shaped delta forms as the main stream channel splits into many smaller **distributaries**. As the channel shifts back and forth dropping off sediments and moving to a new channel location a wide triangular deposit forms.

There are three types of beds that make up a delta (**Figure** 10.6). The first particles to be dropped off are the coarsest sediments and these form sloped layers called foreset beds that make up the front edge of the delta. Further out into calmer water, lighter, more fine grained sediments form thin, horizontal layers. These are called bottomset beds. During floodstage, the whole delta can be covered by finer sediments which will overlie the existing delta. These are called topset beds. These form last and lie on top of the rest of the delta.

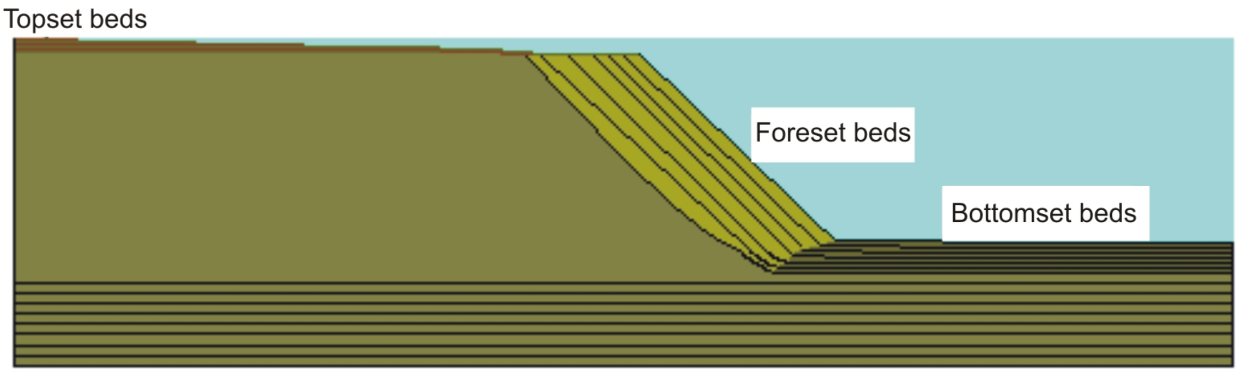


Figure 10.6: The three types of beds that form the layers of a delta. (10)

Not all large rivers form deltas as they meet the ocean. Whether a delta forms depends on the action of waves and tides. If the water is quiet water such as a gulf or shallow sea, a delta may form. If the sediments are carried away, then no delta will form. Sediments brought to the shore and distributed along coastlines by longshore transport form our beaches and barrier islands.

If a river or stream suddenly reaches nearly flat ground, like a broad flat valley or plain, an **alluvial fan** develops at the base of the slope (**Figure** 10.7). An alluvial fan is a curved top, fan shaped deposit of coarse sediments that drop off as the stream suddenly loses velocity. The fan spreads out in a curve in the direction of the flat land as many stream channels move across the curved surface of the alluvial fan, forming and unforming many channels as sediments are deposited. Alluvial fans generally form in more arid regions.

Groundwater Erosion and Deposition

Introduction

Not all water that falls on the land flows through rivers and streams. When it rains, much of the water sinks into the ground and moves through pore spaces in soil and cracks and fractures in rock. This water necessarily moves slowly, mostly under the influence of gravity. Yet groundwater is still a strong erosional force, as this water works to dissolve away solid rock. If you have ever explored a cave or seen a sinkhole, you have some experience with the work of groundwater (**Figure** 10.8).

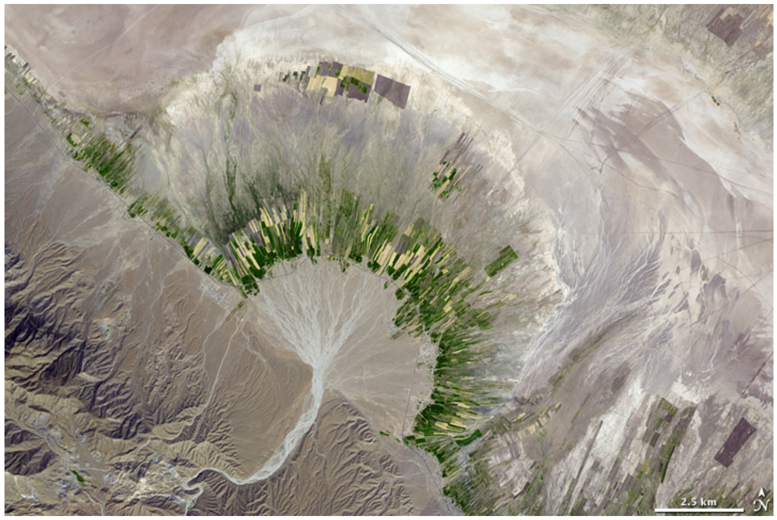


Figure 10.7: This satellite photo of an alluvial fan in Iran show the typical fan shape of these deposits. The mountains in this image are in the lower right corner of the photograph. (44)

Figure 10.8: Groundwater forms when water sinks into the ground rather than forming rivers or streams. (1)

Formation of Caves

As groundwater moves through spaces between mineral grains, it works to dissolve and carry away different elements. Some types of minerals are easily dissolved by groundwater. Rainwater absorbs carbon dioxide (CO_2) as it falls through the air. The carbon dioxide combines with water to form carbonic acid. This naturally occurring weak acid readily dissolves many types of rock, including limestone. If you have ever watched an antacid tablet dissolve in water, you have seen an example of just how quickly this type of rock is eroded away. Caves are one of nature's most spectacular demonstrations of erosion (**Figure** 10.9). Working slowly over many years, groundwater dissolves and carries away elements of once solid rock in solution. First it travels along small cracks and fractures, gradually enlarging them. In time, caverns many football fields long and as high as many meters tall can form.

Figure 10.9: Caves form where groundwater erodes away rock. (26)

A **sinkhole** could form if the roof of an underground cave collapses. Some sinkholes are large enough to swallow up a home or several homes in a neighborhood (**Figure** 10.10). As groundwater dissolves away solid rock, it carries those minerals in solution as it travels. As groundwater drips through openings, several interesting types of formations occur. **Stalactites** are icicle like deposits of calcium carbonate which form as layer on layer of calcite drips from the ceiling, coating the 'icicle' (**Figure** 10.11). As mineral rich material drips to the floor of a cave, **stalagmites** form rounded deposits of calcium carbonate on the floor of the cave. The word stalactite has a '**C**,' so you can remember it forms from the ceiling, while the '**G**' in stalagmite reminds you it forms on the ground. If a stalactite and stalagmite join together, they form a column. One of the wonders of visiting a cave is to witness the beauty of these amazing and strangely captivating structures. Caves also produce a beautiful type of rock, formed from calcium carbonate called **travertine.** This happens when groundwater saturated with calcium carbonate suddenly precipitates out as the mineral calcite or aragonite. Mineral springs that produce travertine can be hot springs or the water may just be warm or could even be cold (**Figure** 10.12).

Figure 10.10: This sinkhole formed in Florida. (50)

When lots of calcium carbonate is carried by groundwater, we call the water 'hard.' If the water in your area is hard, it might be difficult to get soap to lather or make soapsuds. Hard water might also have a taste to it, perhaps one that some people don't like as much as pure water. If your water is 'hard,' you may treat your water with a filter before you drink it. Zeolites are minerals that help to absorb ions from the water as it passes through the filter. When the water passes through the filter, it comes out tasting good!

Figure 10.11: Stalactites form as calcium carbonate drips from the ceiling of a cave, forming beautiful icicle like formations. (12)

Figure 10.12: Travertine is a beautiful form of limestone that forms as calcium carbonate precipitates. (17)

Lesson Summary

- Rivers and streams erode the land as they move from higher elevations to the sea.
- Eroded materials can be carried in a river as dissolved load, suspended load or bed load.
- A river will deeply erode the land when it is far from its base level, the elevation where it enters standing water like the ocean.
- As a river develops bends, called meanders, it forms a broad, flat area known as a floodplain.
- At the end of a stream, a delta or an alluvial fan might form where the river drops off much of the load of sediments it carries.
- Caves form underground as groundwater gradually dissolves away rock.

Review Questions

1. What are the three kinds of load that make up the particles a stream carries. Name and define each type.
2. What is a stream's gradient? What effect does it have on the work of a stream?
3. Describe several erosional areas produced by streams. Explain why erosion occurs here.
4. What type of gradient or slope would a river have when it is actively eroding its stream bed? Explain.
5. When would a river form an alluvial fan and when will it form a delta? Describe the characteristics of each type of deposit.
6. What are two formations that form inside caves?
7. What erosional feature formed by groundwater could swallow up your house?

Vocabulary

alluvial fan Curved top, fan shaped deposit of coarse sediments that forms when a stream suddenly meets flat ground.

base level The elevation at which a river meets standing water; a stream cannot erode below this level.

bed load The largest particles moved by streams; move by rolling or bumping along the stream bed.

competence A measure of the largest particle a stream can carry.

delta A flat topped, triangular shaped deposit of sediments that forms where a river meets standing water.

dissolved load The elements carried in solution by a stream.

distributaries Smaller branching channels that spread out over the surface of a delta.

floodplain Broad, flat lying plain surrounding a stream channel; created by the stream.

gradient The slope of a stream.

groundwater Water that moves through pore spaces and fractures in soil and rock.

meander A bend or curve in a stream channel.

natural levees Coarse grained deposits of sediments that build up along a stream's banks as it floods.

saltation The intermittent movement of bed load particles, as they are carried by the flow and then settle back down.

sinkhole Circular hole in the ground that forms as the roof of a cave collapses.

stalactite An icicle like formation of calcium carbonate that forms as saturated water drips from the ceiling of a cave.

stalagmite Rounded, cone shaped formation of calcium carbonate that forms in caves as water drips onto the floor.

suspended load Solid particles that are carried in the main stream flow.

travertine Beautiful deposit of calcium carbonate that forms around hot springs.

Points to Consider

- Would a stream that begins at high elevation be likely to do more erosion than a stream that begins at lower elevations?
- What differences would there be on the Earth's surface without rivers and streams?
- Do you think a flash flood along a normally dry river valley would be a dangerous event?
- Do you think caves could form in your neighborhood?

10.2 Wave Erosion and Deposition

Lesson Objectives

- Describe how the action of waves produces different shoreline features.
- Discuss how areas of quiet water produce deposits of sand and sediment.
- Discuss how some of the structures humans build to help defend against wave erosion.

Wave Action and Erosion

Have you ever been to visit a beach? Some beaches have large, strong rolling waves that rise up and collapse as they crash into the shore. All waves are *energy* traveling through some type of material (**Figure** 10.13). The waves that we are most familiar with travel through water. Most of these waves form from wind blowing over the water; sometimes steady winds that blow and sometimes from a storm that forms over the water. The energy of waves does the work of erosion when a wave reaches the shore. When you find a piece of frosted glass along a beach, you have found some evidence of the work of waves. What other evidence might you find?

Figure 10.13: Ocean waves are energy traveling through water. (47)

As wind blows over the surface of the water, it disturbs the water, producing the familiar shape of a wave. You can see this shape in **Figure** 10.14. The highest part of a wave is called the **wave crest.** The lowest part is called the **wave trough.** The vertical distance from the highest part of a wave to the lowest is called the **wave height.** The horizontal distance between one wave crest and the next crest, is called the **wavelength.** Three things influence how big a wave might get. If the wind is very strong, and it blows steadily for a long time over a long distance, the very largest waves will form. The wind could be strong, but if it gusts for just a short time, large waves won't form. Bigger waves do more work of erosion which changes our shorelines. Each day that waves break along the shore, they steadily erode away a little bit of the shoreline. When one day, a really big storm like a hurricane arrives, it will do a lot of damage in just a very short time.

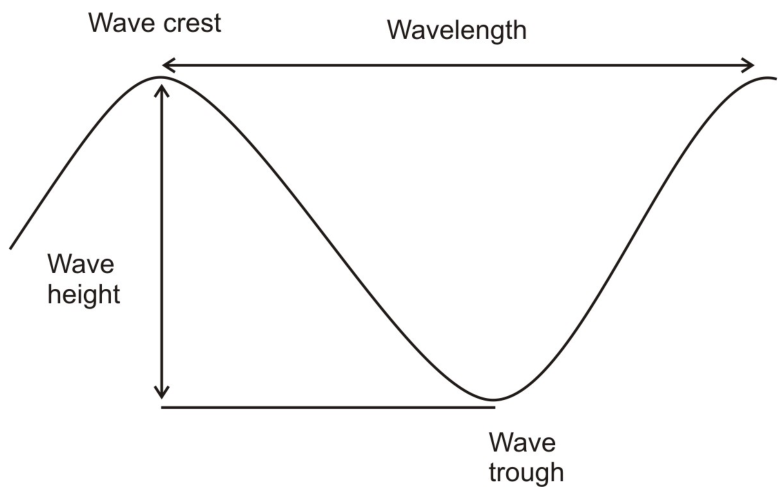


Figure 10.14: Each wave form has a wave crest, trough, height and wavelength. (14)

As waves come into shore, they usually reach the shore at some angle. This means one part of the wave reaches shallow water sooner than the parts of the wave that are further out. As a wave comes into shore, the water 'feels' the bottom which slows down the wave. So the shallower parts of the wave slow down more than the parts that are further from the shore. This makes the wave 'bend,' which is called **refraction.** The way that waves bend as they come into shore either concentrates wave energy or disperses it. In quiet water areas like bays, wave energy is dispersed and sand gets deposited. Areas like cliffs that stick out into the water, are eroded away by the strong wave energy that concentrates its power on the cliff (**Figure** 10.15).

Wave-cut cliffs form where waves cut into the bottom part of the cliff, eroding away the soil and rocks there. First the waves cut a notch into the base of the cliff. If enough material is cut away, the cliff above can collapse into the water. Many years of this type of erosion can form a **wave-cut platform** (**Figure** 10.16).

If waves erode a cliff from two sides, the erosion produced can form an open area in the cliff called an **arch** (**Figure** 10.17). If the material above the arch eventually erodes away, a piece of tall rock can remain in the water, which is called a **sea stack** (**Figure** 10.18).

Figure 10.15: Cliffs are eroded by wave action that concentrates energy in these areas. (5)

Figure 10.16: This large wave cut platform was formed by the cutting action of waves on the cliffs to the left. (52)

Figure 10.17: A sea arch can form if waves erode from opposite sides of a cliff. (46)

Figure 10.18: A sea stack forms if the upper layers of rock collapse, leaving an isolated pinnacle. (53)

Wave Deposition

Rivers carry the sand that comes from erosion of mountains and land areas of the continents to the shore. Soil and rock are also eroded from cliffs and shorelines by waves. That material is transported by waves and deposited in quieter water areas. As the waves come onto shore and break, water and particles move along the shore. When lots of sand accumulates in one place, it forms a beach. Beaches can be made of mineral grains, like quartz, but beaches can also be made of pieces of shell or coral or even bits of broken hardened lava (**Figure** 10.19).

Figure 10.19: Quartz, rock fragments and shell make up the sand along a beach. (2)

Waves continually move sand grains along the shore. Smaller particles like silt and clay don't get deposited at the shore because the water here is too turbulent. The work of waves moves sand from the beaches on shore to bars of sand offshore as the seasons change. In the summer time, waves of lower energy bring sand up onto the beach and leave it there. That is good for the many people who enjoy sitting on soft sand when they visit the beach (**Figure** 10.20). In the wintertime, waves and storms of higher energy bring the sand from the beach back offshore. If you visit your favorite beach in the wintertime, you will find a steeper, rockier beach than the flat, sandy beach of summer. Some communities truck in sand to resupply sand to beaches. It is very important to study the energy of the waves and understand the types of sand particles that normally make up the beach before spending lots of money to do this. If the sand that is trucked in has pieces that are small enough to be carried away by the waves on that beach, the sand will be gone in a very short time.

Sand transported by the work of waves breaking along the shore can form sand bars that stretch across a bay or ridges of sand that extend away from the shore, called **spits.** Sometimes the end of a spit hooks around towards the quieter waters of the bay as waves refract,

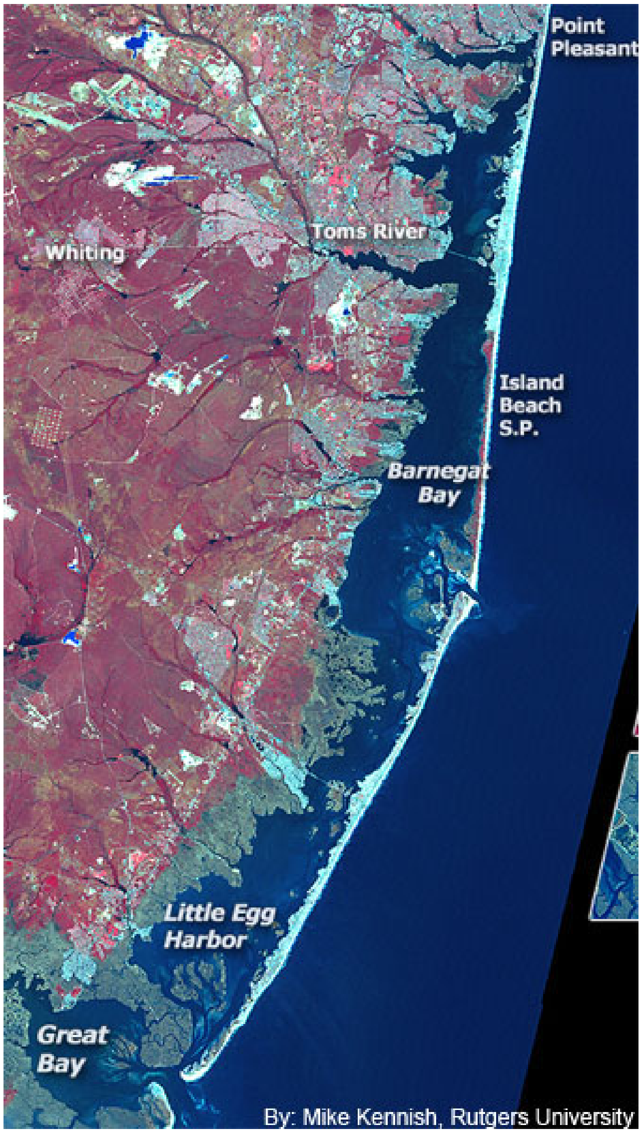
Figure 10.20: Sand deposits in quiet areas along a shoreline to form a beach. (7)

causing the sand to curve around in the shape of a hook.

When the land that forms the shore is relatively flat and gently sloping, the shoreline may be lined with long narrow islands called **barrier islands** (**Figure** 10.21). Most barrier islands are just a few kilometers wide and tens of kilometers long. Many famous beaches, like Miami Beach, are barrier islands. In its natural state, a barrier island acts as the first line of defense against storms like hurricanes.

Figure 10.21: These sand dunes are part of Padre Island off the coast of Texas, which is a barrier island. (42)

Instead of keeping barrier islands natural, these areas end up being some of the most built up, urbanized areas of our coastlines. That means storms, like hurricanes, damage houses and businesses rather than hitting soft, vegetated sandy areas. Some hurricanes have hit barrier islands so hard that they break right through the island, removing sand, houses and anything in the way.



Protecting Shorelines

Humans build several different types of structures to try to slow down the regular work of erosion that waves produce and to help prevent damage to homes from large storms. One structure that people build, called a **groin,** is a long narrow pile of rocks that extends out into the water, at right angles to the shoreline (**Figure** 10.22). The groin traps sand on one side of the groin, keeping the sand there, rather than allowing it to move along the coastline. This works well for the person who is on the upcurrent side of the groin, but it causes problems for the people on the opposite, downcurrent side. Those people no longer have sand reaching the areas in front of their homes. What happens as a result is that people must build another groin to trap sand there. This means lots of people build groins, but it is not a very good answer to the problem of wave erosion.

Figure 10.22: Groins are built perpendicular to the shoreline to help keep sand from moving off the beach. (54)

Some other structures that people build include **breakwaters** and **sea walls** (**Figure** 10.23). Both of these are built parallel to the shoreline. A breakwater is built out away from the shore in the water while a sea wall is built right along the shore. Breakwaters are built in bay areas to help keep boats safe from the energy of breaking waves. Sometimes enough sand deposits in these quiet water areas that people then need to work to remove the sand. Seawalls are built to protect beach houses from waves during severe storms. If the waves in a storm are very large, sometimes they erode away the whole sea wall, leaving the area unprotected entirely. People do not always want to choose safe building practices, and instead choose to build a beach house right on the beach. If you want your beach house to stay in good shape for many years, it is smarter to build your house away from the shore.

Lesson Summary

- Waves in the ocean are what we see as energy travels through the water.
- The energy of waves produces erosional formations like cliffs, wave cut platforms, sea arches and sea stacks.
- When waves reach the shore, deposits like beaches, spits and barrier islands form in certain areas.
- Groins, jetties, breakwaters and seawalls are structures humans build to protect the shore from the erosion of breaking waves.

Figure 10.23: Breakwaters are visible in this satellite image, built parallel to the shoreline to protect areas from strong waves. (4)

Review Questions

1. Name three structures that people build to try to prevent wave erosion.
2. Name three natural landforms that are produced by wave erosion.
3. What are the names of the parts of a waveform?
4. Describe the process that produces wave refraction.
5. If you were to visit a beach in a tropical area with coral reefs, what would the beach there be made of?

Vocabulary

arch An erosional landform that is produced when waves erode through a cliff.

barrier island Long, narrow island, usually composed of sand that serves as nature's first line of defense against storms.

breakwater Structure built in the water, parallel to the shore to protect boats or harbor areas from strong waves.

groin Long, narrow piles of stone or timbers built perpendicular to the shore to trap sand.

sea stack Isolated tower of rock that forms when a sea arch collapses.

sea wall Structure built along the shore, parallel to the shore, to protect against strong waves.

spit Long, narrow bar of sand that forms as waves transport sand along shore.

wave-cut platform Flat, level area formed by wave erosion as waves undercut cliffs.

wave crest The highest part of a waveform.

wave height The vertical distance from wave crest to wave trough.

wave length The horizontal distance from wave crest to wave crest.

wave trough The lowest part of a wave form.

Points to Consider

- What situations would increase the rate of erosion by waves?
- If barrier islands are nature's first line of defense against ocean storms, why do people build on them?
- Could a seawall ever increase the amount of damage done by waves?

10.3 Wind Erosion and Deposition

Lesson Objectives

- Describe the ways particles are carried by wind.
- Discuss several ways that wind erosion changes land surfaces.
- Describe how sand dunes form.
- Describe the type of deposits formed by windborne silts and clays.

Introduction

Moving water does much of the work of erosion that shapes the land surface of our Earth. Wind also flows over the Earth's surface, sometimes carrying particles long distances before they are deposited. Wind blows from areas of high pressure to areas of lower pressure. The erosive power of wind varies with the strength of the winds that blow, but usually wind transports smaller particles like silt and clay. Somewhat larger particles may be bumped or rolled along by the wind. Wind can carry particles across ocean basins and to great heights within our atmosphere. Wind is a stronger erosional force in arid regions than humid areas for two reasons. In arid regions, temperatures change greatly from night to day, which produces wind. Even strong winds in humid areas are less effective erosional agents because the ground is wet, so soil particles are heavier and less likely to be removed or transported by wind.

Transport of Particles by Wind

Wind is able to transport the smallest particles of sediment, like silt and clay, over great distances and areas. Once these particles become mixed into the air, wind can keep them suspended for hours or maybe even days at a time. If nothing disturbs these tiny particles, wind would have trouble picking them off the ground surface. This is because very close to the ground, there is very little motion due to wind. Look behind a car or truck as it drives over an unpaved road. You will see a big cloud of dust that wasn't there before the truck disturbed the ground surface. Once these fine particles are disturbed, wind easily picks them up and distributes them.

Just as water carries different size particles in various ways, wind also transports particles as both **bed load** and **suspended load.** For wind, sand sized particles make up the bed load. These sand grains are moved along by the wind in a bump, roll and jump kind of motion. First, a grain of sand gets knocked into the air. It is too heavy to have wind carry it for long in suspension, so it falls back to the ground, possibly knocking another sand grain into the air as it hits the ground. This starts the process all over again. This process is called **saltation,** which comes from a Latin word meaning 'to leap' (**Figure** 10.24). The suspended load for wind will always be very small particles of silt and clay, which are still able to be carried suspended in the air by wind.

Erosion by Wind

As wind moves sand sized particles, they will remain close to the ground, usually less than a meter from the ground even in the strongest winds. In a sandstorm, about a quarter of the particles are sand which moves as bed load. In arid regions, a sandstorm actually moves much smaller particles than sand in the winds. Wind can carry these small particles high into the air and these particles can infiltrate cracks around windows and doors in a dust storm (**Figure** 10.25).

Sometimes these small particles are deposited in areas relatively close to their original source, but often silts and clays have been carried halfway across a continent or from desert areas on one continent across an entire ocean basin. Wind is more effective at erosion in arid regions because in humid regions smaller particles are held together by the moisture in the soil and by plant roots from the vegetation. Where it is dry, plants don't grow as well, so both these factors increase the ability of wind to transport particles, eroding the landscape.

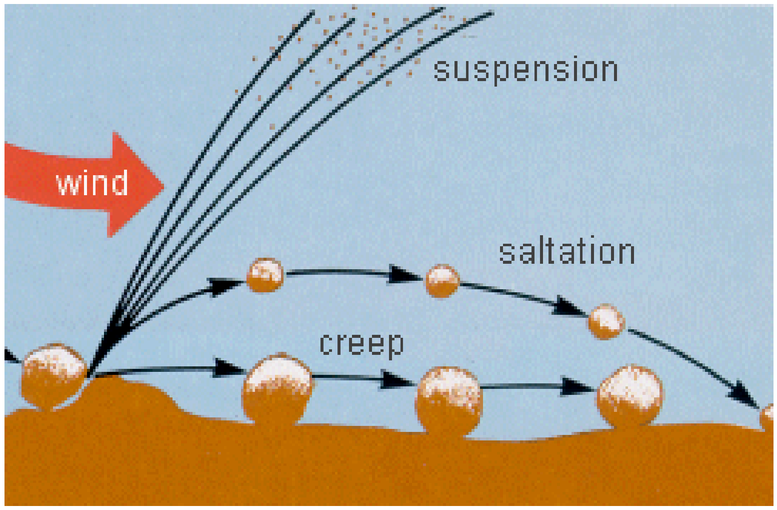


Figure 10.24: Saltation moves sand size particles along the desert floor or on sand dunes. (55)

Figure 10.25: A dust storm approaches Al Asad, Iraq. (51)

The process of smaller particles being selectively transported by the wind is called **deflation** (**Figure** 10.26). This means the ground surface gets lower and rockier, as more and more small particles are blown away. Eventually, most of the smaller particles will have been removed and the rockier surface left behind is called **desert pavement.** This surface is covered by pebbles and gravel sized particles that are not easily moved by wind. If no disturbance from vehicles or animals disrupts the surface, deflation will stop once this rocky surface has formed.

Figure 10.26: This desert pavement formed in the Mojave Desert as a result of deflation. (33)

All the particles moved by wind, whether as suspended load or by saltation as bed load, do the work of abrasion. As one particle hits another, each grain erodes another. You may have seen workers sandblasting the front of a building in order to remove paint or dirt. In the natural situation, erosion by wind polishes surfaces of rock. In the desert, rocks or boulders develop different polished flat surfaces as wind blows from different directions. These polished stones are called **ventifacts** (**Figure** 10.27).

Exposed rocks in desert areas often develop a dark brown to black coating called **desert varnish.** This coating forms on stable rock surfaces that don't get much precipitation. The first part of the process is the transport of clay sized particles by wind which chemically react with other substances at high temperatures. The coating is formed of iron and manganese oxides. Ancient people carved into these darkened surfaces to make **petroglyphs** (**Figure** 10.28).

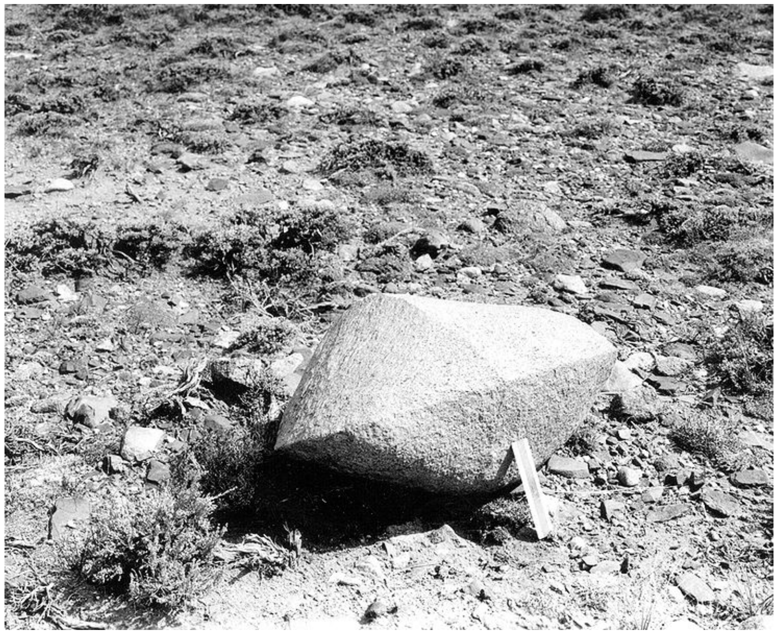


Figure 10.27: A polished stone called a ventifact, is produced by abrasion from sand grains. (41)

Figure 10.28: These petroglyphs were carved into desert varnish near Canyonlands National Park in Utah. (34)

Deposition by Wind

When you think of a desert or perhaps even a beach, the image that comes to mind might include **sand dunes** (**Figure** 10.29). In coastal regions, you will find sand dunes in the landward direction of the beach. Sand dunes form here as sand is blown from the shore inland. The sand dunes along a beach are likely to be composed of individual grains of the mineral quartz, unless the beach is in a tropical area. In humid regions, other minerals break down readily to form clays, leaving behind only the more resistant quartz. In the tropics, sand dunes may be composed of calcium carbonate. In a desert, the sand dunes may be composed of a variety of minerals. This is because a desert region, by definition, has very little water. This means that mostly mechanical weathering and very little chemical weathering occurs here. So desert sand dunes will include even unstable minerals.

Just as water waves are very selective about the size particles they carry and deposit, so will the size of the sand grains in a dune be very uniform. The sand dunes are formed of a particular size particle which is too heavy for the wind to transport. This process is sometimes so selective that wind will transport and carry rounded grains of sand, which roll easily, more readily than angular grains.

The faster and stronger the wind, the more particles it can carry. As wind slows down, it will drop off the heaviest particles first. This often happens as wind moves over some type of obstacle, such as a rock or an area of vegetation. As the wind moves up and over the obstacle, it increases in speed, but as soon as it passes the article, wind speed decreases. That is why you will often see deposits of sand on the downwind side of an obstacle. These deposits are the starting material for formation of sand dunes. This is the first condition needed for dunes to form.

In order for sand dunes to form, two more conditions must be met. The first of these conditions is that there is an abundant supply of sand. The last condition is that there are steady winds. As steady winds blow over an ample supply of sand, sand grains will bump and roll along, moving by saltation up the gently sloping, upwind side of the dune. As a grain of sand reaches the crest of the dune, it cascades down the steeper, downwind side of the dune, forming the **slip face** of the dune. The slip face is steep because it forms at the angle of repose for dry sand, which is about 34º (**Figure** 10.30).

So as wind erodes and transports sand grains along the gently sloped upwind side of a dune, it deposits sand along the downwind slip face. As each new layer of sand falls down the slip face of the dune, cross beds are formed. Cross beds are named for the way each layer is formed at an angle to the ground. Some of the most beautiful sandstones are crossbedded sandstones (**Figure** 10.31). These sandstones preserve sands originally deposited as sand dunes in deserts millions of years ago.

Sand is always moving up the gently sloped side of a dune, and depositing on the downwind side, which means that dunes themselves slowly migrate in the downwind direction. This means that over a period of years, sand dunes will move many meters downwind. This is

Figure 10.29: This sand dune in Morocco shows secondary sand ripples along its slip face. (38)

Figure 10.30: Sand dunes have a gently sloping face in the upwind direction. Downwind, a steeper slip face forms. (37)

Figure 10.31: These beautiful rocks are crossbedded sandstones from the Canyons of the Escalante in Utah. (28)

something that beach house owners need to consider if they live near coastal sand dunes. Once a sand dune becomes stabilized by vegetation, such as sea grasses, its migration will stop. Beach goers need to be careful not to disturb these grasses when they go to and from the beach.

Reducing Wind Erosion – Types of Sand Dunes

There are several different forms that sand dunes will take. The differences are due to the amount of sand available to be moved, the character and direction of the wind and the type of ground the sand is moving over. The most usual crescent shaped dune is called a **barchan dune** (**Figure** 10.32). This type of dune forms when there is an adequate amount of sand being moved by constant winds that blow from one direction over hard ground. The crescent shape will curve in the direction the wind blows. In an area of constant winds with an abundant supply of sand, barchan dunes blend together into large scale sand ripples called **transverse dunes.** Many coastal dunes are this type of dune. Desert areas that are completely sand covered can join many transverse dunes together into a sand sea.

Star shaped dunes form in areas of constantly changing wind direction with enough sand for dunes to form. They are called stars because several ridges of sand all radiate out from a central point. Linear dunes form when there isn't much sand and winds come together from different directions. This type of dune forms long straight lines of sand that line up parallel to the wind direction. Coastlines are places of steady winds and abundant supplies of sand. Parabolic dunes form where some type of vegetation at least partly covers the sand. These coastal dunes form a curved shape that curves into the direction of the wind. This probably occurs as the central portion of sand is blown out, leaving a U-shaped curve of sand.

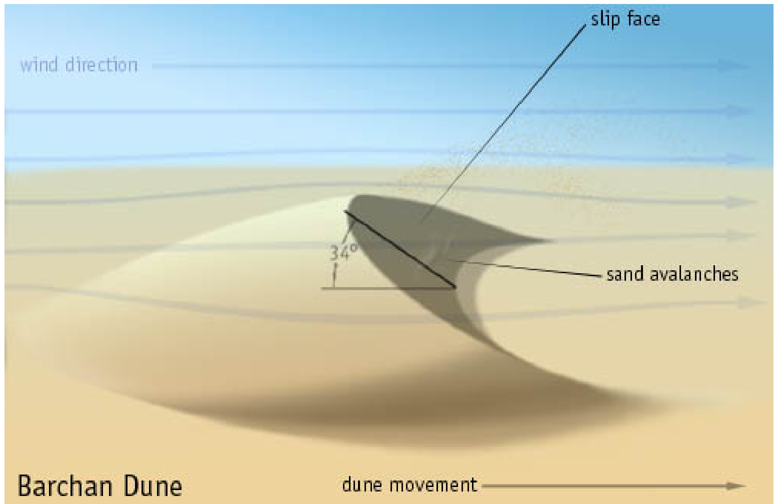


Figure 10.32: This crescent shaped dune forms from constant winds moving sand over hard ground. (35)

Loess

In many parts of the world, the finest grains of windblown silt and clay are deposited layer on layer, covering whole regions with these tiny particles (**Figure** 10.33). Geologists call these deposits **loess,** which comes from the German word 'loose.' These deposits form downwind of areas of glacial outwash or desert areas. There are extensive loess deposits in China where deserts are the original source for these fine grained, windborne particles. One unusual characteristic of loess deposits is their ability to form nearly vertical cliffs, without grains sliding or slumping down the face. In China, people once built homes directly into these deposits because they are easy to dig into and they keep their shape. Loess deposits are also the source of wind transported materials that make very fertile soils in many regions of the world.

Much of the fine grained mud that covers the deepest parts of the ocean floor comes from silts and clays brought there by winds from the land. These tiny particles are easily carried long distances by wind. Once they are deposited on the water surface, they settle ever so slowly to the deep ocean floor, forming brown, greenish or reddish clays. Another source of windborne particles is volcanic activity. Explosive volcanoes eject volcanic ash and dust high into the air, sometimes reaching the stratosphere. Once these fine grained particles are airborne, they can travel hundreds or thousands of kilometers. Regions closest to the volcano are the areas with thickest deposits, but volcanic ash has even completely circled the Earth in extremely violent eruptions like Krakatau in 1883. Windborne volcanic ash can produce spectacularly beautiful sunsets, as well as decreasing worldwide temperatures, as ash and dust block out incoming sun's rays.

Figure 10.33: These vertical cliffs are formed from fine grained, windblown silt and clay. (39)

Lesson Summary

- Wind can carry small particles like sand, silt and clay.
- Wind erosion produces sand blasting of surfaces and produces desert pavement, ventifacts and desert varnish.
- Sand dunes are some of the most common wind born deposits, which come in many different shapes and sizes.
- Loess is a very fine grained, wind borne deposit that is important to soil formation in many regions.

Review Questions

1. Discuss suspended load and bed load transport by wind.
2. Describe how desert pavement forms.
3. Discuss the factors necessary for sand dunes to form.
4. Name four types of sand dunes that form in desert areas.
5. Name one type of wind deposition.
6. Why is wind erosion more important in arid regions than humid areas?

Vocabulary

barchan dune Crescent shaped dune that forms in regions of ample sand, constant winds & hard ground.

bed load The portion of sand carried by wind as grains roll, bump and jump along the ground surface.

deflation The process of wind removing finer grains of silt and clay; causes the ground surface to subside.

desert pavement Rocky, pebbled surface created as finer silts and clays are removed by wind.

desert varnish Dark mineral coating that forms on stable, exposed rock surfaces as wind-borne clays are deposited.

loess Extremely fine grained, windborne deposit of silts & clays; forms nearly vertical cliffs.

petroglyphs Rock carvings formed by cutting into desert varnish of exposed rock surfaces.

saltation Movement of sand sized particles by rolling, bumping and jumping along the ground surface.

sand dune Deposit of sand formed in regions of abundant sand and constant winds.

slip face Steeper, downwind side of a dune; region where sand grains fall down from the crest of the dune.

suspended load Particles of silt and clay carried in the air by the energy of winds.

ventifacts Polished, faceted stones formed by abrasion of sand particles.

Points to Consider

- Do you think strong hurricane winds along a coastline would produce wind related erosion?
- What would be needed to convert a desert area back to a productive region for farming?
- Do you think wind could sculpt exposed rocks? Explain how this might happen.

10.4 Glacial Erosion and Deposition

Lesson Objectives

- Discuss the different erosional features formed by alpine glaciers.
- Describe the processes by which glaciers change the underlying rocks.
- Discuss the sorting and types of particles deposited by glaciers as they advance and recede.
- Describe the landforms created by glacial deposits.

Introduction

Today glaciers cover about 10% of the land surface on Earth, but there have been times in Earth's recent history when glaciers have covered as much as 30% of the land surface. Around eight to six hundred million years ago, geologists believe that almost all of the Earth was covered in snow and ice. So today, scientists do a kind of detective work to figure out where the ice once was. We can figure this out by observing the ways the land has been eroded and by looking at the deposits that have been left behind. It is possible that there once was ice on the land where you are living right now. How can you find out? Let's talk about some of the features that scientists look for.

Formation and Movement of Glaciers – Continental and Valley Glaciers

Today, we have glaciers near Earth's poles and at high altitudes in mountainous regions. The ice in a glacier erodes away the underlying rocks, just as rivers and streams shape the land they flow over. Like rivers and streams, glaciers tend to flow along existing valleys, but while the thick ice of glaciers is slowly moving over the land, it scours away the rocks below somewhat like a very slow and steady bulldozer. Especially up in the mountains, rivers cut 'V' shaped valleys as running water cuts deep into the rock. As a glacier flows through this same valley, it widens the valley and forms steeper sides to the valley walls, making a 'U' shape valley instead (**Figure** 10.34).

In mountainous areas, often many smaller glaciers flow from higher elevations joining the main glacier as they move to lower places. Generally, these smaller glaciers carve shallower 'U' shaped valleys than the main glacier. A beautiful erosional feature, called a **hanging valley,** forms where the smaller 'U' shaped valley meets the deeper one of the main glacier. River water cascades down the steep valley walls forming breathtaking waterfalls (**Figure** 10.35).

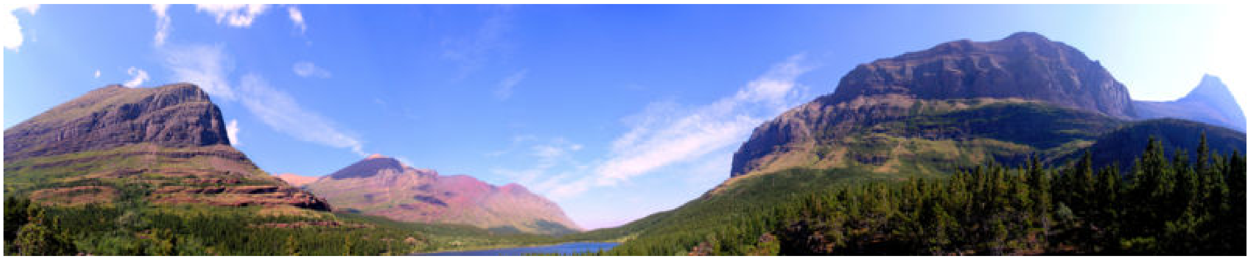


Figure 10.34: This valley in Glacier National Park shows the characteristic 'U' shape of a glacially carved valley. (23)

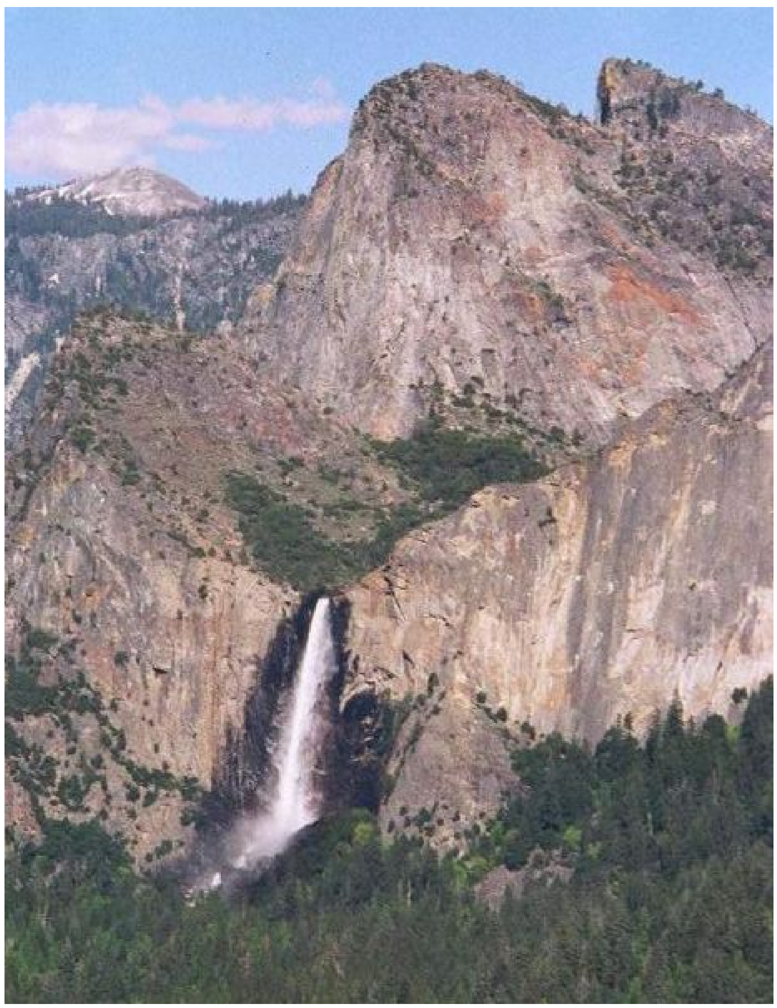


Figure 10.35: Bridalveil Falls waterfall flows today in the hanging valley produced where a smaller glacier joins the main glacier. (8)

Glacial Erosion

The two main ways that glaciers erode the underlying rock are **abrasion** and **plucking.** As the thick layer of ice pushes against the underlying rock, it scrapes and polishes the rock surface. As glaciers flow, they scratch the underlying bedrock with all the rocky material they are carrying. These scratches make long, parallel grooves in the bedrock, called **glacial striations,** which show the direction the glacier moved. Also as the glacier slowly moves over the rock, glacial meltwater seeps into cracks and fractures of the underlying rock. As the water freezes, it pushes pieces of rock out of the underlying rock surface. These pieces of rock get plucked out and carried away by the flowing ice of the moving glacier (**Figure** 10.36).

Figure 10.36: Iceberg Cirque in Glacier National Park was carved by glaciers. (18)

There are several erosional features that form as a glacier both scours the rock and pulls pieces away. As rocks are pulled away from valley walls, a steep sided, bowl shaped depression forms at the top of a mountain, called a **cirque.** The word comes from the French word for circle. Once the ice melts away, a high altitude lake, called a **tarn** often forms from meltwater trapped in the cirque. If several glaciers flow down in different directions from a central mountain peak, these steep walled depressions can leave behind an angular, sharp sided peak called a **horn.** The Matterhorn in Switzerland is the most famous example of this type of erosion (**Figure** 10.37).

When two glaciers move down opposite sides of the mountain, the erosional landform that is created where they meet is a sharp edged, steep sided ridge, called an **arête.** Sometimes hiking trails follow along these narrow ridges, providing dramatic views in all directions (**Figure** 10.38).

Figure 10.37: The Matterhorn in Switzerland is a classic example of a horn. (16)

As glaciers flow down a mountainside, the ice may also sculpt and shape the underlying bedrock as it flows. When a knob of bedrock is carved into an asymmetrical hill, it is called a **roche moutonnée.** In French, it means 'sheep rock.' Perhaps the villagers below the mountain thought these hills looked like sheep grazing in the valley. A roche moutonnée has a gently sloping side in the uphill direction of ice flow, with a steep side facing the downslope direction (**Figure** 10.39).

Depositional Features of Glaciers

As glaciers flow over many years, all sorts of debris falls onto the glacier through mechanical weathering of the valley walls. Glaciers are solid ice, so unlike water, they can carry pieces of rock of any size. Glaciers move boulders as large as a house as easily as the smallest particles of sand and silt. These pieces of rock are carried by the glacier for many kilometers and are only deposited as the ice melts. When you think of a glacier, you may think of white ice and snow, but actually glaciers have lots of rocky bits all over them. Each of these different deposits has its own name based on where it forms, but as a group they are called **moraines.** A long pile of rocky material at the edge of a glacier is called a lateral moraine and one in the middle of the glacier is called a medial moraine. Lateral moraines form at the edges of the glacier as material drops onto the glacier from erosion of the valley walls. Medial moraines form where two glaciers join together. In this case, the lateral moraines from the edges of each glacier meet in the middle to form the medial moraine (**Figure** 10.40).

Wherever a glacier is located, it is always slowly flowing downhill. Sometimes the rate at which it is flowing downhill is faster than the rate at which it melts. In this situation, you will see the glacier advancing down the valley, with more and more ice with each successive year. More likely what you will see today if you get the chance to visit a glacier, is that the

Figure 10.38: When glaciers move down opposite sides of a mountain, a sharp edged ridge forms between them. (22)

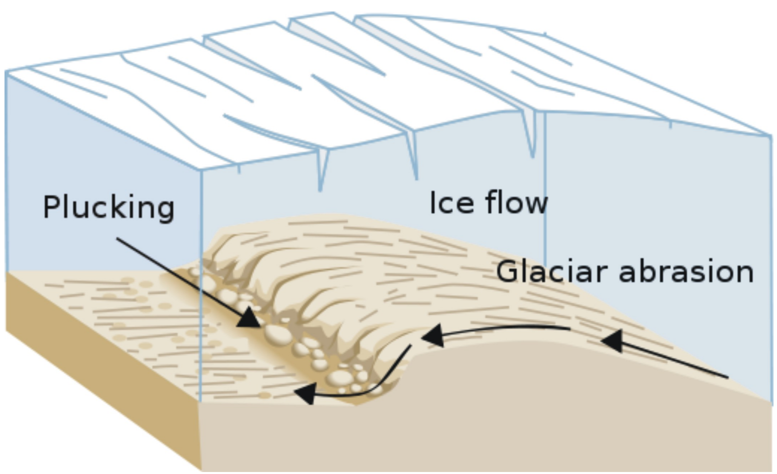


Figure 10.39: A roche moutonée forms where glaciers smooth the uphill side of the bedrock and pluck away rock from the downslope side. (40)

Figure 10.40: These long, dark lines on the Aletsch glacier in Switzerland are examples of medial and lateral moraines. (13)

glacier is retreating. This means that is there is less ice in the glacier this year than there was the year before (**Figure** 10.41).

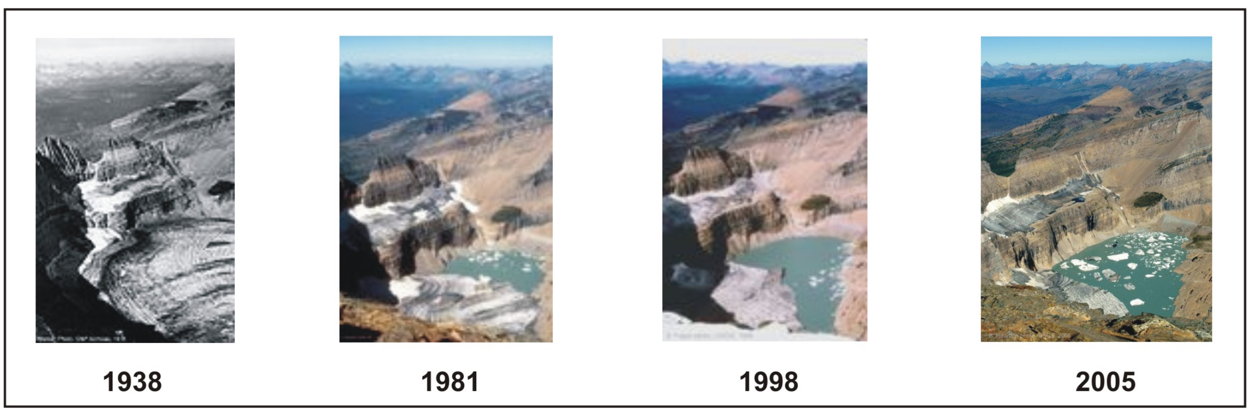


Figure 10.41: These photographs of the Grinnell Glacier in Glacier National Park were taken over an almost 70 year period. The glacier is clearly visible and well developed in 1938. From 1981 through 2005, the amount of glacial ice has decreased and the meltwater forming the lake has increased. In 2005, icebergs are further evidence of glacial melting. (32)

When glaciers melt more than they flow forward, they deposit all the big and small bits of rocky material they have been carrying. In general, all these unsorted deposits of rock, formed directly by the ice, are called **glacial till.** If you live in an area where glaciers once were, you may have seen large boulders in the woods or even in the middle of a field. If these large rocks are a different type of rock than the bedrock in that area, they are called **glacial erratics** (**Figure** 10.42). Scientists know only ice could carry these large boulders great distances. The largest glacial erratic, called Big Rock found in Alberta, Canada weighs thousands of tons!

Figure 10.42: A large boulder dropped by a glacier is called a glacial erratic. (31)

Sometimes long ridges of rock are deposited at the furthest point that the glacier reached. These are called terminal and **end moraines.** Just as the conveyor belt at the grocery store moves your groceries to the end of the counter, a glacier transports rock and sediment while it flows. If you couldn't stop the conveyor belt at the grocery store, you would end up with a big jumbled pile of food at the end of the counter. An end moraine is a little bit like that. Whatever the glacier has been carrying, all gets left behind in a pile as the ice melts away. Geologists study these materials to figure out how far glaciers once extended and they can also figure out how long it took them to melt away. Long Island in New York was formed by two glacial end moraines. The end moraine that formed this pile of rock and stone deposited by glaciers extends all the way out to Cape Cod, Massachusetts.

Even while a glacier is flowing slowly downhill, it deposits a layer of sediment underneath the glacier, which scientists call **ground moraine.** This layer of sediment makes a thick layer of unsorted sediment under the glacier that fills in low spots and evens out higher areas. Ground moraine is an important contribution to the fertile transported soils in many regions. Scientists knew that all these rocks and thick soils came from somewhere else but for a while they did not know that they came from glacial ice. This is easy to understand because the ice is not there today. Many scientists thought the big rocks looked like they had been dropped there and they thought maybe icebergs carried by a huge flood had brought them there. Because of this early hypothesis, lots of glacial deposits are called 'drift', because they were thought to have drifted in on icebergs. They correctly understood that only ice could have brought these materials, but not that there were thick 'rivers' of ice moving over the Earth in places where no ice exists today.

Another glacial depositional landform which forms under a glacier by water melting from the ice is an **esker** (**Figure** 10.43). These curving ridges of sand are deposited by streams that run within the ice along the base of the glacier. A normal stream carves its channel into the ground, forming a 'V' shaped channel, with the wide part of the 'V' at ground level. Because the water in this stream moves through the ice, not on the ground, only the deposits mark where these streams flowed. When the ice melts, the sediments form an upside down 'V' on the ground.

A **drumlin** is another type of asymmetrical hill that glaciers form but this one is made of sediments. A drumlin is an upside down teaspoon shaped hill which lines up with the direction the ice moved. The sediments dropped by the glacier are thought to be formed into a long narrow hill by the flowing glacier with the gentle sloped end pointing in the direction of ice flow. Usually drumlins are found in groups called drumlin fields.

Once material has been deposited by the glacier, water melting from the glacier can sort and retransport these sediments. An important difference between glacial deposits formed directly from the ice and those that form from glacial meltwater is their degree of sorting. Ice is capable of carrying a tremendous range of particle sizes, but solid ice does not sort any of these particles. So when material is dropped as ice melts, you will find very large pieces jumbled together in an unsorted deposit along with all the other size particles it carried. A very different situation occurs when running water moves particles. Liquid water cannot carry the large particles that ice carries. So as water moves through these unsorted deposits, it will select out only the smaller bits of sand and silt that it can carry. This produces a sorted deposit of just the sand and smaller particles transported by liquid water. Often these deposits form layer on layer and show the direction that rivers flowed. These deposits are called **stratified drift.** Often a broad area of stratified drift blankets the region just beyond

Figure 10.43: An esker is a winding ridge of sand and gravel deposited under a glacier by glacial meltwater. (45)

the furthest reach of the glacier, as meltwater streams spread material out forming a broad plain called an **outwash plain** (**Figure** 10.44).

Figure 10.44: Stratified drift carried by meltwater spreads out to form an outwash plain just beyond the furthest reaches of the glacial ice. (25)

If an isolated block of ice remains behind as the glacier retreats, it may be surrounded and eventually covered over by these layers of sediment. In many years time, as the ice melts, it fills the depression with water, forming small circular lakes called **kettle lakes** (**Figure** 10.45). These small lakes are common in the areas where glaciers made their farthest advances.

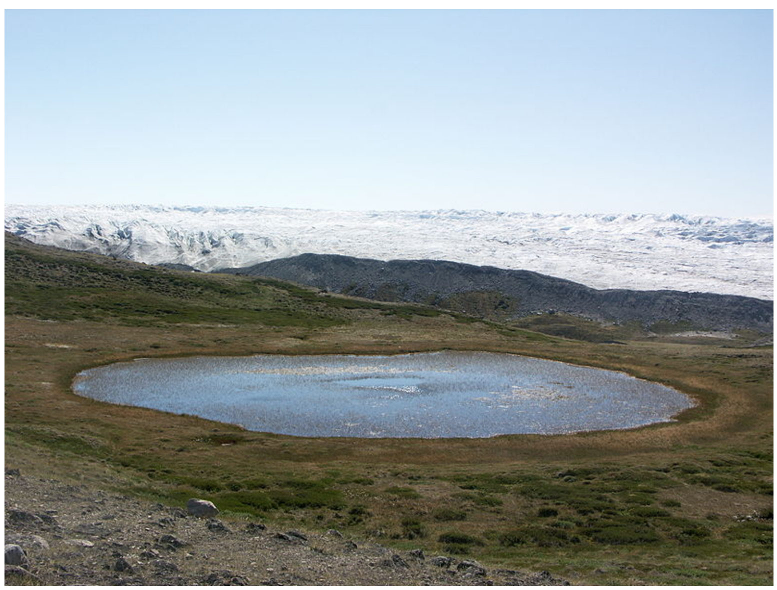


Figure 10.45: Small, circular lakes are common in areas of glacial outwash. They form from blocks of ice left behind as the glacier retreats. (21)

Several types of stratified deposits form in glacial regions but are not formed directly by the ice. In glaciated areas, lakes are covered by ice in the winter. During the winter months, darker, fine grained clays sink to the bottom of the quiet waters in the lake. In the spring, with glaciers producing lots of melting water, lighter colored sands are deposited on top of the darker layers at the bottom of the lakes. These distinctive layers, called **varves** have paired dark/light layers, with each layer representing one year of deposits.

Loess is a very fine grained, wind transported deposit which forms in areas of stratified drift glacial deposits. It is common in the middle of North America as well as the eastern central portion of Europe. This fine sediment is produced as glaciers grind the underlying rock producing a fine powder called **rock flour.**

Lesson Summary

- The movement of ice in the form of glaciers has transformed our mountainous land surfaces with its tremendous power of erosion.
- U-shaped valleys, hanging valleys, cirques, horns and aretes are just a few of the features sculpted by ice.
- The eroded material is later deposited as large glacial erratics, in moraines, stratified drift, outwash plains and drumlins.
- Varves are a very useful yearly deposit that forms in glacial lakes.

Review Questions

1. How much of the Earth's land surface is covered by glaciers today? Was the Earth ever covered by more ice than it is today?
2. What is the shape of a valley that has been eroded by glaciers? How did it get that shape?
3. What are two different features that can form as smaller side glaciers join the central main glacier?
4. Name and describe the two processes by which glaciers erode the surrounding rocks.
5. Name the erosional feature that would form as several glaciers in a mountainous region move downslope in different directions from a central peak.
6. Describe the different types of moraines formed by glaciers.
7. Describe the difference between glacial till and stratified drift. Give an example of how each type of deposit forms.
8. Name and describe the two asymmetrical hill shaped landforms created by glaciers.

Vocabulary

abrasion Scraping of the underlying bedrock, produced as ice flows against it.

arête Steep sided, sharp edged ridge that forms as two glaciers erode in opposite directions.

cirque Steep sided, bowl shaped depression formed as a glacier plucks and erodes underlying bedrock.

drumlin An asymmetrical hill formed from sediments under the flowing glacier.

end moraine Unsorted pile of glacial till that marks the furthest reach of a glacier's advance.

esker Long, curving, upside down 'V' shaped ridge of sediment deposited under a glacier by meltwater.

glacial erratic Large boulder with a different rock type or origin from the surrounding bedrock.

glacial striations Long, parallel scratches carved into underlying bedrock by moving glaciers.

glacial till Any unsorted deposit of sediment deposited by glacial ice.

ground moraine Thick layer of sediment deposited under a flowing glacier.

horn Sharp sided, angular peak formed as glaciers move away from a central peak.

kettle Lake Often circular lake formed in the outwash plain by stranded ice.

moraine Deposit of unsorted, rocky material on, under or left behind by glacial ice.

plucking Removal of blocks of underlying bedrock by the glacier as meltwater seeps into cracks & freezes.

roche moutonnée Asymmetrical hill of bedrock formed by abrasion and plucking of the moving glacier.

rock flour Fine sediments produced by abrasion of glaciers scrape over bedrock.

tarn Mountain lake formed by glacial meltwater and precipitation.

varve Paired deposit of light colored, coarser sediments and darker, fine grained sediments.

Points to Consider

- What features would you look for around where you live, to determine if glaciers had ever been present there?
- If glaciers had never formed on Earth, how would that affect the type of soil in the middle of North America?
- Can the process of erosion produce landforms that are beautiful?

10.5 Erosion and Deposition by Gravity

Lesson Objectives

- Describe the ways that material can move downhill by gravity.
- Discuss the factors that increase the possibility of landslides.
- Describe the different types of gravity driven movement of rock and soil.
- Describe ways to prevent and be aware of potential landslides or mudflows.

Introduction

So far in this chapter, you have learned about erosion and deposition by moving water in rivers and the ocean, erosion and deposition by glacial ice and erosion and deposition by wind. With this long list, you may think that we have covered all the types of erosion and deposition that can possibly occur. The force you may have forgotten is gravity! Perhaps because it is a constant force or perhaps because it is invisible, students often forget that gravity also acts to shape the Earth's surface. The examples we will consider here include sudden, dramatic events like **landslides,** as well as slow steady movements that happen over long periods of time. Whatever the example, we know that the force of gravity will always be there and it is changing the Earth's surface right now.

Gravity Moves Material Downhill

There are several ways that gravity can move material from a higher place to a lower one. Sometimes this happens along a cliff or a very steep slope. Material that has been loosened by some type of weathering simply falls away from the cliff because there is nothing to keep it in place. If you were to keep nudging your notebook towards the edge of your desk, eventually enough of the notebook would be off the desk to cause it to fall. Landslides happen when large amounts of rock suddenly fall down a cliff or mountainside.

Other times gravity simply makes things slide along rather slowly. You may have seen this as a classmate moves further and further down in their seat. It's not a very fast or dramatic movement, like your notebook falling to the floor, but slowly your friend is no longer sitting up straight in the seat. The same thing can happen to rock or even whole parts of a hillside. This might happen over a period of days or even weeks. In the end, the whole area of soil or rock has slid to a lower spot.

The last way that gravity moves material along is when it becomes very wet. **Saturated** soil flows downhill, often removing trees, homes and bridges that are in the way. To help you understand how water increases the chances of movement, think about playing in sand at the beach. If you were making a sand castle with dry sand, you could not build walls very well. If you add a little bit of water, it helps your walls to stand. A little bit of water helps to hold grains of sand or soil together. However, if you added lots of water, what would happen? Too much water causes the sand to flow quickly away. There are a couple of ways that soil or rock can get very wet and flow. Sometimes this happens if it has been raining for a very long time or if it rains very hard. In the spring, snow and ice begins to melt and much of this water moves into the ground. Springtime is a particularly dangerous time for landslides because there are heavier and more frequent rainfalls at this time of year and it is also the season when snow and ice melt. Extra water in the soil adds more weight to the slope and also makes the grains of soil lose contact with each other, allowing them to flow.

Contributing Factors

There are several factors that increase the chance that a landslide will occur. Some of these we can prevent and some we cannot. Whenever we dig into the base of a slope, this contributes to the likelihood of a landslide. There are many reasons why we might need to do this. We may want to build a house on flat ground, so we level out an area by cutting into a hillside. Roads and railroad tracks also need to be flat and level, so excavation of a slope could be necessary in areas where we travel frequently. This is particularly dangerous when the underlying rock layers also slope towards the area that is cut away or when layers of clay are present. If rock layers slope towards the region that is removed, then the support for those layers is gone and the overlying rocks can slip away, causing a landslide (**Figure** 10.46).

Soils rich in clay are water holding types of soils. If you have ever worked with clay in art class, you know that when clay is wet, it is very slippery. If there is a lot of clay in the soil, the clays hold onto the water when it rains. This slippery clay layer provides an easy surface for materials to slide over.

When construction workers need to cut into slopes for building a home or road, it is important to stabilize the slope to help prevent a landslide (**Figure** 10.47). Some ways that you may have seen on steep slopes along a highway include building supports into the slope or planting vegetation to keep the soil in place. Trees have deeper roots than grasses, but each type of plant produces benefits for particular areas. It is also a good idea to provide drainage for groundwater so that the slope does not become saturated.

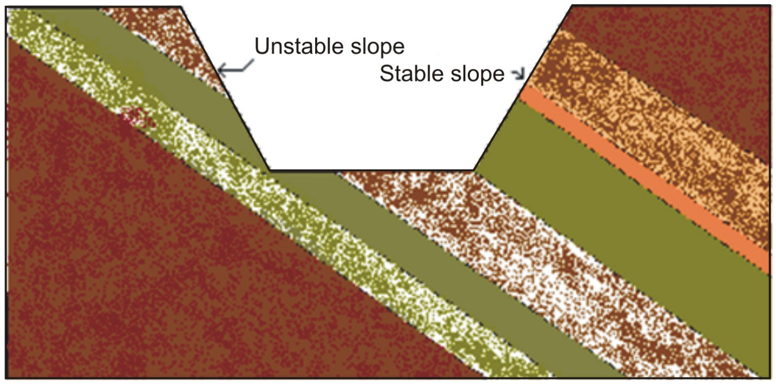


Figure 10.46: The slope of underlying materials must be considered when making road cuts. (43)

One well known cause of landslides is from the ground shaking. Sometimes the ground shakes from an earthquake, a volcanic eruption or even just a truck going by. We can't control earthquakes or volcanoes and some of the most devastating landslides have been started by these other natural hazards. Skiers and hikers need to be aware of the ways they disturb the snow they travel over or through to avoid setting off an **avalanche.** Most people buried by an avalanche do not survive, either because they freeze, are crushed by the weight of the snow or are unable to breathe. If you ski or snow board in deep powder, you should carry a small shovel in your backpack and attach a long, red lightweight cord to your waist or carry a GPS radio transmitter to help rescuers locate you in the event of an avalanche.

Types of Movement Caused by Gravity

Mechanical weathering loosens pieces of rock as water seeps into cracks in the rock and freezes. As these rocks fall, they form a big pile of angular rocks at the base of a cliff called a **talus slope** (**Figure** 10.48). If you travel along a road or highway through regions such as these, you may see signs warning of the danger along the road side. Sometimes as one rock falls, it hits another rock lower down, which hits another and so on and so forth. This is one way that a landslide or an avalanche can begin.

Landslides and Avalanches

Landslides and avalanches are the most dramatic, sudden and dangerous examples of earth materials moved by gravity. Usually the term landslide is used to mean solid rock that falls suddenly, whereas an avalanche is formed from snow. Most landslides happen along convergent plate boundaries, in regions of the world that are tectonically active. These regions are often mountainous and are places of frequent earthquakes and volcanic eruptions. When large amounts of rock suddenly break loose from a cliff or mountainside, they move quickly

Figure 10.47: It is important to reinforce a slope that has been cut away in order to prevent landslides. (19)

Figure 10.48: Pieces of rock regularly fall to the base of cliffs and form slopes known as talus slopes. (20)

and with tremendous force (**Figure** 10.49). Scientists believe that air gets trapped under the falling rocks and acts as a cushion that keeps the rock from slowing down. Landslides and avalanches can move as fast as 200 to 300 km/hour (**Figure** 10.50).

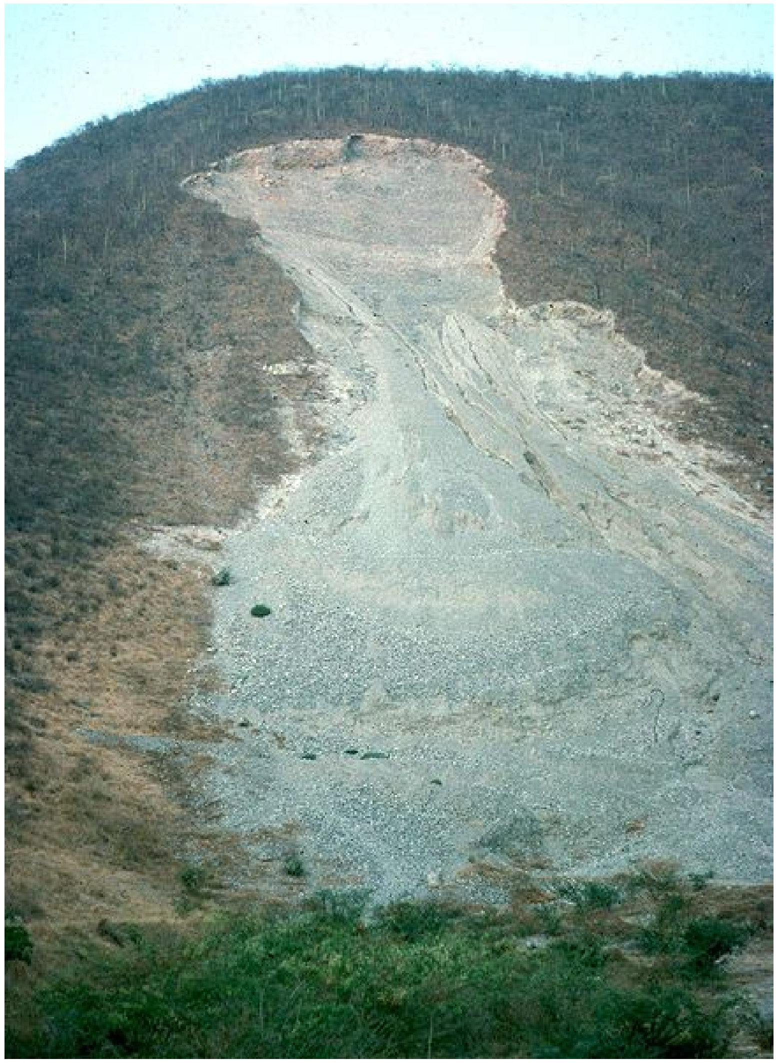


Figure 10.49: Landslides are called rock slides by geologists. (49)

Landslides are exceptionally destructive. They can bury everything in their path, including entire villages. Some landslides have created lakes when the rocky material dams a river or stream. Often homes are destroyed as hillsides collapse. If a landslide flows into a lake or bay, they can trigger a tsunami. In July of 1958, a landslide of 30.6 cubic meters of rock fell from 914m up on a steep slope at the end of Lituya Bay in Alaska (**Figure** 10.51). As that large volume of rock suddenly pushed away all the water, a 524m tsunami was formed. The tsunami produced by the landslide knocked down all the trees and vegetation surrounding the bay. In the area directly opposite the landslide, trees at elevations higher than the

Figure 10.50: An avalanche of snow moves suddenly and quickly down slope, burying everything in its path. (36)

Empire State Building were scoured off the valley walls. Fortunately, this event happened in an area where very few people were living. Most of the people who witnessed this event were in boats and most of them were able to survive because their boats rode on top of the wave, rather than being smashed by it.

Figure 10.51: This photograph of Lituya Bay in Alaska shows (in light gray) the areas damaged by the tsunami produced by a landslide sent 30.6 million cubic meters of rock into the bay. (24)

Landslides occur often in dry or semi-arid climates in areas with steep slopes or mountains. The California coastline, with its steep cliffs and years of drought punctuated by seasons of abundant rainfall, is more prone to landslides than many other regions. In areas where landslides are a frequent hazard, communities have put together warning systems, to help people be better prepared. Around San Francisco Bay, the National Weather Service and the United States Geological Survey have a set of rain gauges that monitor the condition of the soil. If soil becomes saturated, the weather service will issue a warning. Earthquakes, which can happen along western California's abundant faults, can also trigger landslides.

Mudflows and Lahars

Mudflows and **lahars** are also dramatic and dangerous natural hazards produced by the force of gravity (**Figure** 10.52). Mudflows tend to follow existing stream channels or ravines. Mudflows often occur on hillsides with soils rich in clay and with little sand or gravel. Where there is little rain, there is not much vegetation to hold the soil. That means mud will flow when a large storm produces a lot of rain in a short time. The saturated soils, without plant roots to keep them in place, flow downhill, following river channels, washing out bridges, trees and homes that are in their path.

Figure 10.52: The white areas on the otherwise green mountainsides mark scars from numerous mudflows. Mud deposited by the flow can be seen along the river channels. (27)

Some mudflows are as small as a few meters in length, width and depth. Others can travel for thousands of meters, moving materials tens of meters deep and hundreds of meters wide. On steep slopes, a mudflow might travel very quickly, ending abruptly when it reaches flatter ground. Thicker, more viscous mudflows move over a period of days or even years. The movement could be as slow as several millimeters/day or perhaps several meters/day.

A lahar is a particular type of mudflow that flows down the steep sides of a stratovolcano (**Figure** 10.53). These explosive volcanoes produce tremendous quantities of ash and dust as they erupt. Snow and ice from the top of the volcano melt, producing floods of meltwater.

This now hot water mixes with volcanic ash to produce exceptionally hazardous flows that move as fast as 60 km/hour. In Columbia, the eruption of Nevado del Ruiz in 1985 produced a lahar that killed more than 23,000 people as it swept over villages and flattened everything in its way. In 1991, a typhoon arrived just after Mt. Pinatubo in the Philippines erupted. The rains soaked the volcanic ash and dust that blanketed the entire region and produced lahars that killed 1,500 people and displaced thousands more from their homes.

Figure 10.53: A lahar is a mudflow that forms from volcanic ash and debris. (9)

Slump and Creep

Fortunately not all types of erosion by gravity cause so many problems. Some less dramatic types of movement, correctly called **slump** and **creep,** move earth materials slowly down a hillside. When materials slump down a hillside, they tend to move as a large block along a curved surface. This type of earth movement often happens when a slope is undercut, leaving little or no support for the overlying materials. It can also happen when too much weight is added to an unstable slope. It is very unfortunate when that extra weight comes from building someone's home on a slippery slope. When earth materials slump down a hillside, a crescent shaped scar marks the place they moved from (**Figure** 10.54). A wise homeowner will look for these crescent shaped scars along surrounding hillsides when considering buying a new home. If they are present, it is a good possibility that earth materials have slipped before.

The term creep is used to describe the very gradual movement of soil downhill, because it just barely creeps along. Creep is such a slow way that earth materials move that no human would likely notice. One way to tell that earth materials are slowly moving downhill is to look at the growth of trees. Have you ever seen a tree whose trunk bends almost horizontally to the ground and then grows upwards? If there are many trees growing this

Figure 10.54: Material that slumps down a hillside often moves as a whole unit, leaving behind a crescent shaped scar. (3)

way, it is likely that the ground is slowly moving down hill (**Figure** 10.55). Tilted telephone or power company poles are also signs that this type of motion is occurring.

Prevention and Awareness

Landslides cause $1-2 billion damage in the United States each year and cause traumatic and sudden loss of life and homes in many areas of the world. Wherever you live, it is important to be aware of your surroundings and notice the changes in the natural world that occur. In times of heavy rainfall, look for areas of soil that are unusually wet, cracks or bulges in soil along hillsides, tilting of decks or patios, leaning poles or fences. Even sticking windows and doors can mean that the ground is moving. As soil pushes slowly against a house it can put pressure on the walls that knocks windows and doors out of plumb. Areas that are very likely to produce landslides are places where they have occurred before, at the top or bottom of a steep slope and anywhere where slopes have been steepened for construction of homes or roads. You can help to prevent landslides around your home by planting vegetation and trees along slopes to help hold soil in place. Different types of retaining walls can help to keep a slope stable. It is important to install good drainage in a hill that is near a home or road to keep the soil from getting saturated. Loss of life and property can be minimized or prevented with good planning and awareness.

Figure 10.55: Trees with curved trunks are often signs that the hillside is slowly creeping downhill. (15)

Lesson Summary

- Gravity moves earth materials from higher elevations to lower elevations.
- Landslides, avalanches and mudflows are very rapid and dangerous examples of erosion by gravity.
- Slump and creep happen slowly but surely, moving material downslope.
- Planting trees and vegetation, building retaining walls and providing good drainage are ways to help prevent this type of erosion.

Review Questions

1. Name three ways that gravity moves materials. Describe each.
2. What natural events and human actions can trigger a landslide or avalanche?
3. What makes landslides and avalanches move at such great speeds?
4. Compare and contrast a mudflow and a lahar.
5. Name two ways that soil can move slowly down a slope.
6. What can people do to help prevent landslides or mudflows?

Vocabulary

avalanche Mass of snow that suddenly moves down a mountain under the influence of gravity.

creep Exceptionally slow movement of soil down hill.

lahar Volcanic mudflow formed when heavy rains or snow and ice melt and combine with volcanic ash & dust.

landslide Rapid movement downslope of rock and debris under the influence of gravity.

mudflow Saturated soil that can flow very rapidly or slowly down a slope depending on the viscosity of the flow.

saturated Soil that has become completely soaked with water.

slump Downslope slipping of a mass of soil or rock, generally along a curved surface.

talus slope A pile of angular rock fragments formed at the base of a cliff or mountain.

Points to Consider

- Why might someone build a home on top of land where a landslide has happened before?
- Could a landslide happen anywhere in the world? What would make it likely or unlikely in your area?
- What new technologies might help people to know when a landslide will occur?

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(41) http://en.wikipedia.org/wiki/File:Bradley_1930_dreikanter.jpg. GNU-FDL.

(42) http://en.wikipedia.org/wiki/File:Padre_Island_National_Seashore_-_sand_dunes3.jpg. GNU-FDL.

(43) Julie Sandeen. . CC-BY-SA.

(44) http://en.wikipedia.org/wiki/File:Alluvial_fn_in_Iran.jpg. GNU-FDL.

(45) http://en.wikipedia.org/wiki/File:Esker_(PSF).png. CC-BY-SA.

(46) http://en.wikipedia.org/wiki/File:Durdledoor.jpg. GNU-FDL.

(47) http://en.wikipedia.org/wiki/File:Ocean_surface_waves.jpg. GNU-FDL.

(48) http://en.wikipedia.org/wiki/File:Meander.jpg. GNU-FDL.

(49) http://en.wikipedia.org/wiki/File:Slide-guerrero1.jpg. CC-BY-SA.

(50) http://en.wikipedia.org/wiki/File:WOAHdubs.jpg. GNU-FDL.

(51) http://en.wikipedia.org/wiki/File:Sandstorm.jpg. GNU-FDL.

(52) http://en.wikipedia.org/wiki/File:Wavecut_platform_southerndown_pano.jpg. GNU-FDL.

(53) http://en.wikipedia.org/wiki/File:Dorset,_stack_(small).jpg. GNU-FDL.

(54) http://en.wikipedia.org/wiki/File:53sitges.jpg. GNU-FDL.

(55) http://en.wikipedia.org/wiki/File:Saltation-mechanics.gif. GNU-FDL.

Chapter 11

Evidence About Earth's Past

11.1 Fossils

Lesson Objectives

- Explain why it is rare for an organism to be preserved as a fossil.
- Distinguish between body fossils and trace fossils.
- Describe five types of fossilization.
- Explain the importance of index fossils, and give several examples.
- Describe what a living fossil is.

Introduction

Throughout human history, people have discovered fossils and wondered about the creatures that lived long ago. In ancient times, fossils inspired legends of monsters and other strange creatures. The Chinese writer Chang Qu reports the discovery of "dragon bones," which were probably dinosaur fossils in China 2,000 years ago. The griffin, a mythical creature with a lion's body and an eagle's head and wings, was probably based on skeletons of *Protoceratops* that were discovered by nomads in Central Asia (**Figure** 11.1).

Another fossil reminded the Greeks of the coiled horns of a ram. The Greeks named them ammonites after the ram god *Ammon.* Similarly, legends of the Cyclops may be based on fossilized elephant skulls found in Crete and other Mediterranean islands. Can you see why (**Figure** 11.2)?

Many of the real creatures whose bones became fossilized were no less marvelous than the mythical creatures they inspired (**Figure** 11.3). The giant pterosaur *Quetzalcoatlus* had a wingspan of up to 12 meters (39 feet). The dinosaur *Argentinosaurus* had an estimated

Figure 11.1: Griffin (left) and *Protoceratops* (right). (1)

Figure 11.2: Ammonite (left) and Elephant Skull (right). (23)

weight of 80,000 kg, equal to the weight of seven elephants! Other fossils, such as the trilobite and ammonite, impress us with their bizarre forms and delicate beauty.

Figure 11.3: Kolihapeltis sp (left) and Ammonite (right). (24)

How Fossils Form

A **fossil** is any remains or trace of an ancient organism. Fossils include **body fossils**, left behind when the soft parts have decayed away, as well as **trace fossils**, such as burrows, tracks, or fossilized waste (feces) (**Figure** 11.4).

Figure 11.4: Coprolite (fossilized waste or feces) from a meat-eating dinosaur. (4)

The process of a once living organism becoming a fossil is called **fossilization**. Fossilization is a very rare process: of all the organisms that have lived on Earth, only a tiny percentage of them ever become fossils. To see why, imagine an antelope that dies on the African plain. Most of its body is quickly eaten by scavengers, and the remaining flesh is soon eaten by insects and bacteria, leaving behind only scattered bones. As the years go by, the bones are scattered and fragmented into small pieces, eventually turning into dust and returning their nutrients to the soil. It would be rare for any of the antelope's remains to actually be preserved as a fossil.

On the ocean floor, a similar process occurs when clams, oysters, and other shellfish die. The soft parts quickly decay, and the shells are scattered over the sea floor. If the shells are in shallow water, wave action soon grinds them into sand-sized pieces. Even if they are not in shallow water, the shells are attacked by worms, sponges, and other animals (**Figure** 11.5).

For animals that lack hard shells or bones, fossilization is even more rare. As a result, the fossil record contains many animals with shells, bones, or other hard parts, and few soft-bodied organisms. There is virtually no fossil record of jellyfish, worms, or slugs. Insects, which are by far the most common land animals, are only rarely found as fossils. Because mammal teeth are much more resistant than other bones, a large portion of the mammal fossil record consists of teeth. This means the fossil record will show many organisms that had shells, bones or other hard parts and will almost always miss the many soft-bodied organisms that lived at the same time.

Because most decay and fragmentation occurs at the surface, the main factor that contributes to fossilization is quick burial. Marine animals that die near a river delta may be buried by sediment carried by the river. A storm at sea may shift sediment on the ocean floor, covering and helping to preserve skeletal remains.

On land, burial is rare, so consequently fossils of land animals and plants are less common than marine fossils. Land organisms can be buried by mudslides or ash from a volcanic eruption, or covered by sand in a sandstorm. Skeletons can be covered by mud in lakes, swamps, or bogs as well. Some of the best-preserved skeletons of land animals are found in the La Brea Tar Pits of Los Angeles, California. Although the animals trapped in the pits probably suffered a slow, miserable death, their bones were preserved perfectly by the sticky tar.

In spite of the difficulties of preservation, billions of fossils have been discovered, examined, and identified by thousands of scientists. The fossil record is our best clue to the history of life on Earth, and an important indicator of past climates and geological conditions as well. The fossil record also plays a key role in our lives. **Fossil fuels** such as coal, gas, and oil formed from the decayed remains of plants and animals that lived millions of years ago.

Types of Fossils

Fossilization can occur in many ways. Most fossils are preserved in one of five processes (**Figure** 11.6):

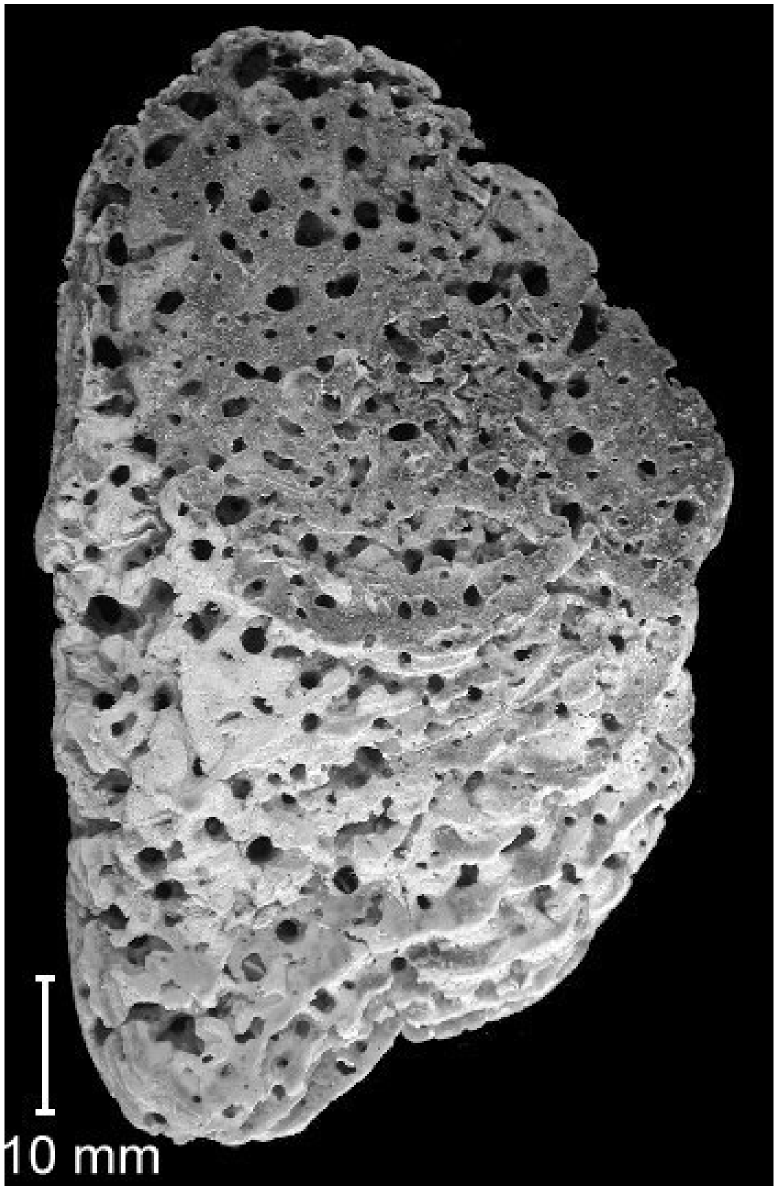

Figure 11.5: Fossil shell that has been attacked by a boring sponge. (12)

Preserved Remains

The most rare form of fossilization is the preservation of original skeletal material and even soft tissue. For example, insects have been preserved perfectly in **amber**, which is ancient tree sap. Several mammoths and even a Neanderthal hunter have been discovered frozen in glaciers. These preserved remains allow scientists the rare opportunity to examine the skin, hair, and organs of ancient creatures. Scientists have collected DNA from these remains and compared the DNA sequences to those of modern creatures.

Permineralization

The most common method of fossilization is **permineralization**. After a bone, wood fragment, or shell is buried in sediment, it may be exposed to mineral-rich water that moves through the sediment. This water will deposit minerals into empty spaces, producing a fossil. Fossil dinosaur bones, petrified wood, and many marine fossils were formed by permineralization.

Molds and Casts

In some cases, the original bone or shell dissolves away, leaving behind an empty space in the shape of the shell or bone. This depression is called a **mold**. Later the space may be filled with other sediments to form a matching **cast** in the shape of the original organism. Many mollusks (clams, snails, octopi and squid) are commonly found as molds and casts because their shells dissolve easily.

Replacement

In some cases, the original shell or bone dissolves away and is replaced by a different mineral. For example, shells that were originally calcite may be replaced by dolomite, quartz, or pyrite. If quartz fossils are surrounded by a calcite matrix, the calcite can be dissolved away by acid, leaving behind an exquisitely preserved quartz fossil.

Compression

Some fossils form when their remains are compressed by high pressure. This can leave behind a dark imprint of the fossil. Compression is most common for fossils of leaves and ferns, but can occur with other organisms, as well.

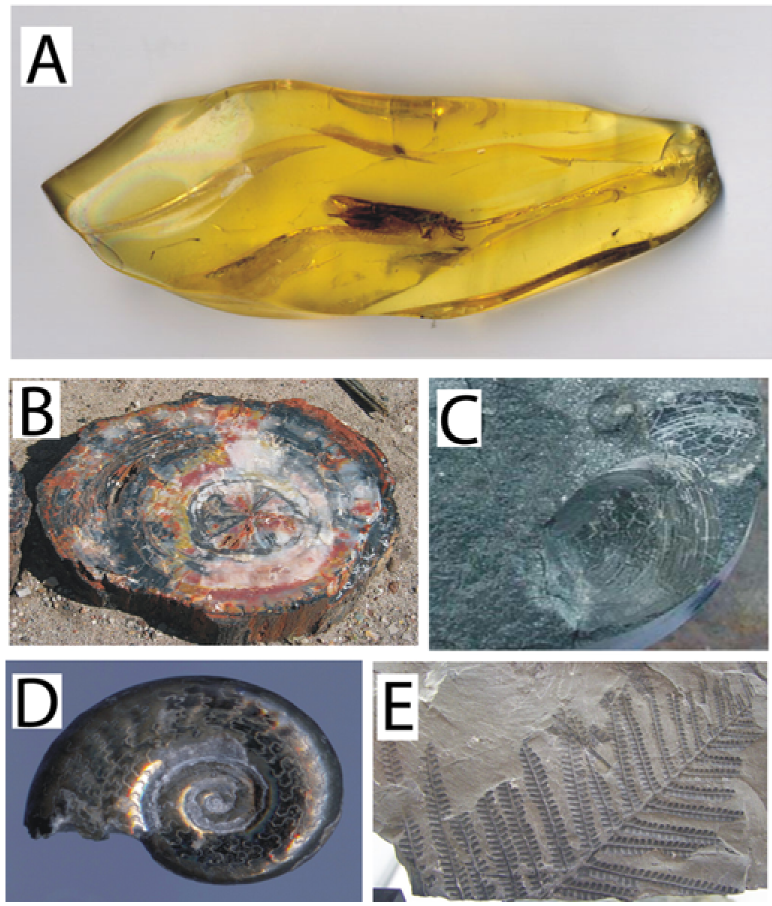

Figure 11.6: Five types of fossils: (A) Insect preserved in amber (B) Petrified wood (permineralization) (C) Cast and mold of a clam shell (D) Pyritized ammonite (E) Compression fossil of a fern. (8)

Exceptional Preservation

Some rock beds have produced exceptional fossils. Fossils from these beds may show evidence of soft body parts that are not normally preserved. Two of the most famous examples of soft organism preservation are the Burgess Shale in Canada and the Solnhofen Limestone in Germany. The Burgess Shale is 505 million years old and records the first explosion of shelled organisms in Earth's oceans. Many of the Burgess Shale fossils are bizarre animals that seem unrelated to any other animal group. The Solnhofen Limestone is 145 million years old and contains fossils of many soft-bodied organisms that are not normally preserved, such as jellyfish. The most famous Solnhofen fossil is *Archaeopteryx,* one of the earliest birds. Although it resembles a dinosaur fossil, impressions of feathers can clearly be seen (**Figure** 11.7).

Figure 11.7: Fossils from Lagerstätten: *Archaeopteryx* (left) and *Anomalocaris* (right). *Archaeopteryx* was an early bird. *Anomalocaris* was an enormous predator (one meter long) that lived 500 million years ago. (13)

Index Fossils and Living Fossils

The fossil record shows clearly that over time, life on Earth has changed. Fossils in relatively young rocks tend to resemble animals and plants that are living today. In older rocks, fossils are less similar to modern organisms.

As scientists collected fossils from different rock layers and formations, they discovered that they could often recognize the rock layer by the assemblage of fossils it contained. Some fossils proved particularly useful in matching up rock layers from different regions. These fossils, called **index fossils**, are widespread but only existed for a relatively brief period of time. When a particular index fossil is found, the relative age of the bed is immediately known.

Many fossils may qualify as index fossils. Ammonites, trilobites, and graptolites are often used as index fossils, as are various **microfossils**, or fossils of microscopic organisms. Fossils of animals that drifted in the upper layers of the ocean are particularly useful as index fossils, as they may be distributed all over the world.

In contrast to index fossils, **living fossils** are organisms that have existed for a tremendously long period of time without changing very much at all. For example, the Lingulata brachiopods have existed from the Cambrian period to the present, a time span of over 500 million years! Modern specimens of Lingulata are almost indistinguishable from their fossil counterparts (**Figure** 11.8).

Figure 11.8: Fossil *Lingula* (left) and Modern *Lingula* (right). (25)

Clues from Fossils

Fossils are our best form of evidence about the history of life on Earth. In addition, fossils can give us clues about past climates, the motions of plates, and other major geological events.

The first clue that fossils can give is whether an environment was **marine** (underwater) or **terrestrial** (on land). Along with the rock characteristics, fossils can indicate whether the water was shallow or deep, and whether the rate of sedimentation was slow or rapid. The amount of wear and fragmentation of a fossil can allow scientists to estimate the amount of wave action or the frequency of storms.

Often fossils of marine organisms are found on or near tall mountains. For example, the Himalayas, the tallest mountains in the world, contain trilobites, brachiopods, and other marine fossils. This indicates that rocks on the seabed have been uplifted to form huge mountains. In the case of the Himalayas, this happened when the Indian Subcontinent began to ram into Asia about 40 million years ago.

Fossils can also reveal clues about past climate. For example, fossils of plants and coal beds have been found in Antarctica. Although Antarctica is frozen today, in the past it must have been much warmer. This happened both because Earth's climate has changed and because Antarctica has not always been located at the South Pole.

One of the most fascinating patterns revealed by the fossil record is a number of **mass extinctions**, times when many species died off. Although the mass extinction that killed the dinosaurs is most famous, the largest mass extinction in Earth history occurred at the end of the Permian period, about 250 million years ago. In this catastrophe, it is estimated that over 95% of species on Earth went extinct! The cause of these mass extinctions is not definitely known, but most scientists believe that collisions with comets or asteroids were the cause of at least a few of these disasters.

Lesson Summary

- A fossil is any remains of ancient life. Fossils can be body fossils, which are remains of the organism itself or trace fossils, such as burrows, tracks, or other evidence of activity.
- Preservation as a fossil is a relatively rare process. The chances of becoming a fossil are enhanced by quick burial and the presence of preservable hard parts, such as bones or shells.
- Fossils form in five ways: preservation of original remains, permineralization, molds and casts, replacement, and compression.
- Rock formations with exceptional fossils are called very important for scientists to study. They allow us to see information about organisms that we may not otherwise ever know.
- Index fossils are fossils that are widespread but only existed for a short period of time. Index fossils help scientists to find the relative age of a rock layer and match it up with other rock layers.
- Living fossils are organisms that haven't changed much in millions of years and are still alive today.
- Fossils give clues about the history of life on Earth, environments, climate, movement of plates, and other events.

Review Questions

1. What factors make it more likely that an animal will be preserved as a fossil?
2. What are the five main processes of fossilization?
3. A scientist wants to determine the age of a rock. The rock contains an index fossil and an ancient relative of a living fossil. Which fossil will be more useful for dating the rock, and why?
4. The island of Spitzbergen is in the Arctic Ocean north of Norway, near the North Pole. Fossils of tropical fruits have been found in coal deposits in Spitzbergen. What does this indicate?

Further Reading / Supplemental Links

- http://www.fossils-facts-and-finds.com/index.html
- http://www.sdnhm.org/kids/fossils/index.html
- http://www.sdnhm.org/kids/fossils/index.html
- http://www.amnh.org/exhibitions/mythiccreatures
- http://www.amnh.org/exhibitions/mythiccreatures/land/griffin.php
- http://www.tonmo.com/science/fossils/mythdoc/mythdoc.php
- http://www.geo.ucalgary.ca/~macrae/Burgess_Shale
- http://www.ucmp.berkeley.edu/mesozoic/jurassic/solnhofen.html

Vocabulary

amber Fossilized tree sap.

body fossil The remains of an ancient organism. Examples include shells, bones, teeth, and leaves.

cast A structure that forms when sediments fill a mold and harden, forming a replica of the original structure.

fossil Any remains or trace of an ancient organism.

fossil fuel A fuel that was formed from the remains of ancient organisms. Examples include coal, oil, and natural gas.

fossilization The process of becoming a fossil.

index fossil A fossil that identifies and shows the relative age of the rocks in which it is found. Index fossils come from species that were widespread but existed for a relatively brief period of time.

living fossil A modern species or genus that has existed on Earth for millions of years without changing very much.

marine Of or belonging to the sea.

mass extinction A period of time when an unusually high number of species became extinct.

microfossil A fossil that must be studied with the aid of a microscope.

mold An impression made in sediments by the hard parts of an organism.

permineralization A type of fossilization in which minerals are deposited into the pores of the original hard parts of an organism.

terrestrial Of or belonging to the land.

trace fossil Evidence of the activity of an ancient organism. Examples include tracks, trails, burrows, tubes, boreholes, and bite marks.

Points to Consider

- What are some other examples of mythical creatures that may be based on fossils?
- Why is it so rare for an animal to be preserved as a fossil?
- Some organisms are more easily preserved than others. Why is this a problem for scientists who are studying ancient ecosystems?
- Why are examples of amazing fossil preservation so valuable for scientists?
- Many fossils of marine organisms have been found in the middle of continents, far from any ocean. What conclusion can you draw from this?

11.2 Relative Ages of Rocks

Lesson Objectives

- Explain Steno's laws of superposition and original horizontality.
- Based on a geological cross-section, identify the oldest and youngest formations.
- Explain what an unconformity represents.
- Use fossils to correlate rock layers.

Introduction

In 1666, a young doctor named Nicholas Steno was invited to dissect the head of an enormous great white shark that had been caught by local fisherman near Florence, Italy. Steno was struck by the resemblance of the shark's teeth to fossils, known as "tongue stones," recovered from inland mountains and hills (**Figure** 11.9).

Figure 11.9: Fossil Shark Tooth (left) and Modern Shark Tooth (right). (2)

While it may seem obvious today, most people at the time did not believe that fossils were once part of living creatures. The reason was that the fossils of clams, snails, and other marine animals were found in tall mountains, miles from any ocean. Two schools of thought explained these fossils. Some religious writers believed that the shells were washed up during the Biblical flood. But this explanation could not account for the fact that fossils were not only found on mountains, but also *within* mountains, in rocks that had been quarried from deep below Earth's surface. Seeking an alternate explanation, other writers proposed that the fossils had formed within the rocks as a result of mysterious forces. In other words, fossil shells, bones, and teeth were never a part of a living creature!

Steno had other ideas. For Steno, the close resemblance between fossils and modern organisms was impossible to ignore. Instead of invoking supernatural forces to explain fossils, Steno concluded that fossils were once parts of living creatures. He then sought to explain how fossil seashells could be found in rocks far from any ocean. As in the Tyrannosaurus rex **Figure** 11.10, fossils resemble living organisms.

Superposition of Rock Layers

Steno first proposed that if a rock contained the fossils of marine animals, the rock was formed from sediments that were deposited on the seafloor. These rocks were then uplifted to become mountains. Based on those assumptions, Steno made a remarkable series of conjectures that are now known as **Steno's Laws**.

Figure 11.10: Tyrannosaurus rex fossil resembling a living organism. (16)

Original Horizontality

Because sediments are deposited under water, they will form flat, horizontal layers (**Figure** 11.11). If a sedimentary rock is found tilted, the layer was tilted after it was formed.

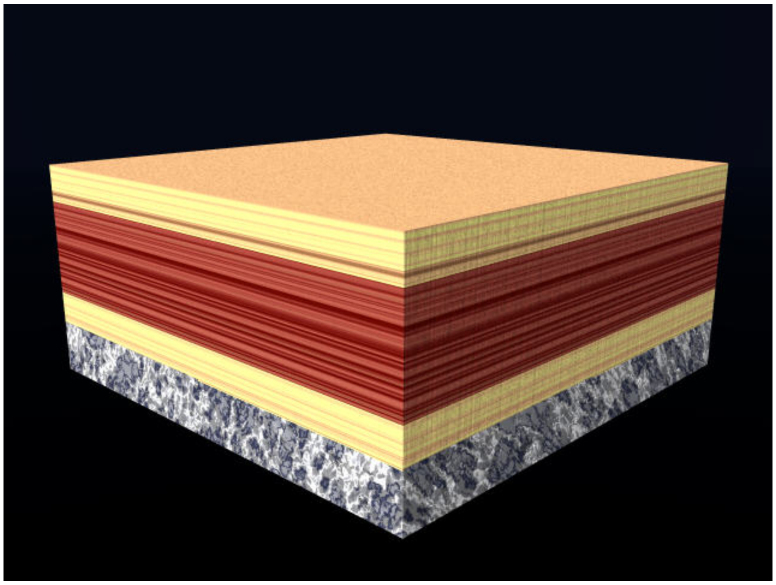

Figure 11.11: Sedimentary layers that have been deposited horizontally. (26)

Lateral Continuity

Sediments were deposited in continuous sheets that spanned the body of water that they were deposited in. When a valley cuts through sedimentary layers, it can be assumed that the rocks on either side of the valley were originally continuous.

Superposition

Sedimentary rocks are deposited one on top of another. Therefore, the youngest layers are found at the top, and the oldest layers are found at the bottom of the sequence.

Cross-Cutting Relationships

A rock formation or surface that cuts across other rock layers is younger than the rock layers it disturbs. For example, if an igneous intrusion goes through a series of metamorphic rocks, the intrusion must be younger than the metamorphic rocks that it cuts through (**Figure** 11.12).

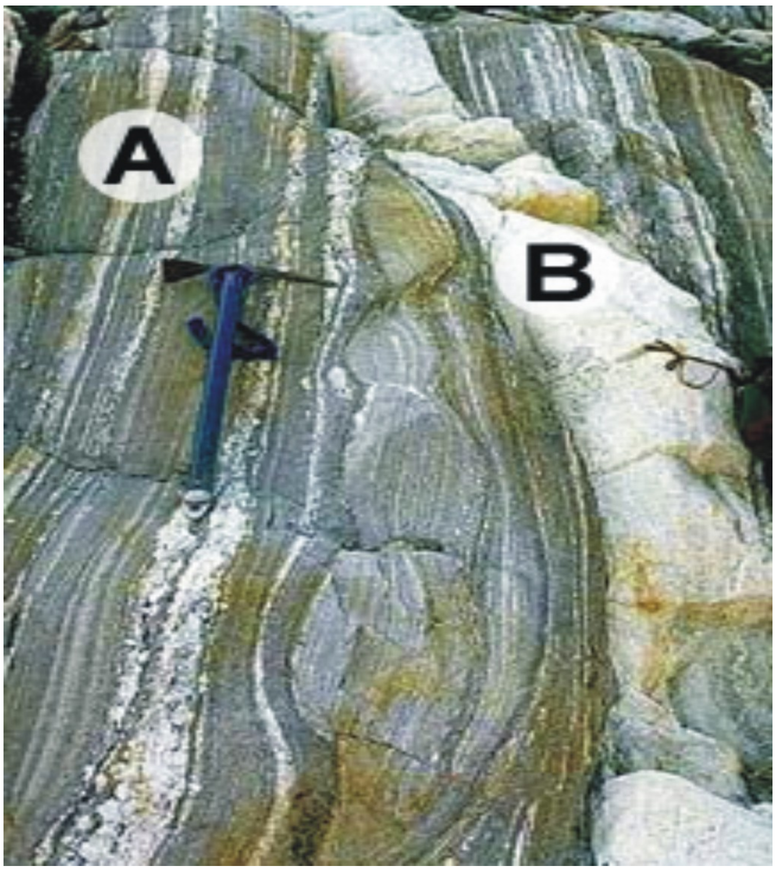

Figure 11.12: Cross cutting relationships: (A) Older banded gneiss (B) The white granite intrusion. The granite must be younger than the gneiss, because it cuts across the existing gneiss. (20)

The Grand Canyon provides an excellent illustration of Steno's laws. **Figure** 11.13 shows the many horizontal layers of sedimentary rock that make up the canyon. This nicely illustrates the principle of original horizontality. The youngest rock layers are at the top of the canyon, while the oldest are at the bottom, which is described by the law of superposition. Distinctive rock layers, such as the Kaibab Limestone, can be matched across the broad expanse of the canyon. We know these rock layers were once connected, which is described in the rule of lateral continuity. Finally, the Colorado River cuts through all the layers of sedimentary rock to form the canyon. Based on the principle of cross-cutting relationships, the river must be younger than all of the rock layers that it cuts through.

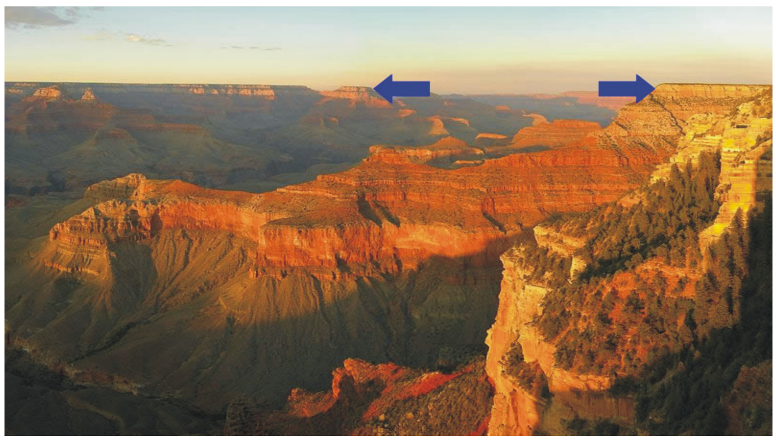

Figure 11.13: Grand Canyon, with the Kaibab Limestone marked with arrows. (6)

Determining the Relative Ages of Rocks

The **relative age** of a rock is its age in comparison with other rocks. If you know the relative ages of two rock layers, you know which is older and which is younger, but you do not know how old the layers are in years. In some cases, it is very tricky to determine the sequence of events that leads to a certain formation. Take the example, **Figure** 11.14:

The principle of cross-cutting relationships states that a fault or intrusion is younger than the rocks that it cuts through. The fault labeled "E" cuts through all three sedimentary rock layers (A, B, and C) and also cuts through the intrusion (D). So the fault must be the youngest formation that is seen. The intrusion (D) cuts through the three sedimentary rock layers, so it must be younger than those layers.

The principle of superposition states that the oldest sedimentary rock units are at the bottom, and the youngest are at the top. Based on this, layer C is oldest, followed by B and A. So the full sequence of events is as follows:

1. Layer C formed.

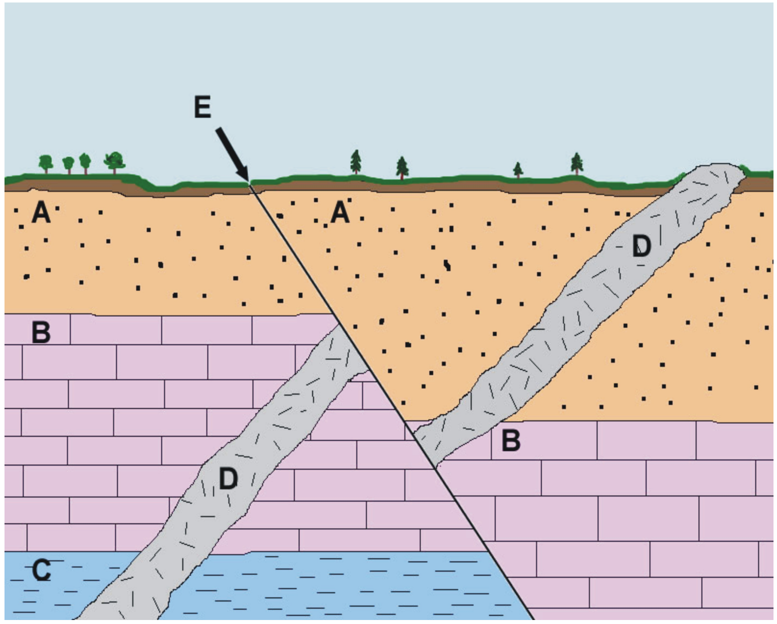

Figure 11.14: Cross-section of sedimentary layers: (A-C) Igneous intrusion (D) Cross-section (E) Fault. (14)

2. Layer B formed.
3. Layer A formed.
4. When layers A-B-C were present,intrusion D formed.
5. Intrusion D cut through layers A – C.
6. Fault E formed, shifting rocks A through C and intrusion D.
7. Weathering and erosion occurred, forming a layer of soil on top of layer A.

Unconformities in Rock Layers

Steno discovered the rules for determining the relative age of rock beds, but he did not have a good understanding of how long it would take for these rock formations to form. At the time, most Europeans believed that the Earth was around 6,000 years old, a figure that was based on the amount of time estimated for the events described in the Bible. One of the first to question this time scale was a Scottish geologist named James Hutton (1726-1797). Often described as the founder of modern geology, Hutton formulated a philosophy called **uniformitarianism**: *The present is the key to the past.* According to uniformitarianism, the same processes we see around us today operated in the past as well. For example, if erosion and deposition occur slowly now, they probably have always occurred slowly.

Hutton discovered places where sedimentary rock beds lie on an eroded surface. Such a formation is called an **unconformity**, or a gap in rock layers, where some rocks were eroded away. Hutton reconstructed the sequence of events that led to this formation. For example, consider the famous unconformity at Siccar Point, on the coast of Scotland (**Figure** 11.15).

Figure 11.15: Hutton's Unconformity on the Coast of Scotland. (17)

Based on figure 5, at least nine geological events can be inferred:

1. A series of sedimentary beds is deposited on an ocean floor.
2. The sediments harden into sedimentary rock.
3. The sedimentary rocks are uplifted and tilted, exposing them above the ocean surface.
4. The tilted beds are eroded by rain, ice, and wind to form an irregular surface.
5. A sea covers the eroded sedimentary rock layers.
6. New sedimentary layers are deposited.
7. The new layers harden into sedimentary rock.
8. These layers are tilted.
9. Uplift occurs, exposing the new sedimentary rocks above the ocean surface.

Hutton realized that an enormous period of time was needed to account for the repeated episodes of deposition, rock formation, uplift, and erosion that led to the formation of an unconformity, like the one at Siccar Point. Hutton realized that the age of Earth should not be measured in thousands of years, but millions of years.

Matching Rock Layers

Superposition and cross-cutting are helpful when rocks are touching one another, but are useless when rocks are kilometers or even continents apart. Three kinds of clues help geologists match rock layers across great distances. The first is the fact that some sedimentary rock formations span vast distances, recognizable across large regions. For example, the Pierre Shale formation can be recognized across the Great Plains, from New Mexico to North Dakota. The famous White Cliffs of Dover in southwest England can be matched to similar white cliffs in Denmark and Germany.

Figure 11.16: White layer of clay that marks the Cretaceous-Tertiary Boundary. (5)

A second clue could be the presence of a **key bed**, or a particularly distinctive layer of rock that can be recognized across a large area. Volcanic ash flows are often useful as key beds because they are widespread and easy to identify. Probably the most famous example of a key bed is a layer of clay found at the boundary between the Cretaceous Period and the Tertiary Period, the time that the dinosaurs went extinct (**Figure** 11.16). This thin layer of sediment, only a few centimeters thick, contains a high concentration of the element iridium. Iridium is rare on Earth but common in asteroids. In 1980, a team of scientists led by Luis Alvarez and his son Walter proposed that a huge asteroid struck Earth about 66 million years ago, causing forest fires, acid rain, and climate change that wiped out the dinosaurs.

A third type of clue that helps scientists compare different rock layers is index fossils. Recall that index fossils are the remains of organisms that were widespread but only existed for a relatively short period of time. If two rock units both contain the same type of index fossil, their age is probably very similar.

As scientists collected fossils from all over the world, they recognized that rocks of different ages contain distinctive types of fossils. This pattern led to the creation of the **geologic time scale** and helped to inspire Darwin's theory of evolution (**Figure** 11.17).

Each era, period, and epoch of the geologic time scale is defined by the fossils that appeared at that time. For example, Paleozoic rocks typically contain trilobites, brachiopods, and crinoid fossils. The presence of dinosaur bones indicate that a rock is from the Mesozoic era, and the particular type of dinosaur will allow the rock to be identified as Triassic, Jurassic, or Cretaceous. The Cenozoic Era is also known as the Age of Mammals, and the Quaternary Period represents the time when the first humans spread across Earth.

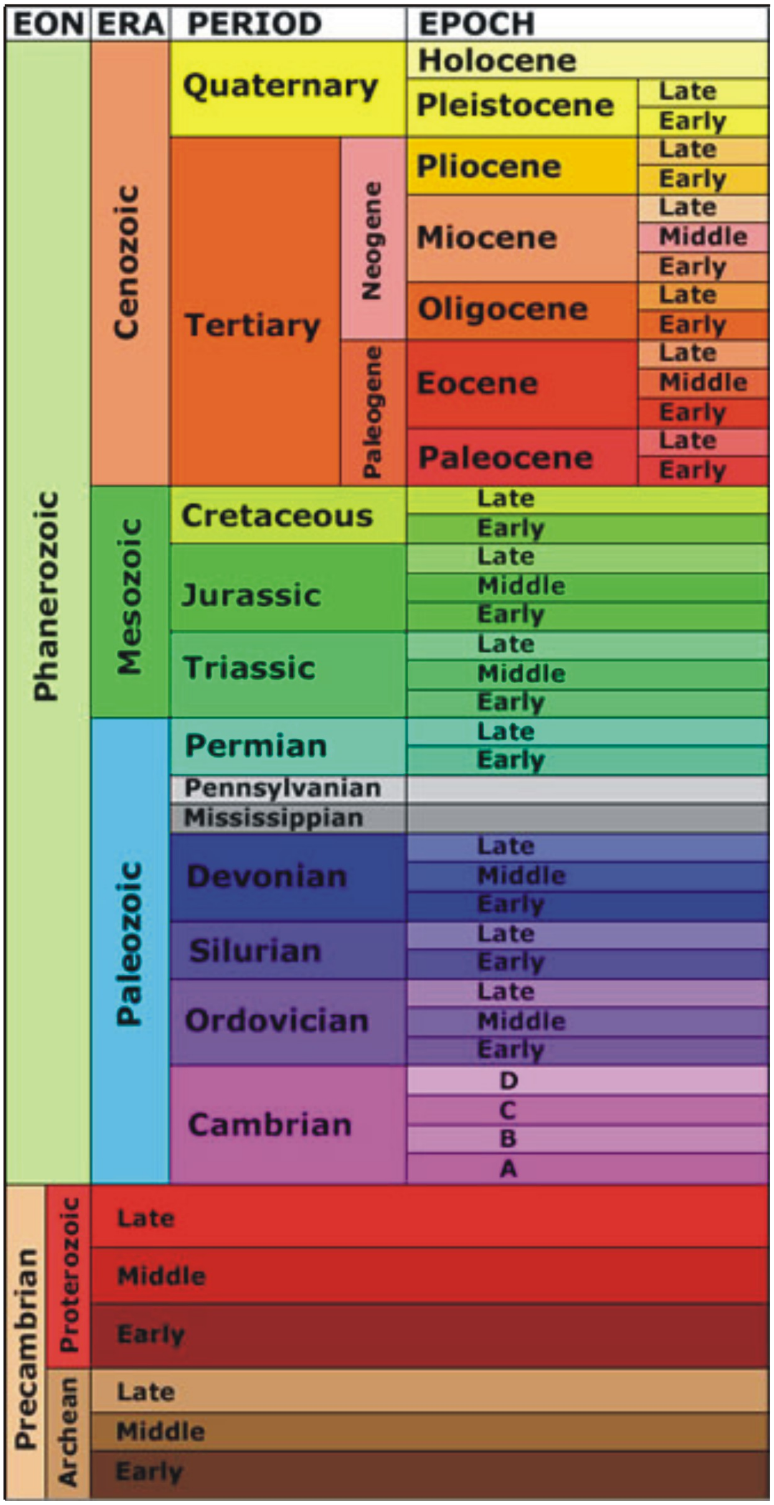

Figure 11.17: Geologic Time Scale. (19)

Lesson Summary

- Nicholas Steno first formulated the principles that allow scientists to determine the relative ages of rocks in the 17th century. Steno stated that sedimentary rocks are formed in continuous, horizontal layers, with younger layers on top of older layers. A century later, James Hutton discovered the law of cross-cutting relationships: a fault or igneous intrusion is younger than the rocks that it cuts through. Hutton also was the first to realize the vast amounts of time that would be needed to create an unconformity, a place where sedimentary rocks lie above an eroded surface.
- Other methods come into play when comparing rock layers that are separated by a large distance. Many sedimentary rock formations are large and can be recognized across a region. Distinctive rock layers, called key beds, are also useful for correlating rock units. Fossils, especially index fossils, are the most useful way to compare different rock layers. Changes of fossils over time led to the development of the geologic time scale.

Review Questions

1. In the 15th century, a farmer finds a rock that looks exactly like a clamshell. What did the farmer probably conclude about how the fossil got there?
2. Which of Steno's Laws is illustrated by each of the following images in **Figure** 11.18?
3. What is the sequence of rock units in **Figure** 11.19, from oldest to youngest?
4. What kind of geological formation is shown in the outcrop in **Figure** 11.20, and what sequence of events does it represent?
5. The three outcrops in **Figure** 11.21 are very far apart. Based on what you see, which fossil is an index fossil, and why?

Further Reading / Supplemental Links

- http://pubs.usgs.gov/gip/fossils/contents.html
- http://www.ucmp.berkeley.edu/exhibits/index.php
- http://alan-cutler.com/excerpt.html
- http://www.uvm.edu/~ccoutu/evolution/qanda/?Page=time/relative.html&SM=time/timemenu.html
- http://www.ucmp.berkeley.edu/fosrec/McKinney.html
- http://en.wikipedia.org

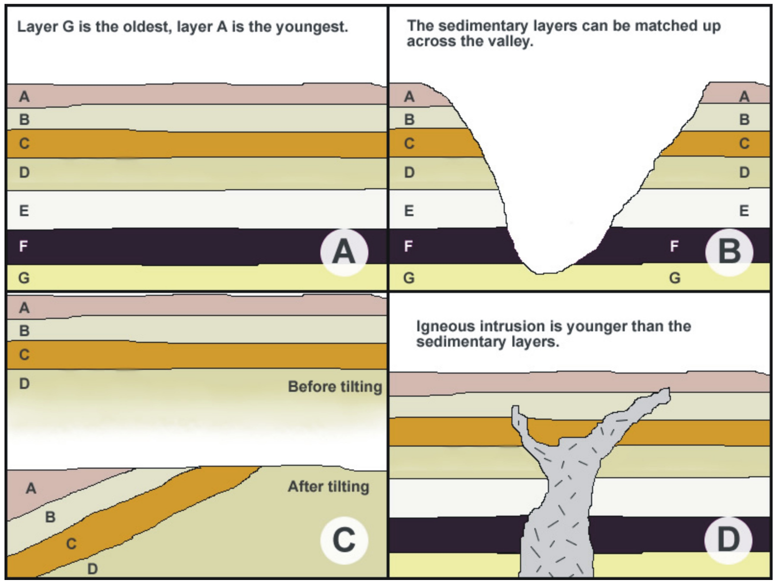

Figure 11.18: Illustration of Steno's Laws (22)

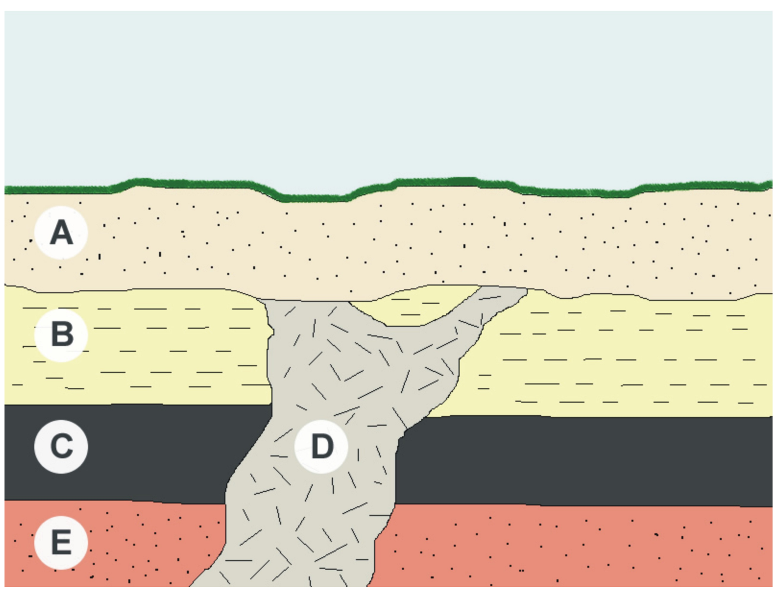

Figure 11.19: Sequence of Rock Units (27)

Figure 11.20: Outcrop (9)

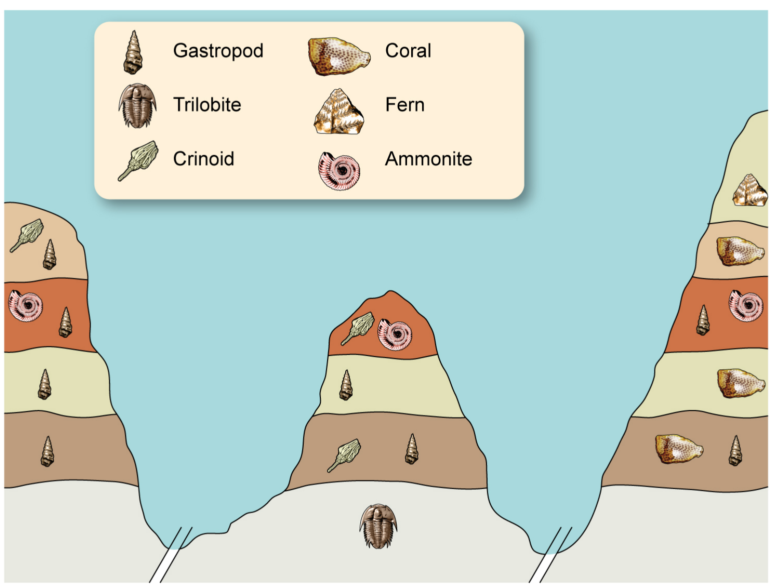

Figure 11.21: Fossils (11)

Vocabulary

cross-cutting relationships One of Steno's principles that states that an intrusion or fault is younger than the rocks that it cuts through.

geologic time scale A division of Earth's history into blocks of time distinguished by geologic and evolutionary events.

key bed A distinctive, widespread rock layer that formed at a single time.

lateral continuity One of Steno's principles that states that a sedimentary rock layer extends sideways as wide as the basin in which it forms.

original horizontality One of Steno's principles that states that sedimentary layers were horizontal or flat lying at the time they were deposited.

relative age The age of an object in comparison with the age of other objects.

superposition One of Steno's principles that states that in a sequence of sedimentary rock layers, the oldest layer is at the bottom and the youngest layer is at the top.

unconformity A boundary between rocks of very different ages. Unconformities are often marked by an erosional surface.

uniformitarianism The idea that the geologic processes that shape the land today have acted in basically the same way throughout Earth's history.

Points to Consider

- In Nicholas Steno's time, why didn't most people believe the fossils were the remains of ancient organisms?
- How did Steno explain the presence of marine fossils in high mountains?
- What was the significance of unconformities to James Hutton?
- How can you determine the relative age of two rock layers that are very far apart?

11.3 Absolute Ages of Rocks

Lesson Objectives

- Define the difference between absolute age and relative age.

- Describe four methods of absolute dating.
- Explain what radioactivity is and give examples of radioactive decay.
- Explain how the decay of radioactive materials helps to establish the age of an object.
- Estimate the age of an object, given the half-life and the amounts of radioactive and daughter materials.
- Give four examples of radioactive materials that are used to date objects, and explain how each is used.

Introduction

As we learned in the previous lesson, index fossils and superposition are effective methods of determining the **relative age** of objects. In other words, you can use superposition to tell you that one rock layer is older than another. But determining the **absolute age** of a substance (its age in years) is a much greater challenge. To accomplish this, scientists use a variety of evidence, from tree rings to the amounts of radioactive materials in a rock.

Tree Rings

In regions outside the tropics, trees grow more quickly during the warm summer months than during the cooler winter. This pattern of growth results in alternating bands of light-colored, low density "early wood" and dark, high density "late wood." Each dark band represents a winter; by counting rings it is possible to find the age of the tree (**Figure** 11.22). The width of a series of growth rings can give clues to past climates and various disruptions such as forest fires. Droughts and other variations in the climate make the tree grow slower or faster than normal, which shows up in the widths of the tree rings. These tree ring variations will appear in all trees growing in a certain region, so scientists can match up the growth rings of living and dead trees. Using logs recovered from old buildings and ancient ruins, scientists have been able to compare tree rings to create a continuous record of tree rings over the past 2,000 years. This tree ring record has proven extremely useful in creating a record of climate change, and in finding the age of ancient structures.

Ice Cores and Varves

Several other processes result in the accumulation of distinct yearly layers that can be used for dating. For example, layers form within glaciers because there tends to be less snowfall in the summertime, allowing a dark layer of dust to accumulate on top of the winter snow (**Figure** 11.23). To study these patterns, scientists drill deep into ice sheets, producing cores hundreds of meters long. Scientists analyze these ice cores to determine how the climate has changed over time, as well as to measure concentrations of atmospheric gases. The longest cores have helped to form a record of polar climate stretching hundreds of thousands of years back.

Figure 11.22: Cross-section showing growth rings. The thick, light-colored part of each ring represents rapid spring and summer growth. The thin, dark part of each ring represents slow autumn and winter growth. (3)

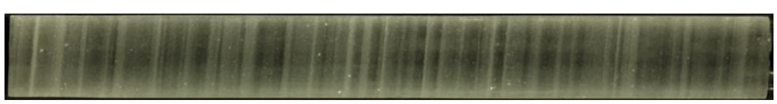

Figure 11.23: Ice core section showing annual layers. (7)

Another example of yearly layers is the deposition of sediments in lakes, especially the lakes that are located at the end of glaciers. Rapid melting of the glacier in the summer results in a thick, sandy deposit of sediment. These thick layers alternate with thin, clay-rich layers deposited during the winter. The resulting layers, called **varves**, give scientists clues about past climate conditions. For example, an especially warm summer might result in a very thick layer of sediment deposited from the melting glacier. Thinner varves can indicate colder summers, because the glacier doesn't melt as much and carry as much sediment into the lake.

Age of Earth

While tree rings and other annual layers are useful for dating relatively recent events, they are not of much use on the vast scale of geologic time. During the 18th and 19th centuries, geologists tried to estimate the age of Earth with indirect techniques. For example, geologists measured how fast streams deposited sediment, in order to try to calculate how long the stream had been in existence. Not surprisingly, these methods resulted in wildly different estimates, from a few million years to "quadrillions of years." Probably the most reliable of these estimates was produced by the British geologist Charles Lyell, who estimated that 240 million years have passed since the appearance of the first animals with shells. Today scientists know his estimate was too young; we know that this occurred about 530 million years ago.

In 1892, William Thomson (later known as Lord Kelvin) calculated the age of Earth in a systematic fashion (**Figure** 11.24). He assumed that the Earth began as a ball of molten rock, which has steadily cooled over time. From these assumptions, he calculated that the Earth was 100 million years old. This estimate was a blow to geologists and supporters of Charles Darwin's theory of evolution, which required an older Earth to provide time for evolution to take place.

Thomson's calculations, however, were soon shown to be flawed when radioactivity was discovered in 1896. **Radioactivity** is the tendency of certain atoms to decay into lighter atoms, emitting energy in the process. Radioactive materials in Earth's interior provide a steady source of heat. Calculations of Earth's age using radioactive decay showed that Earth is actually much older than Thomson calculated.

Radioactive Decay

The discovery of radioactive materials did more than disprove Thomson's estimate of Earth's age. It provided a way to find the absolute age of a rock. To understand how this is done, it is necessary to review some facts about atoms.

Atoms contain three particles: protons, neutrons, and electrons. Protons and neutrons are located in the nucleus, while electrons orbit around the nucleus. The number of protons

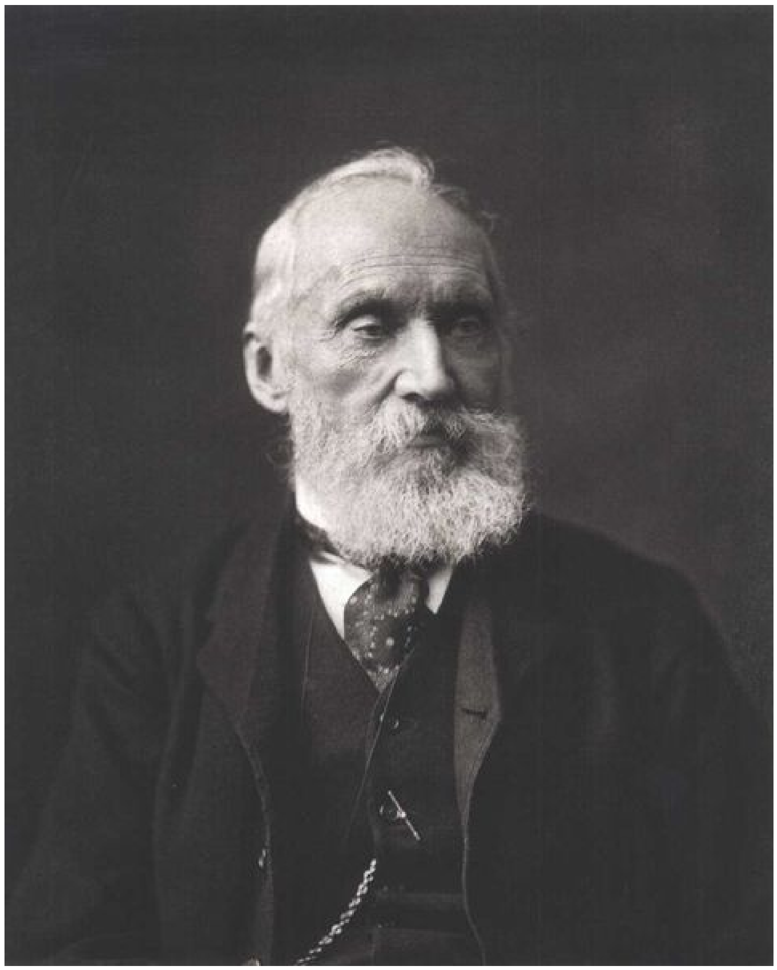

Figure 11.24: Lord Kelvin. (18)

determines which element you're examining. For example, all atoms of carbon have six protons, all atoms of oxygen have eight protons, and all atoms of gold have 79 protons. The number of neutrons, however, is variable. An atom of an element with a different number of neutrons is an **isotope** of that element. For example, the isotope carbon-12 contains 6 neutrons in its nucleus, while the isotope carbon-13 has 7 neutrons.

Some isotopes are **radioactive**, which means they are unstable and likely to decay. This means the atom will spontaneously change from an unstable form to a stable form. There are two forms of nuclear decay that are relevant in how geologists can date rocks (**Table** (11.1)):

Table 11.1: **Types of Radioactive Decay**

Particle	Composition	Effect on Nucleus
Alpha	2 protons, 2 neutrons	The nucleus contains two fewer protons and two fewer neutrons.
Beta	1 electron	One neutron decays to form a proton and an electron, which is emitted.

(*Source:* Kurt Rosenkrantz, *License:* CC-BY-SA)

If an element decays by losing an alpha particle, it will lose 2 protons and 2 neutrons. If an atom decays by losing a beta particle, it loses just one electron.

So what does this have to do with the age of Earth? Radioactive decay eventually results in the formation of stable **daughter products**. Radioactive materials decay at known rates. As time passes, the proportion of radioactive isotopes will decrease and the proportion of daughter isotopes will increase. A rock with a relatively high proportion of radioactive isotopes is probably very young, while a rock with a high proportion of daughter products is probably very old.

Scientists measure the rate of radioactive decay with a unit called **half-life**. The half-life of a radioactive substance is the amount of time, on average, it takes for half of the atoms to decay. For example, imagine a radioactive substance with a half-life of one year. When a rock is formed, it contains a certain number of radioactive atoms. After one year (one half-life), half of the radioactive atoms have decayed to form stable daughter products, and 50% of the radioactive atoms remain. After another year (two half-lives), half of the remaining radioactive atoms have decayed, and 25% of the radioactive atoms remain. After the third year (three half-lives), 12.5% of the radioactive atoms remain. After four years (four half-lives), 6.25% of the radioactive atoms remain, and after 5 years (five half-lives), only 3.125% of the radioactive atoms remain.

If you find a rock whose radioactive material has a half life of one year and measure 3.125%

radioactive atoms and 96.875% daughter atoms, you can assume that the substance is 5 years old. The decay of radioactive materials can be shown with a graph (**Figure** 11.25). If you find a rock with 75% of the radioactive atoms remaining, about how old is it?

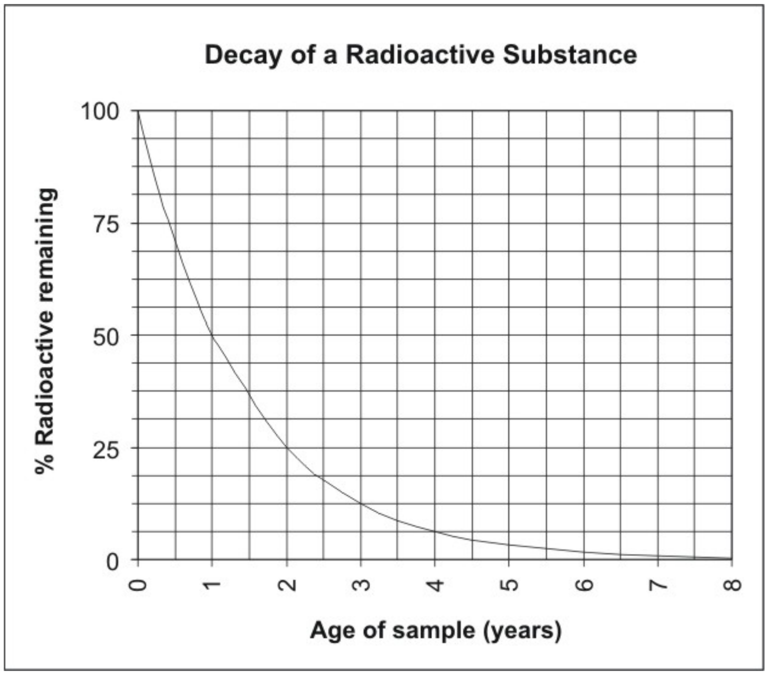

Figure 11.25: Decay of an imaginary radioactive substance with a half-life of one year. (10)

Radiometric Dating of Rocks

In the process of **radiometric dating**, several isotopes are used to date rocks and other materials. Using several different isotopes helps scientists to check the accuracy of the ages that they calculate.

Carbon Dating

Earth's atmosphere contains three isotopes of carbon. Carbon-12 is stable and accounts for 98.9% of atmospheric carbon. Carbon-13 is also stable and accounts for 1.1% of atmospheric carbon. Carbon-14 is radioactive and is found in tiny amounts. Carbon-14 is produced naturally in the atmosphere when cosmic rays interact with nitrogen atoms. The amount of carbon-14 produced in the atmosphere at any particular time has been relatively stable through time.

Radioactive carbon-14 decays to stable nitrogen-14 by releasing a beta particle. The nitrogen atoms are lost to the atmosphere, but the amount of carbon-14 decay can be estimated by measuring the proportion of radioactive carbon-14 to stable carbon-12. As a substance ages, the relative amount of carbon-14 decreases.

Carbon is removed from the atmosphere by plants during the process of photosynthesis. Animals consume this carbon when they eat plants or other animals that have eaten plants. Therefore carbon-14 dating can be used to date plant and animal remains. Examples include timbers from an old building, bones, or ashes from a fire pit. Carbon dating can be effectively used to find the age of materials between 100 and 50,000 years old.

Potassium-Argon Dating

Potassium-40 decays to argon-40 with a half-life of 1.26 billion years. Because argon is a gas, it can escape from molten magma or lava. Therefore any argon that is found in a crystal probably formed as a result of the decay of potassium-40. Measuring the ratio of potassium-40 to argon-40 will yield a good estimate of the age of the sample.

Potassium is a common element found in many minerals such as feldspar, mica, and amphibole. The technique can be used to date igneous rocks from 100,000 years to over a billion years old. Because it can be used to date geologically young materials, the technique has been useful in estimating the age of deposits containing the bones of human ancestors.

Uranium-Lead Dating

Two isotopes of uranium are used for radiometric dating. Uranium-238 decays to form lead-206 with a half-life of 4.47 billion years. Uranium-235 decays to form lead-207 with a half-life of 704 million years.

Uranium-lead dating is usually performed on crystals of the mineral zircon (**Figure** 11.26). When zircon forms in an igneous rock, the crystals readily accept atoms of uranium but reject atoms of lead. Therefore, if any lead is found in a zircon crystal, it can be assumed that it was produced from the decay of uranium.

Uranium-lead dating can be used to date igneous rocks from 1 million years to around 4.5 billion years old. Some of the oldest rocks on Earth have been dated using this method, including zircon crystals from Australia that are 4.4 billion years old.

Limitations of Radiometric Dating

Radiometric dating can only be used on materials that contain measurable amounts of radioactive materials and their daughter products. This includes organic remains (which compared to rocks are relatively young, less than 100,000 years old) and older rocks. Ideally, several different radiometric techniques will be used to date the same rock. Agreement between these values indicates that the calculated age is accurate.

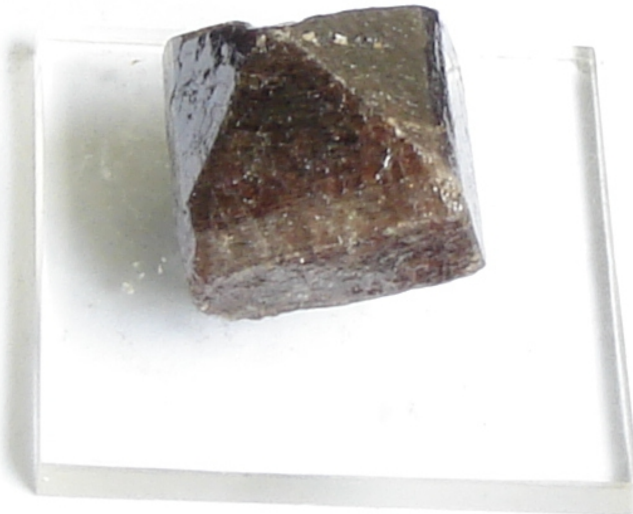

Figure 11.26: Zircon crystal. (15)

In general, radiometric dating works best for igneous rocks and is not very useful for determining the age of sedimentary rocks. To estimate the age of a sedimentary rock deposit, geologists search for nearby or interlayered igneous rocks that can be dated. For example, if a sedimentary rock layer is sandwiched between two layers of volcanic ash, its age is between the ages of the two ash layers.

Using a combination of radiometric dating, index fossils, and superposition, geologists have constructed a well-defined timeline of Earth history. For example, an overlying lava flow can give a reliable estimate of the age of a sedimentary rock formation in one location. Index fossils contained in this formation can then be matched to fossils in a different location, providing a good age measurement for that new rock formation as well. As this process has been repeated all over the world, our estimates of rock and fossil ages has become more and more accurate.

Lesson Summary

- Techniques such as superposition and index fossils can tell you the relative age of objects, which objects are older and which are younger. Other types of evidence are needed to establish the absolute age of objects in years. Geologists use a variety of techniques to establish absolute age, including radiometric dating, tree rings, ice cores, and annual sedimentary deposits called varves.
- Radiometric dating is the most useful of these techniques—it is the only technique that can establish the age of objects older than a few thousand years. The concentrations of several radioactive isotopes (carbon-14, potassium-40, uranium-235 and -238) and

their daughter products are used to determine the age of rocks and organic remains.

Review Questions

1. What four techniques are used to determine the absolute age of an object or event?
2. A radioactive substance has a half-life of 5 million years. What is the age of a rock in which 25% of the original radioactive atoms remain?
3. A scientist is studying a piece of cloth from an ancient burial site. She determines that 40% of the original carbon-14 atoms remain in the cloth. Based on the carbon decay graph (**Figure** 11.27), what is the approximate age of the cloth?

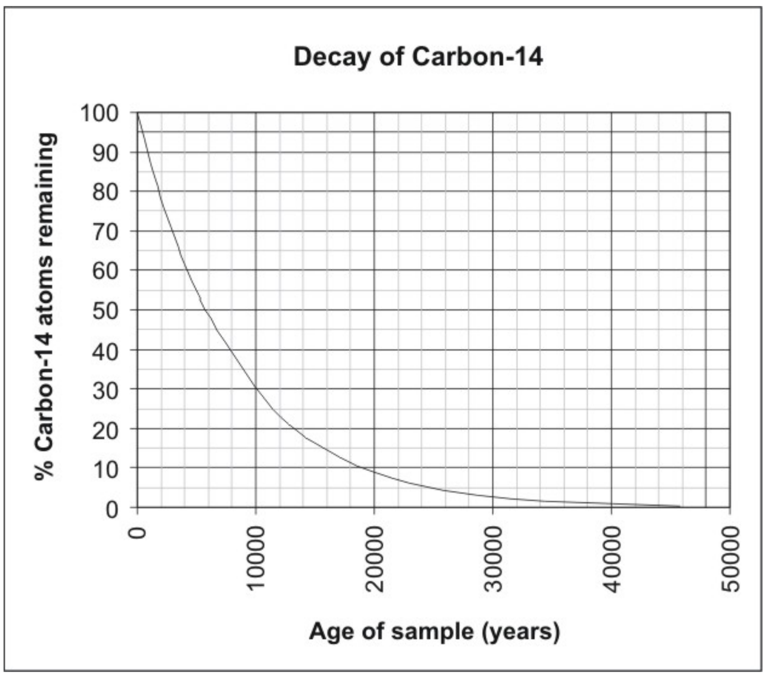

Figure 11.27: (21)

4. Which radioactive isotope or isotopes would you use to date each of the following objects? Explain each of your choices.
   (a) A 4 billion year old piece of granite.
   (b) A one million year old bed of volcanic ash that contains the footprints of hominids (human ancestors).
   (c) The fur of a woolly mammoth that was recently recovered frozen in a glacier.
   (d) A fossilized trilobite recovered from a bed of sandstone that is about 500 million years old.
5. The principle of uniformitarionism states that the present is the key to the past. In other words, the processes that we see happening today probably worked in a similar

way in the past. Why is it important to assume that the rate of radioactive decay has remained constant over time?

Further Reading / Supplemental Links

- http://www.pbs.org/wgbh/nova/elnino/reach/living.html
- http://nvl.nist.gov/pub/nistpubs/jres/109/2/j92cur.pdf
- http://pubs.usgs.gov/gip/geotime/radiometric.html

Vocabulary

absolute age The age of an object in years.

alpha particle Particle consisting of two protons and two neutrons that is ejected from the nucleus during radioactive decay.

beta particle Particle consisting of a single electron that is ejected from the nucleus during radioactive decay. A beta particle is created when a neutron decays to form a proton and the emitted electron.

daughter product Stable substance that is produced by the decay of a radioactive substance. For example, uranium-238 decays to produce lead-207.

half-life Amount of time required for half of the atoms of a radioactive substance to decay and form daughter products.

ice core Cylinder of ice extracted from a glacier or ice sheet.

isotope An atom of an element that has a differing number of neutrons.

radioactive Substance that is unstable and likely to emit energetic particles and radiation.

radioactivity Emission of high-energy particles and/or radiation by certain unstable atoms.

radiometric dating Process of using the concentrations of radioactive substances and daughter products to estimate the age of a material. As substances age, the amounts of radioactive atoms decrease while the amounts of daughter materials increase.

relative age Age of an object as compared to other objects.

tree ring Layer of wood in a tree that forms in one year. You can determine the age of a tree by counting its rings.

varve Thin layer of sediment deposited on a lakebed over the course of one year usually found at the bottom of glacial lakes.

Points to Consider

- Why are techniques like tree rings, ice cores, and varves only useful for events that occurred in the last few thousand years?
- Why was it so important for Darwin and his followers to prove that the Earth was very old?
- Why is it important to use more than one method to find the age of a rock or other object?

Image Sources

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(2) Tribal,Eli Hodapp. *teeth in stone.jpg,*`http://www.flickr.com/photos/io` *burn/1805341269/ Fossil Shark Tooth (left) and Modern Shark Tooth (right).*. GNU-FDL,CC-A 2.0.

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(21) .

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Chapter 12

Earth's History

12.1 Geologic Time Scale

In this Earth's history chapter, you will learn about some of the ways that scientists study the history of Earth and how they use clues from rocks and fossils to piece together pictures of how the Earth has changed over billions of years. You will learn how the Earth formed and how life gradually developed on Earth. You will also gain an appreciation for how life changes on Earth and how living things respond to changes in their environments.

Lesson Objectives

- Discuss how scientists know that the Earth is billions of years old.
- Describe how Earth's history can be represented by the geologic time scale.

Introduction

How many years is a "long time?" We often express time in hours or days, and 10 or 20 years certainly feels like a long time. Imagine if you needed to think about one million, 100 million, or even several billion years. These exceptional lengths of time seem unbelievable, but they are exactly the spans of times that scientists use to describe the Earth.

The Earth is 4 1/2 billion years old. That's 4,500,000,000 years! Have places like the Grand Canyon and the Mississippi River been around for all of those years, or were they formed more recently? When did the giant Rocky Mountains form and when did dinosaurs walk the Earth? To answer these questions, you have to think about times that were millions or billions of years ago.

Historical geologists are scientists who study the Earth's past. They study clues left on the

Earth to learn two main things: the *order* in which events happened on Earth, and *how long* it took for those events to happen. For example, they have learned that the Mississippi River formed many millions of years after the Grand Canyon began forming. They have also concluded that dinosaurs lived on the Earth for about 200 million years.

Scientists have put together the **geologic time scale** to describe the order and duration of major events on Earth for the last 4 1/2 billion years. Some examples of events listed on the geologic time scale include the first appearance of plant life on Earth, the first appearance of animals on Earth, the formation of Earth's mountains, and the **extinction** of the dinosaurs.

You will learn about some of the scientific principles that historical geologists use to describe Earth's past. You will also learn some of the clues that scientists use to learn about the past and shows you what the geologic time scale looks like.

Evaluating Prior Knowledge

Before you work through this lesson, think about the following questions. Be sure that you can answer each one. They will help you better understand this lesson.

What is a fossil and how does a fossil form?

How does a sedimentary rock form?

In what types of locations do sedimentary rocks form?

How do you determine the relative and absolute ages of rock layers?

Geologic Time

The first principle you need to understand about geologic time is that the laws of nature never change. This means that the laws describing how things work are the same today as they were billions of years ago. For example, water freezes at 0ºC. This law has always been true and always will be true. Knowing that natural laws never change helps you think about Earth's past, because it gives you clues about how things happened very long ago. It means that we can use present-day processes to interpret the past. Imagine you find **fossils** of sea animals in a rock. The laws of nature say that sea animals must live in the sea. That law has never changed, so the rock must have formed near the sea. The rock may be millions of years old, but the fossils in it are a clue for us today about how it formed.

Now imagine that you find that same rock with fossils of a sea animal in a place that is very dry and nowhere near the sea. How could that be? Remember that the laws of nature never change. Therefore, the fossil means that the rock definitely formed by the sea. This tells you that even though the area is now dry, it must have once been underwater. Clues like this have helped scientists learn that Earth's surface features have changed many times. Spots that were once covered by warm seas may now be cool and dry. Places that now have tall mountains may have once been low, flat ground. These kinds of changes take place over many millions of years, but they are still slowly going on today. The place where you live right now may look very different in the far away future.

Relative and Absolute Age Dating of Rocks

The clues in rocks help scientists put together a picture of how places on Earth have changed. Scientists noticed in the 1700s and 1800s that similar layers of sedimentary rocks all over the world contain similar fossils. They used **relative dating** to order the rock layers from oldest to youngest. In the process of relative dating, scientists do not determine the exact age of a fossil but do learn which ones are older or younger than others. They saw that the fossils in older rocks are different from the fossils in younger rocks. For example, older rock layers contain only reptile fossils, but younger rock layers may also contain mammal fossils.

Scientists divided Earth's history into several chunks of time when the fossils showed similar things living on the Earth. They gave each chunk of time a name to help them keep track of how Earth has changed. For example, one chunk of time when many dinosaurs lived is called the Jurassic. We find fossils of Earth's first green plants from the chunk of time named the Ordovician. Many of the scientists who first assigned names to times in Earth's history were from Europe. As a result, many of the names they used came from towns or other local places where they studied in Europe.

Ordering rock layers from oldest to youngest was a first step in creating the geologic time scale. It showed the order in which life on Earth changed. It also showed us how certain areas changed over time in regard to climate or type of environment. However, the early geologic time scale only showed the order of events. It did not show the actual years that events happened. With the discovery of radioactivity in the late 1800's, scientists were able to measure the exact age in years of different rocks. Measuring the amounts of radioactive elements in rocks let scientists use **absolute dating** to give ages to each chunk of time on the geologic time scale. For example, they are now able to state that the Jurassic began about 200 million years ago and that it lasted for about 55 million years.

Geologic Time Scale

Today, the geologic time scale is divided into major chunks of time called **eons**. Eons may be further divided into smaller chunks called **eras,** and each era is divided into **periods**. **Figure** 12.1 shows you what the geologic time scale looks like. We now live in the Phanerozoic eon, the Cenozoic era, and the Quarternary period. Sometimes, periods are further divided into epochs, but they are usually just named "early" or "late," for example, "late Jurassic," or "early Cretaceous." Note that chunks of geologic time are not divided into equal numbers of years. Instead, they are divided into blocks of time when the fossil record shows that there were similar organisms on Earth.

EON	ERA	PERIOD	MILLIONS OF YEARS AGO
Phanerozoic	Cenozoic	Quaternary	1.6
		Tertiary	66
	Mesozoic	Cretaceous	138
		Jurassic	205
		Triassic	240
	Paleozoic	Permian	290
		Pennsylvanian	330
		Mississippian	360
		Devonian	410
		Silurian	435
		Ordovician	500
		Cambrian	570
Proterozoic	Late Proterozoic Middle Proterozoic Early Proterozoic		2500
Archean	Late Archean Middle Archean Early Archean		3800?
Pre-Archean			

Figure 12.1: The Geologic Time Scale. (15)

One of the first scientists to understand geologic time was James Hutton. In the late 1700s, he traveled around Great Britain and studied sedimentary rocks and their fossils. He believed that the same processes that work on Earth today formed the rocks and fossils from the past. He knew that these processes take a very long time, so the rocks must have formed over millions of years. Before Hutton, most people believed the Earth was only several thousand years old. His work helped us understand that the laws of nature never change and that the Earth is very old. He is sometimes called the "father of geology."

The geologic time scale is often shown with illustrations of how life on Earth has changed. It sometimes includes major events on Earth, too, such as the formation of the major mountains or the extinction of the dinosaurs. **Figure** 12.2 shows you a different way of looking at the geologic time scale. It shows how Earth's environment and life forms have changed.

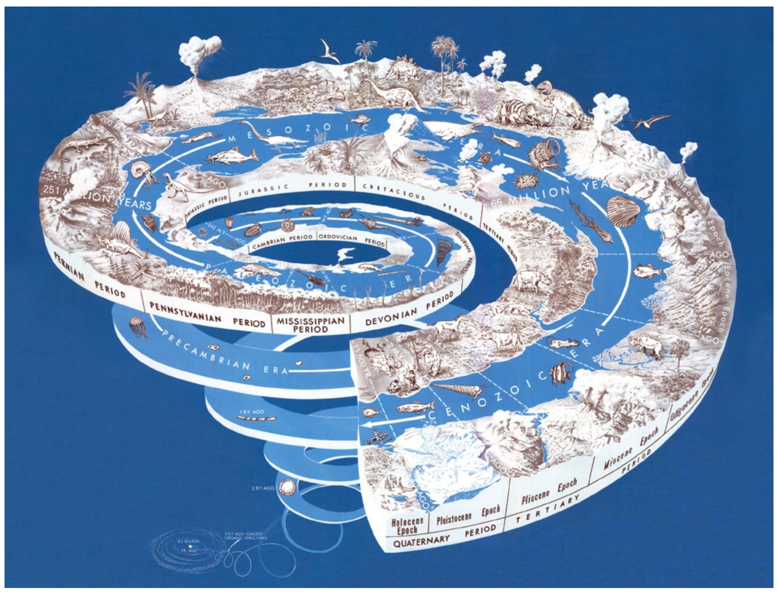


Figure 12.2: A different way of looking at the Geologic Time Scale. (1)

Lesson Summary

- The Earth is very old, and the study of Earth's past requires us to think about times that were millions or even billions of years ago. Scientists use the geologic time scale to illustrate the order in which events on Earth have happened.
- The geologic time scale was developed after scientists observed changes in the fossils going from oldest to youngest sedimentary rocks. They used relative dating to divide Earth's past in several chunks of time when similar organisms were on Earth.
- Later, scientists used absolute dating to determine the actual number of years ago that events happened. The geologic time scale is divided into eons, eras, periods, and epochs.

Review Questions

1. How old is the Earth?
2. Why did early geologic time scales not include the number of years ago that events happened?
3. Dinosaurs went extinct about 66 million years ago. Which period of geologic time was the last in which dinosaurs lived?
4. Can scientists use the same principles they use to study Earth's history to also study the history of other planets?
5. Suppose you are hiking in the mountains of Utah and find a fossil of an animal that lived on the ocean floor. You learn that the rock that holds the fossil is from the Mississippian period. What was the environment like during the Mississippian in Utah?
6. Why are sedimentary rocks more useful than metamorphic or igneous rocks in establishing the relative ages of rock?
7. Which is likely to be more frequently found in rocks: fossils of very old sea creatures or very old land creatures?

Vocabulary

absolute dating Methods used to determine how long ago something happened.

extinction When an organism completely dies out.

fossils The remains of past life, such as bones, shells, or other hard parts; may also include evidence of past life such as footprints or leaf impressions.

geologic time scale A timeline that illustrates Earth's past.

relative dating methods Used to determine the order of geologic events in Earth's history.

Points to Consider

- How did life on Earth change from one period of geologic time to the next?
- When did life first appear on Earth?
- What conditions were necessary on Earth for living things to survive?

12.2 Early Earth

Lesson Objectives

- Describe how the Earth formed with other parts of the solar system more than 4 billion years ago.
- Explain how Earth's atmosphere has changed over time.
- Explain the conditions that allowed the first forms of life to develop on Earth.

Introduction

Figure 12.3: The Earth from space. The Earth looks very different today than it did when it first formed over 4 billion years ago. (22)

Imagine that you had a movie that shows the history of Earth from its beginning to the present day—as if a giant camera in space had recorded pictures of Earth over the last 4 1/2 billion years. How do you think the Earth would look in that movie at different times in history? How do you think it has changed?

If you put the movie in fast-forward, you would see lots of action and lots of change! You would see that our planet has undergone remarkable changes over billions of years (**Figure**

12.3). Huge mountains have formed, been destroyed, and replaced with new mountains. The oceans have opened up and moved around the globe. The continents have moved around, split apart from each other, and collided with each other, until finally reaching their present locations. Life on Earth has also changed tremendously. At first, the Earth was not even able to support life. There was no oxygen in the atmosphere, and Earth's surface was extremely hot. Slowly, over millions of years, the Earth changed so that plants and animals could begin to grow. Living things then changed the Earth even more.

We often enjoy using our imagination to think about what the Earth was like when dinosaurs roamed around (**Figure** 12.4). What images come to your mind when you think about the dinosaurs? Now imagine a time on Earth before even the dinosaurs. Imagine the time before any living thing was on Earth. What images come to mind now? How do you think the Earth looked when it was first formed? This lesson will help you understand how the Earth formed, what it looked like during its earliest years, and how life first developed on Earth.

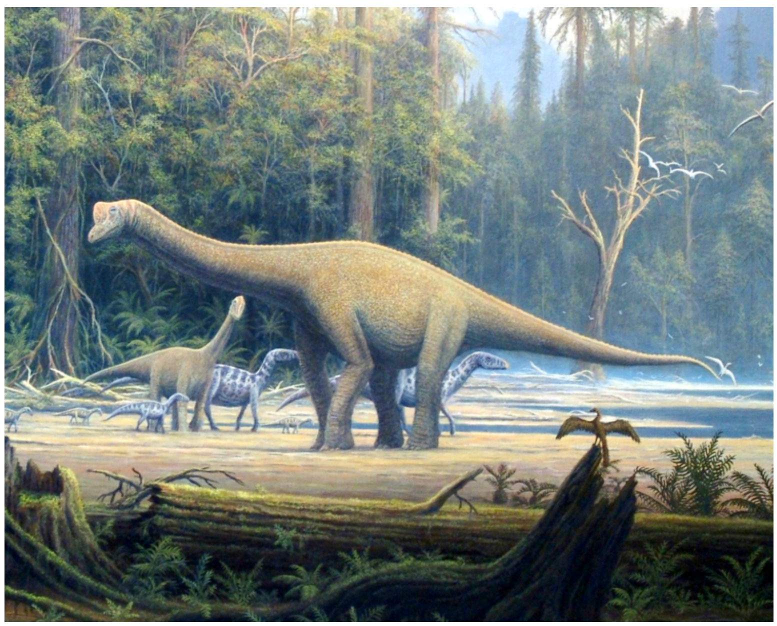


Figure 12.4: The Earth and its dominant life forms have changed throughout the Earth's long history. (18)

Evaluating Prior Knowledge

The following questions are addressed in other chapters and will help you work through this lesson. Research these before you move on.

What are chemical elements?

What conditions do plants and animals require to live?

What is the atmosphere and what is it made of?

How do weathering and erosion affect the Earth?

Formation of Earth and Our Solar System

We can construct the formation history of our solar system by looking at regions where other stars are forming now. Star formation begins when a giant cloud of gas and dust collapses under its own gravity. As the cloud contracts, it begins to spin faster and settles into a disk-shaped structure. We see these disc-shaped objects (called proplyds) in the Orion Nebula (**Figure** 12.13), where the new stars are forming today. Most of the dusty disk material drains toward the center where the density gradually increases until the enormous central pressure triggers nuclear fusion reactions and the star is born.

Figure 12.5: Orion Nebula (9)

However, a relatively small fraction of the disk material is left behind in the form of ice-coated dust grains. The icy mantles of the grains begin sticking together and eventually grow to meter-sized rocky boulders called planetesimals. The planetesimals collide and accrete into larger bodies that are tens of kilometers in diameter called protoplanets. Once the protoplanets clear a gap in the disk, they become bonafide planets and their orbits begin to stabilize (**Figure** 12.14).

The process of planet formation is messy. Not all of the planetesimals are accreted into planets. Millions of planetesimals remain as the leftover debris and are now the asteroids and ice-coated comets in our solar system. In the first hundred million years after the formation of the Sun, collisions between the leftover planetesimals and the planets were

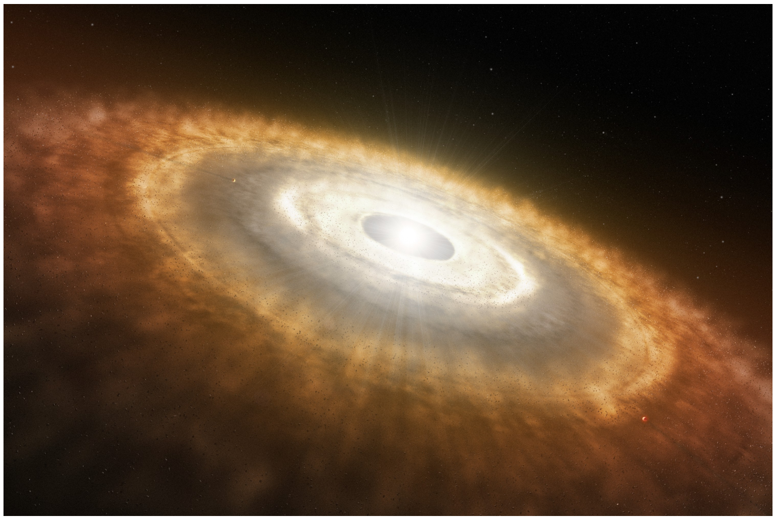


Figure 12.6: An artist's rendition of a baby star still surrounded by a protoplanetary disc in which planets are forming. (10)

common. We see evidence for heavy bombardment by planetesimals on the surfaces of the moon and Mercury (**Figure** 12.7 and **Figure** 12.8).

The same types of collisions would have occurred on the surface of the Earth, however erosive processes have erased all except the most recent of these collisions. Pictured in **Figure** 12.9 is a Meteor Crater in Arizona.

About 100 million years after the formation of the Sun, the gravity of the planets and moons in our solar system had swept up most of the planetesimals. However, millions of these objects still remain in gravitationally stable orbits in the main asteroid belt of the solar system, in the Trojan asteroid belt, or out beyond Neptune and Pluto in the Kuiper belt. Illustrated in the sketch below is the location of the largest reservoir of asteroids in our solar system today (**Figure** 12.10).

Earth is the only object in our solar system known to support life (**Figure** 12.11). Today there are over 1 million known **species** of plants and animals on Earth.

The materials that came together to form the Earth were made of several different chemical elements. Each element has a different **density**, defined as mass per volume. Density describes how heavy an object is compared to how much space the object takes up. After Earth's early formation, the denser elements sank to the center. The lighter elements rose to the surface. You have probably seen something like this happen if you have ever mixed oil and water in a bottle. The water is denser than oil. If you put both in a bottle, shake it up, and then let it sit for a while, the water settles to the bottom and the oil rises up over the top of the water.

Today, the Earth consists of layers that represent different densities (**Figure** 12.12). Earth's

Figure 12.7: The surface of the moon is scarred by collisions with debris that was meters to kilometers in diameter. Most of the planetesimals were accreted into planets or moons, but some of these objects remain as meteors, asteroids, and comets in our solar system today. (7)

Figure 12.8: The surface of Mercury shows similar collisional cratering. Most of the planetesimals were accreted into planets or moons, but some of these objects remain as meteors, asteroids, and comets in our solar system today. (2)

Figure 12.9: Meteor crater in Arizona was formed about 40,000 years ago by the impact of a meteorite that was about 50 meters in diameter. Such collisions are rare today. (11)

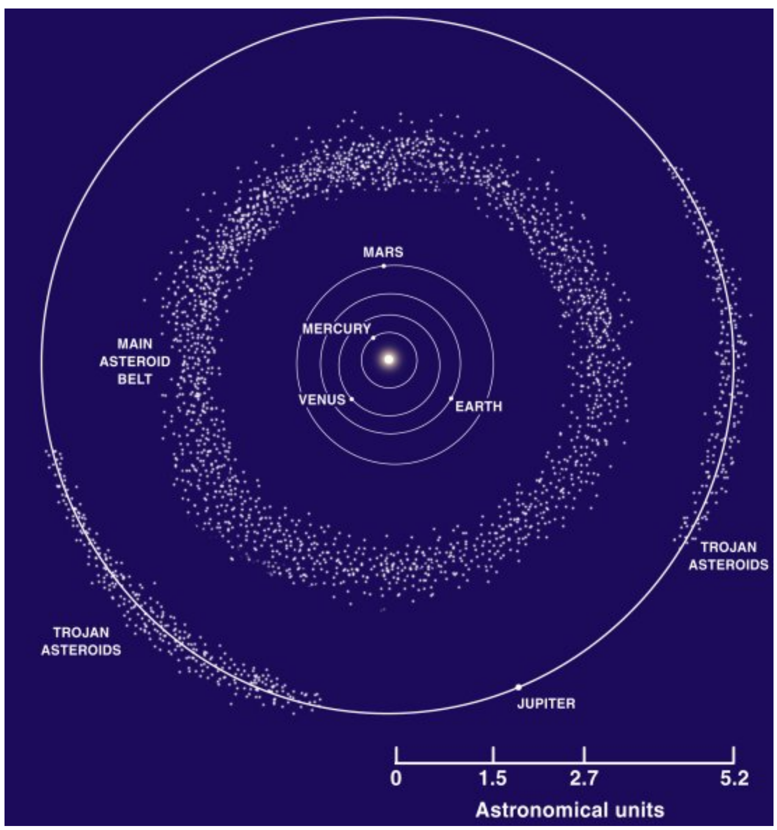


Figure 12.10: This sketch shows the largest reservoir of asteroids in our solar system today. (13)

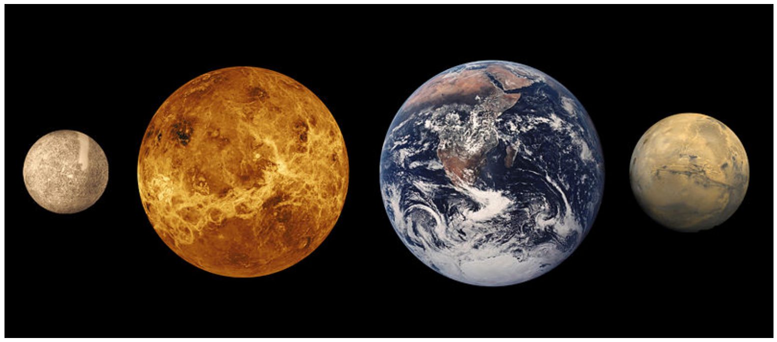


Figure 12.11: The Earth formed at the same time as the other planets in our solar system about 4 1/2 billion years ago. (17)

center is called its core. The core is made of very dense metal elements called iron and nickel. The outermost layer of the Earth is its crust. The crust is made mostly of light elements such as silicon, oxygen, and aluminum. More information on the different layers of the Earth is presented in the lesson on plate tectonics.

Figure 12.12: The Earth is made of several layers that vary in density. The center of the Earth is the core, which is the densest. The outermost layer is the crust, which is the least dense. The middle layers make up the mantle. (19)

Formation of Earth's Atmosphere

The early Earth was very different from our Earth today. The early Earth experienced frequent impacts from asteroids and meteorites and had much more frequent volcanic eruptions. There was no life on Earth for the first billion years because the **atmosphere** was not suitable for life. Earth's first atmosphere had lots of **water vapor** but had almost no oxygen. Later, frequent volcanic eruptions put several different gases into the air (**Figure** 12.13). These gases created a new type of atmosphere for Earth. The volcanic eruptions spewed gases such as nitrogen, carbon dioxide, hydrogen, and water vapor into the atmosphere—but no free oxygen. Without oxygen, there was still very little that could live on Earth.

Figure 12.13: Volcanic eruptions occurred almost constantly on the early Earth. Eruptions put water vapor, carbon dioxide and other gases into the air that helped create Earth's early atmosphere. (6)

Slowly, two processes changed Earth's atmosphere to one that is more oxygen-rich—like the one we have today. First, radiation from the Sun caused water vapor **molecules** to split apart. Remember that a molecule of water is made of the elements hydrogen and oxygen, or H_2O. Radiation from the Sun split some of the water molecules into hydrogen and oxygen. The hydrogen escaped back to outer space. The oxygen accumulated in the atmosphere. The second process that changed Earth's early atmosphere was photosynthesis (**Figure** 12.14). About 2.4 billion years ago, a type of organism called cyanobacteria evolved on the early Earth and began carrying out photosynthesis. Photosynthesis uses carbon dioxide and energy from the Sun to produce sugar and oxygen. The cyanobacteria were very simple organisms but performed an important role in changing Earth's early atmosphere. They carried out photosynthesis to produce the materials they needed to grow. They gave off oxygen to the atmosphere as they did this.

Oxygen in the atmosphere is important for life for two main reasons. First, oxygen makes up the ozone layer. The ozone layer is in the upper part of the atmosphere, and is made of O_3 molecules — a particular type of oxygen molecule. It blocks harmful **radiation** from the sun and keeps it from reaching Earth's surface. Without an ozone layer, intense radiation from the sun reached the early Earth's surface, making life almost impossible. Secondly, oxygen in the atmosphere is necessary for animals, including humans, to breathe. No animals would have been able to breathe in Earth's early atmosphere. However, there were probably several types of bacteria that lived on Earth during this early time. They would have been anaerobic, meaning that they did not need oxygen to live.

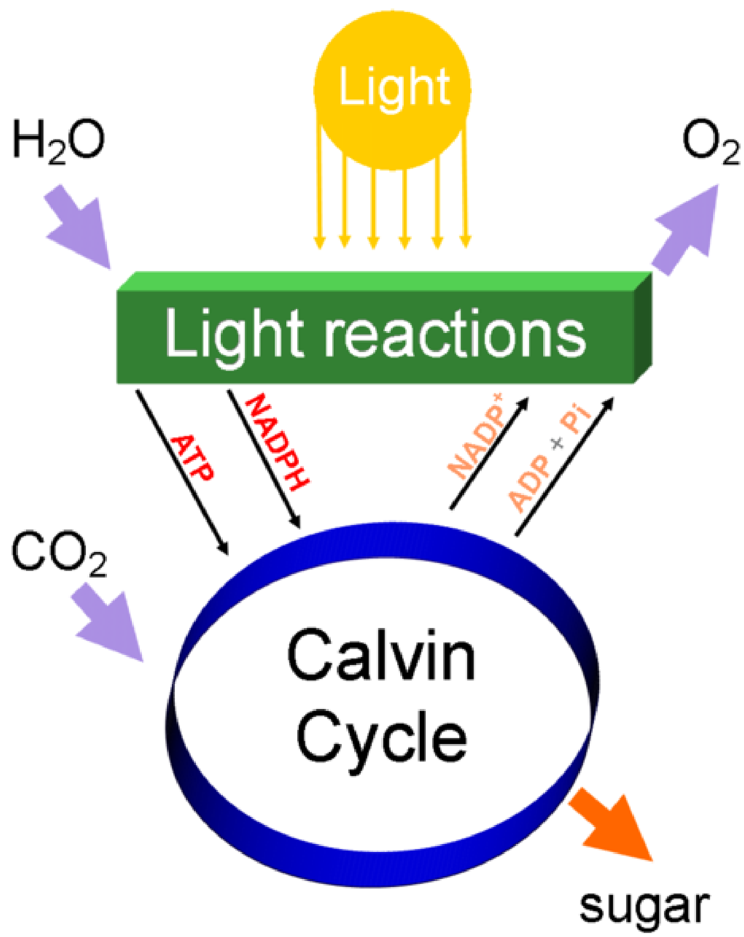


Figure 12.14: Bacteria capable of photosynthesis first appeared on Earth about 2.4 billion years ago. Photosynthesis takes sunlight, carbon dioxide, and water and produces sugar and oxygen. Photosynthesis contributed oxygen to Earth's early atmosphere and helped change it from one rich in carbon dioxide to one rich in oxygen. (8)

Very simple cells lived on Earth for the first few billion years of Earth's history. Some of the oldest fossils of more complex organisms are from about 2 billion years ago. They are found in Australia.

Besides changes in life and the atmosphere, other changes have also happened since the Earth was first formed. Early volcanic eruptions on Earth released large amounts of water vapor into the atmosphere. The water vapor slowly **condensed** and returned to Earth's surface in rainfall. This formed the oceans. Water began to cycle on Earth, and events like rainfall and storms next began to change the Earth's surface through weathering and erosion. The *Earth's Fresh Water* chapter gives more detail on how water cycles on Earth.

The continents were in very different locations than they are now. Scientists do not know how Earth's land looked exactly after the planet's first formation. They do know that North America and Greenland formed one giant landmass called Laurentia about 1.8 billion years ago. By about 1 billion years ago, Antarctica may have been close to the equator, even though it now sits at Earth's South Pole. Today, Earth's continents continue to slowly shift around the globe.

Lesson Summary

- The Earth formed more than 4 billion years ago along with the other planets in our solar system.
- The early Earth had no ozone layer and was probably very hot. The early Earth also had no free oxygen.
- Without an oxygen atmosphere very few things could live on the early Earth. Anaerobic bacteria were probably the first living things on Earth.
- The early Earth had no oceans and was frequently hit with meteorites and asteroids. There were also frequent volcanic eruptions. Volcanic eruptions released water vapor that eventually cooled to form the oceans.
- The atmosphere slowly became more oxygen-rich as solar radiation split water molecules and cyanobacteria began the process of photosynthesis. Eventually the atmosphere became like it is today and rich in oxygen.
- The first complex organisms on Earth first developed about 2 billion years ago.

Review Questions

1. Describe how the different layers of the Earth vary by density. When did the materials that make the Earth separate out by density?
2. Explain two reasons why having an oxygen-rich atmosphere is important for life on Earth.
3. Scientists believe that Earth's ozone layer is shrinking because of human activities and air pollution. What affect might this have on Earth's life forms?
4. Describe the role of cyanobacteria in changing Earth's early atmosphere.
5. List three ways the Earth was different today from when it was first formed.

6. Suppose that the Earth had been much cooler when it first formed. How would the earth's interior be different than it is today?

Vocabulary

atmosphere The mixture of gases that surrounds the Earth and contains the air we breathe.

condensed Cooled and changed from water vapor to liquid water.

density The measure of how much mass an object has in a given volume.

molecules The smallest possible amounts of a chemical substance.

radiation Energy given off by the Sun.

species A group of living things that have similar characteristics.

water Vapor water in a gas form.

Points to Consider

- How did life on Earth develop from simple bacteria to more complex organisms?
- When did complex organisms like fish, reptiles, and mammals appear on Earth?
- When did the major features of the Earth that we know today first form?

12.3 History of Earth's Life Forms

Lesson Objectives

- Describe how adaptations develop.
- Explain how the fossil record shows us that species evolve over time.
- Describe the general development of Earth's life forms over the last 540 million years.

Introduction

In the summer of 1909, an American scientist named Charles Doolittle Walcott (**Figure** 12.15) was in the Rocky Mountains of British Columbia, Canada. He was a paleontologist, which is a scientist who studies past life on Earth. He was searching for fossils. Riding on horseback, he was making his way down a mountain trail when he noticed something on the ground. He stopped to pick it up. It was a fossil! He began to dig around the area and found even more fossils. The fossils that Walcott found were of some of the most **bizarre** organisms anyone had ever seen. One of the organisms preserved in the fossils had a soft body like a worm, five eyes, and a long nose like a vacuum cleaner hose (**Figure** 12.16). Most of the fossils were the remains of animals that do not live today. They are now extinct, which means that nothing of their kind lives and that they are gone forever.

Figure 12.15: Charles Doolittle Walcott. (21)

The organisms in Walcott's fossils lived during a time of geologic history known as the Cambrian. The Cambrian period began about 540 million years ago. It marked the beginning of the Phanerozoic Eon. It also marked the beginning of many new and complex life forms appearing on Earth. In fact, the term Phanerozoic means "time of well-displayed life." We still live today in the Phanerozoic Eon. However, life on Earth is very different today than it was 540 million years ago. This lesson covers some of the history of life on Earth. It will show you how living things have developed and changed over the last 540 million years of the Phanerozoic Eon. You will learn about how species adapt and evolve over time.

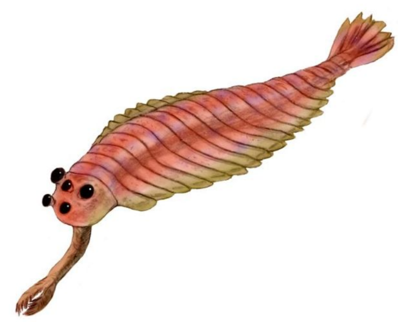


Figure 12.16: This bizarre animal with five eyes lived during the Cambrian. Fossils of it were discovered by Charles Walcott. (12)

Evaluating Prior Knowledge

Be sure that you can answer the following questions before you begin this lesson.

What is a fossil?

How is geologic time divided?

How do organisms depend on their environment to live?

Earth's Diversity

There are over 1 million species of plants and animals known to be currently alive on Earth (**Figure** 12.17). Scientists believe there are millions more that have not been discovered yet. Look around you and you notice that the organisms on this planet have incredible **variation**. One of the most remarkable features of Earth's organisms is their ability to survive in their specific environments. For example, polar bears have thick fur coats that help them stay warm in the icy waters that they hunt in (**Figure** 12.18). Reindeer have sponge-like hoofs that help them walk on snowy ground without slipping and falling. Plants that live in dry desert environments have special stems and leaves that help them conserve water.

Other organisms have special features that help them hunt for food or avoid being the food of another organism. For example, when zebras in a herd run away from lions, the zebras' dark stripes confuse the lions and make it hard for them to focus on just one zebra during the chase. Hummingbirds have long thin beaks that help them drink nectar from flowers. Some plants have poisonous or foul-tasting substances in them that keep animals from eating them.

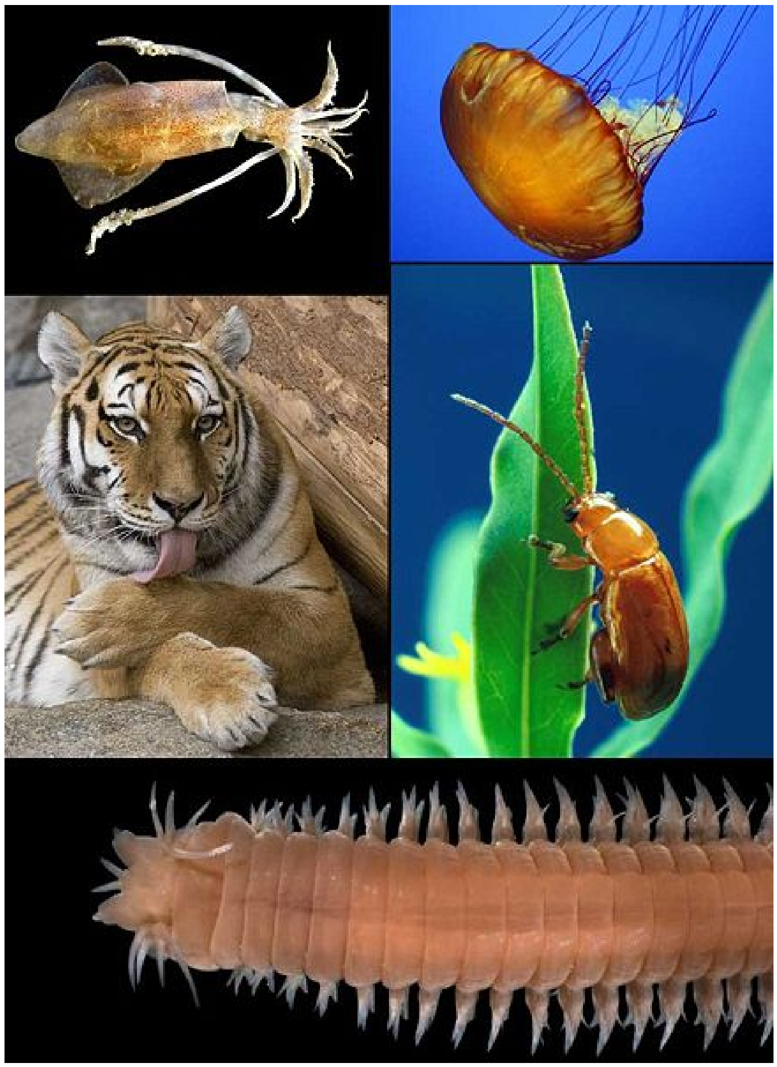


Figure 12.17: There is an amazing diversity of organisms on Earth. (5)

Figure 12.18: Many animals, like this polar bear, have special body features that help them live in a certain environment. (20)

Adaptations and Evolution

The characteristics of an organism that help it survive in a given environment are called **adaptations**. Adaptations develop when certain variations in a population help some members survive better than others (**Figure** 12.19). Often the variation comes from a mutation, or a random change in an organism's genes. The ones that survive pass favorable traits on to their **offspring**.

To help you understand adaptation, think about a population of oak trees. Imagine that most of the trees are easily killed by a certain fungus but that every now and then, there is one tree that has a natural ability to survive the fungus. That one tree displays a variation that gives it a better chance of surviving its environment. It also has a better chance of living to produce seeds and have offspring. It will reproduce and carry on the species, while the other trees will die off. The tree with the natural ability to resist the fungus will pass that trait on to its offspring. The other trees will not live and have offspring. Eventually the population will change so that most of the individual trees have the trait to survive the fungus. This is an adaptation. Adaptations are inherited traits that an organism gets from its parents. Over time traits that help an organism survive become more common. Traits that hinder survival eventually disappear.

Changes and adaptations in a species accumulate over time. Eventually the descendants

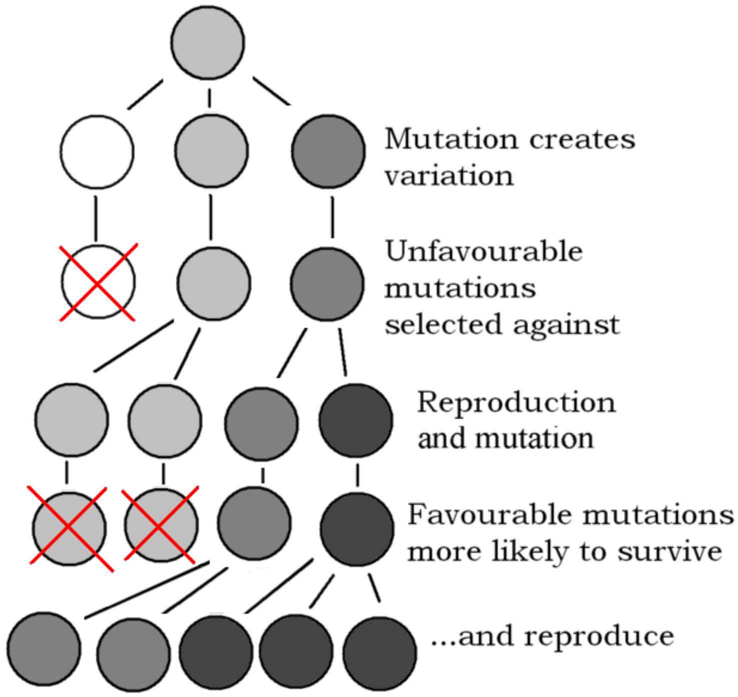


Figure 12.19: An explanation of how adaptations develop. (14)

are very different from their ancestors and may become a whole new species. Changes in a species over time are called evolution. We learn about evolution from the fossil record. It shows us that many of the life forms that live today developed from earlier, different life forms. For example, horse fossils show us that about 60 million years ago horses were much smaller than they are today (**Figure** 12.20). Fossils also show us that horses' teeth and hooves have changed several times as horses have adapted to changes in the environment.

Studying the Fossil Record

Like the organisms that were represented in Walcott's fossils, many of the organisms that once lived on Earth are now extinct. Earth's overall environmental conditions have changed many times since the Cambrian, and many organisms did not have the traits to survive the changes. Those that did survive the changes passed traits on to their offspring. They gave rise to the species that live today.

We study fossils to learn about how species responded to change over the Earth's long history. Fossils show us that simple organisms dominated life on Earth for its first 3 billion years. Then, between 1 and 2 billion years ago, the first multi-cellular organisms appeared on Earth. Life forms gradually evolved and became more complex. During the Cambrian period, animals became more **diverse** and complex. We sometimes refer to this part of the

Figure 12.20: The horse has evolved over the last 60 million years. Horses today are much larger than earlier horses. (3)

Phanerozoic Eon as the Cambrian Explosion—meaning a time when the Earth "exploded" with incredible numbers of new complex life forms.

Phanerozoic Eon

The Phanerozoic Eon is divided into three chunks of time called eras—the Paleozoic, the Mesozoic, and the Cenozoic (**Table** (12.1). They span from about 540 million years ago to the present. We live now in the Cenozoic Era. The table below shows how life has changed during the long span of the Phanerozoic Eon. Notice that different types of organisms developed at different times. However, all organisms evolved from a common ancestor. Life gradually became more diverse and new species branched out from that common ancestor. Most modern organisms evolved from species that are now extinct. To get an idea of how an organism can change from a single common ancestor to many different types, think about all the different types of dogs. All dogs evolved from a common wolf ancestor. Today there are hundreds of varieties of dogs that all look very different.

Table 12.1: **Development of Life During the Phanerozoic Eon**

Era	Millions of Years Ago	Major Forms of Life
Cenozoic	0.2 (200,000 years ago)	First humans
	35	First grasses; grasslands begin to dominate the land
Mesozoic	130	First plants with flowers
	150	First birds on Earth

Table 12.1: (continued)

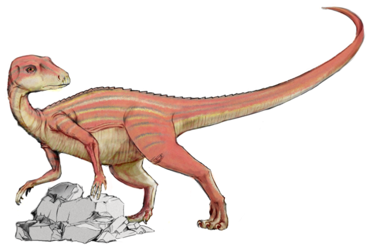
Era	Millions of Years Ago	Major Forms of Life
	200 251	First mammals on Earth Age of dinosaurs begins 
Paleozoic	300 360 400	First reptiles on Earth First amphibians on Earth First insects on Earth 
	475	First plants and fungi begin growing on land

Table 12.1: (continued)

Era	Millions of Years Ago	Major Forms of Life
	500	First fish on Earth 

The eras of the Phanerozoic Eon are separated by events called mass extinctions. A mass extinction occurs when large numbers of organisms become extinct in a short amount of time. Between the Paleozoic and the Mesozoic, nearly 95% of all species on Earth died off. The cause or causes of this extinction are still being debated.

Between the Mesozoic and the Cenozoic, about 50% of all animal species on Earth died off. This mass extinction, 65 million years ago, is the one in which the dinosaurs became extinct. Although there are other hypotheses, most scientists think that this mass extinction took place when a giant meteorite struck Earth with the energy of the most powerful nuclear weapon. The impact kicked up a massive dust cloud. When the particles rained back onto the surface they heated the atmosphere until it became as hot as a kitchen oven, roasting animals. Dust that remained in the atmosphere blocked sunlight for a year or more, causing a deep freeze and ending photosynthesis. Sulfur from the impact mixed with water in the atmosphere to form acid rain, which dissolved the shells of the tiny marine plankton that form the base of the food chain. With little food being produced by land plants and plankton, animals starved. Carbon dioxide was also released from the impact and eventually caused global warming. Life forms could not survive the dramatic temperature swings.

Earth's climate changed numerous times during the Phanerozoic Eon. Just before the beginning of the Phanerozoic, much of the Earth was cold and covered with **glaciers** (**Figure** 12.21). As the Phanerozoic began, however, the climate was changing to a warm and **tropical** one (**Figure** 12.22). The glaciers were replaced with tropical seas. This allowed the Cambrian Explosion of many new life forms on Earth. During the Phanerozoic, Earth's climate has gone through at least 4 major cycles between times of cold glaciers and times of warm tropical seas. Some organisms survived environmental changes in the climate; others became extinct when the climate changed beyond their capacity to cope with it.

Figure 12.21: Just before the Phanerozoic, many parts of Earth were covered with glaciers. After the Earth began to warm and many of the glaciers melted, there was an explosion of new life on Earth. The glaciers in this picture are from the present. However, glaciers are much less common on Earth today than at other times in Earth's history. (4)

Figure 12.22: The Phanerozoic Eon was often characterized by times of warm tropical climates. The age of the dinosaurs was especially mild for most of the Earth. This allowed plants and animals to spread over large areas of land. This picture shows plants in a modern rainforest. Plants of the Phanerozoic may have looked similar. (16)

Lesson Summary

- Adaptations are favorable traits that organisms inherit. Adaptations develop from variations within a population and help organisms to survive in their given environment.
- Changes in populations accumulate over time; this is called evolution.
- The fossil record shows us that present day life forms evolved from earlier different life forms. It shows us that the first organisms on Earth were simple bacteria that dominated the Earth for several billion years.
- Beginning about 540 million years ago more complex organisms developed on Earth. During the Phanerozoic Eon all of the plant and animal types we know today have evolved.
- Many types of organisms that once lived are now extinct. Earth's overall environment, especially the climate, has changed many times, and organisms change too over time.

Review Questions

1. Describe what is meant by adaptation.
2. The first animals on Earth had soft bodies. Gradually many animal species evolved that had hard outer parts called exoskeletons covering their bodies. How might an exoskeleton be a favorable adaptation?
3. Explain why unfavorable traits do not usually get passed to offspring.
4. List the order in which the major types of animals appeared on Earth.
5. How might climate have affected the ability of plants to grow over large areas during a given time?
6. One cause of mass extinctions is meteorite or comet impacts. What might be some additional causes of mass extinctions?

Vocabulary

adaptation A trait that an organism inherits that helps it survive in its natural environment.

evolution The change in an organism's traits over time such that a new species is often the result.

glaciers Large sheets of flowing ice.

paleontologist A scientist who studies Earth's past life forms.

tropical A climate that is warm and humid.

variation Having many differences.

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Chapter 13

Earth's Fresh Water

13.1 Water on Earth

Lesson Objectives

- Describe how water is distributed on Earth.
- Describe what powers the water cycle and how water moves through this cycle.

Introduction

Water is a simple compound, made of two atoms of hydrogen and one atom of oxygen bonded together. More than any other substance on the Earth, water is important to life and has remarkable properties. Without water, life could probably not even exist on Earth. When looking at Earth from space, the abundance of water on Earth becomes obvious — see **Figure** 13.1. On land, water is also common: it swirls and meanders through streams, falls from the sky, freezes into snow flakes, and even makes up most of you and me. In this chapter, we'll look at the distribution of water on Earth, and also examine some of its unique properties.

Distribution of Earth's Water

As **Figure** 13.1 makes clear, water is the most abundant substance on the Earth's surface. About 71% of the Earth's surface is covered with water, most of which is found in the oceans. In fact, 97% of Earth's water, nearly all of it, is in the Earth's oceans. This means that just 3% of Earth's water is **fresh water**, water with low concentrations of salts (**Figure** 13.2). Most freshwater is found as ice in the vast glaciers of Greenland and the immense ice sheets of Antarctica. That leaves just 0.6% of Earth's water that is freshwater that humans can

Figure 13.1: Earth, the "Blue Marble," can be seen in this photograph to be mostly covered with liquid water. (16)

easily use. Most liquid freshwater is found under the Earth's surface as groundwater, while the rest is found in lakes, rivers, and streams, and water vapor in the sky.

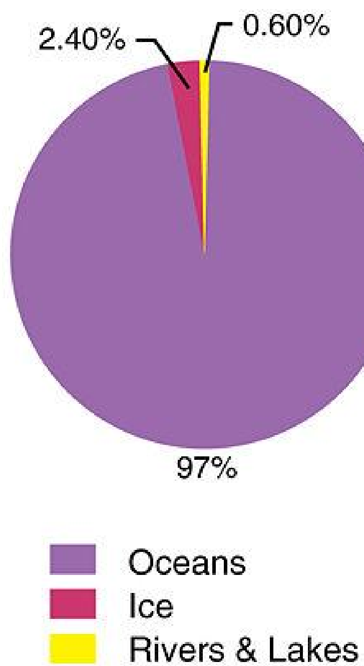

Figure 13.2: Earth's water is mostly in the oceans. Fresh water is only 3% of all the Earth's water, and most of that is in the form of ice. (3)

The Water Cycle

Water is a special substance. It is abundant on Earth and frequently appears as a gas, liquid, and solid. It is one of the few substances on Earth that is frequently found in all three phases of matter. Moreover, it can readily cycle through the globe: the same molecule can travel through many different regions on Earth.

Three States of Water

Part of the reason that water is unique is because of its melting point and boiling point. Under normal atmospheric conditions, water freezes at 0°C (32°F) and boils at 100°C (212°F). Because of our Earth's position in the solar system, Earth's temperature varies from far below the melting point of water to well above that melting point. Even though water does not boil at normal temperatures, it often becomes gaseous **water vapor** by evaporating.

All this means that we frequently see water in its three phases on Earth (See **Figures** 13.3, 13.4, and 13.5).

Figure 13.3: Solid ice floating amidst liquid water. This image shows what an iceberg might look like if you could see both above and below the surface. (13)

Figure 13.4: Liquid water. (25)

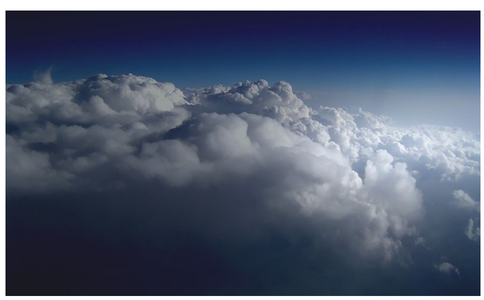

Figure 13.5: Water vapor is invisible to our eyes. However, we can see the clouds that form when water vapor condenses. (15)

The Water Cycle

The water on Earth moves about the Earth in what is known as the **water cycle** (**Figure** 13.6). Because it is a cycle, there truly is no beginning and no end. The very same water molecule found in your glass of water today has probably been on the Earth for billions of years. It may have been in a glacier or far below the ground. It may have been high up in the atmosphere and deep in the belly of a dinosaur. Who knows where it will end up today, when you're done with it!

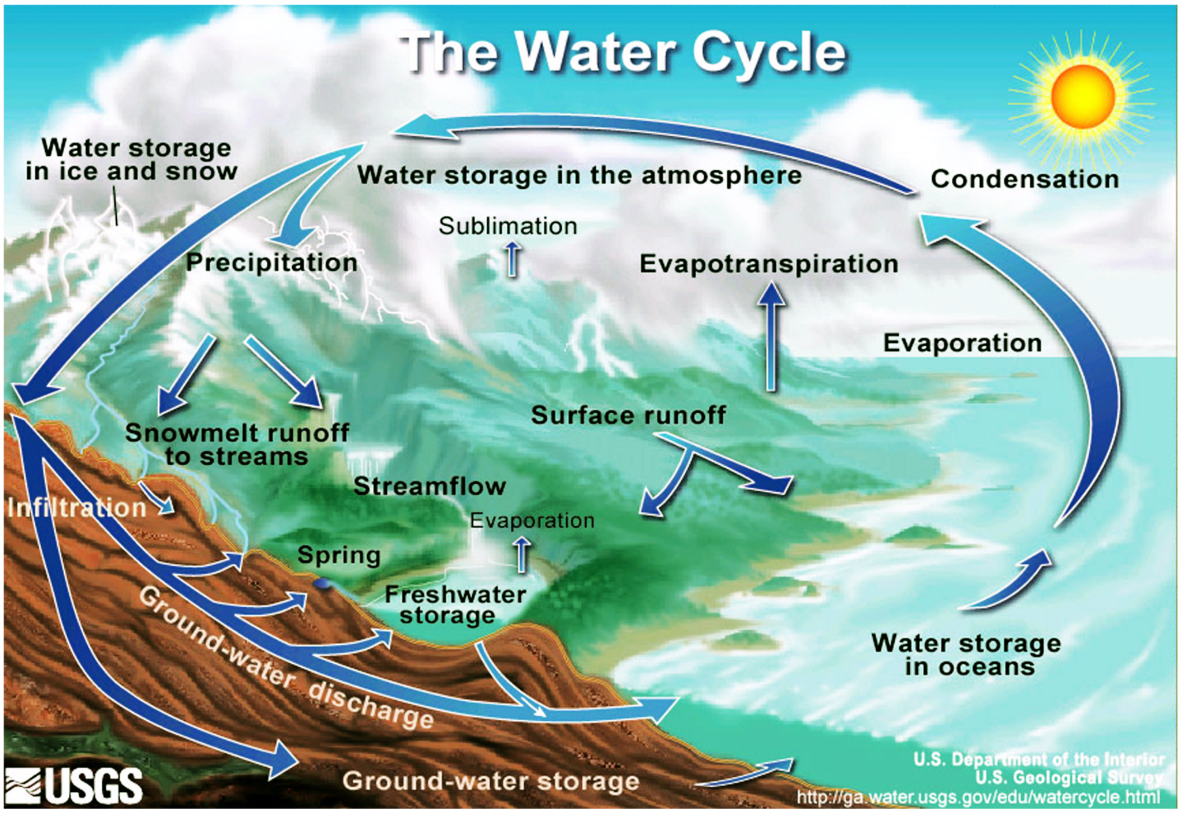

Figure 13.6: Water on Earth is constantly in motion. (22)

Let's study **Figure** 13.6 for a moment. The Sun, many millions of kilometers away, provides the energy which drives the water cycle. Since the ocean holds most of the Earth's water, let's begin there. As you can see in the illustration, water in the ocean evaporates as water vapor into the air. The salt in the ocean does not evaporate with the water, however, so the water vapor is fresh. Some of the invisible water vapor in the air **condenses** to form liquid droplets in clouds. The clouds are blown about the globe by wind. As the water particles in the clouds collide and grow, they fall from the sky as **precipitation.** Precipitation can occur in forms such as rain, sleet, hail, and snow. Sometimes precipitation falls right back into the ocean. Other times, however, it falls onto the solid earth as freshwater.

That freshwater, now on the Earth, may be found in a solid form as snow or ice. Some of it goes directly back into the air to form water vapor and clouds again. However, most of this solid water sits atop mountains and slowly melts over time to provide a steady flow of freshwater to streams, rivers, and lakes below. Some of that water enters the Earth's **groundwater**, seeping below the surface through pores in the ground. This water can form **aquifers** that store freshwater for centuries. Alternatively, it may come to the surface through springs or find its way back to the oceans.

When water falls from the sky is rain it form streams and rivers that flow downward to oceans and lakes. People use these natural resources as their source of water. They also create canals, aqueducts, dams, and wells to direct water to living areas to meet their needs (**Figure** 13.7). Sometimes, our manipulation or pollution of water greatly affects other species. Many scientists are seeking better ways of using Earth's water in a sustainable and efficient way.

Obviously, people are not the only creatures that rely on water. Plants and animals also depend on this vital resource. Plants play an important role in the water cycle because they release large amounts of water vapor into the air from their leaves. This process of **transpiration** moves liquid water from plants into the air. You can see transpiration in action if you cover a few leaves on a plant with a plastic bag. Within a few hours, water vapor released from the leaves will have condensed onto the surface of the bag.

Figure 13.7: Hoover Dam on the Colorado River. (24)

Lesson Summary

- Earth's surface is mostly water covered. Most of that water is in our oceans, leaving only 3% freshwater.

- Water exists on Earth in all three phases: solid, liquid and gas.
- The water cycle moves water from the hydrosphere to the atmosphere to the land and back again.
- The major processes of the water cycle include evaporation and transpiration, condensation, precipitation and return to the oceans via runoff and groundwater supplies.

Review Questions

1. About what percent of the Earth's water is fresh water?
2. About what percent of all of Earth's water is found in groundwater, streams, lakes, and rivers?
3. Explain the following statement: The water on other planets is present in a different form than on Earth.
4. What powers the water cycle?
5. In what state would water be found at 130°C? What state would water be at -45°C?
6. Define the words condensation and evaporation.
7. Summarize the water cycle.
8. Why do you think the atmosphere is so important to the water cycle?
9. Suppose the sun grew much stronger in intensity. How would this affect the water cycle?

Further Reading / Supplemental Links

- http://www.freshwaterlife.org/
- http://www.usgs.gov/

Vocabulary

aquifer A layer of rock, sand, or gravel that holds large amounts of groundwater. Humans often use aquifers as sources of freshwater.

condense To turn from a gas to a liquid.

freshwater Water with a low concentration of salts, which can be consumed and used by humans.

groundwater Water that is found beneath the Earth's surface, between soil or rock particles.

precipitation Water that falls to the Earth from the sky. Precipitation usually takes the form of rain, but can also occur as snow, sleet, or hail.

transpiration The release of water vapor into the air through the leaves of plants; sometimes called evapotranspiration.

water cycle The cycle through which water moves around the Earth, changing both its phase (between solid to liquid to gas) and its location (in the oceans, in clouds, in streams and lakes, and in groundwater).

water vapor Water in the form of a gas. Water vapor is invisible to humans; when we see clouds, we actually are seeing liquid water in the clouds.

Points to Consider

- How does precipitation affect the topography of the Earth?
- What natural disasters are caused by the water cycle?
- How might pollution affect creatures far from the source of the pollution?
- How might building dams disrupt the natural water cycle?
- If the temperature of the Earth increases through global warming, how might the water cycle be altered?

13.2 Surface Water

Lesson Objectives

- Compare streams and rivers and their importance.
- Describe what ponds and lakes are, and why they are important.
- Explain why wetlands are significant in the water cycle, and describe their biodiversity.
- Describe the causes of floods and their effects.

Introduction

As we've learned, some of the freshwater on the Earth is on the surface, in streams, rivers, ponds and lakes. This freshwater is tremendously important to humans, plants, and animals. Wetlands are areas where water bodies and land meet. Wetlands contain high biodiversity and play a key role in naturally removing pollutants from water. At times, surface waters flood, which often creates hazardous conditions for people on the ground.

Streams and Rivers

A **stream** is a body of moving water confined by a bottom (or bed) and earthen sides (or banks). There are many categories of streams including creeks, brooks, tributaries, bayous, and rivers — all of these types of streams vary in their size, depth, speed, and location. Streams are always-changing natural objects where water flows downhill, taking turns through hills and plains as elevation, rock type, and topography guide the stream along. They are responsible for a great deal of erosion and can create great canyons over time, as they slowly move soil, pebbles, and even boulders downstream.

Parts of a Stream

The place at which a stream originates is called the **source**; this is often a spring but it could be the top of a mountain. When two streams come together, the point where they join is called a **confluence.** The smaller of the two streams is considered a **tributary** of the larger stream. A **pool** in a stream is somewhat like a swimming pool — it's a slow part in the stream where water moves more slowly, so that the stream spreads out and becomes deeper. Finally, the point at which a stream comes into a large body of water, like an ocean or a lake is called the **mouth.** These areas are called **estuaries,** and they oftentimes form unique ecosystems where water from the stream and the lake or ocean mix together (**Figure** 13.8).

Figure 13.8: (Left)This estuary at Damas Island, Costa Rica, shows how water, plants, and land all come together in an estuary. (Right) This is a satellite image of the Nile Delta, showing the unique ecosystem around the estuary, and its shape (the name delta comes from the greek letter Δ). (8)

Rivers

Rivers are the largest type of stream, and move large amounts of water through landscapes from higher to lo through landscapes from higher to lower elevations. North America has several **divides** that separate the land up into separate water basins (**Figure** 13.9). In each of these sections, rivers will eventually run to the Atlantic Ocean, Pacific Ocean, the Great Lakes, Arctic Ocean, or the Gulf of Mexico. Most rivers are bordered by **floodplains**, which are flat areas that flood when rivers overflow their banks.

Figure 13.9: The divides of North America. (23)

Rivers generally move a lot of water. The Amazon River, the world's river with the greatest flow, has a flow rate of nearly 220,000 cubic meters per second! By comparison, at Niagara Falls, nearly 1,800 cubic meters of water fall per second (**Figure** 13.10).

Since rivers contain so much water, humans have used them since the beginning of civilization as a source of water, food, transportation, defense, power, recreation, and waste disposal. The water you drink probably comes from a reservoir fed by rivers. The electricity in your house may also come from power plants that use rivers to generate power. Obviously, the natural areas along by rivers are affected by humans use or misuse of the rivers. Sometimes entire populations of organisms can be destroyed by pollution of a river many miles upstream. **Table** 13.1 shows the 10 longest rivers in the world.

Table 13.1:

#	Name	Continent	Rate of Flow m^3/s	Approximate Length (km)
1	The Nile	Africa	2,900	6695
2	The Amazon	South America	225,000	6683
3	Yangtze	Asia	33,000	6380
4	Mississippi River	North America	13,000	5970
5	Ob River	Asia	13,000	5410

Table 13.1: (continued)

#	Name	Continent	Rate of Flow m^3/s	Approximate Length (km)
6	Huang He	Asia	2,600	4830
7	Congo	Africa	43,000	4630
8	Lena	Asia	17,000	4400
9	Amur	Asia	6,000	4350
10	Yenisei River	Asia	20,000	4106

Ponds and Lakes

Streams and rivers, by definition, are bodies of water that have a current; they are in constant motion. Ponds and lakes, on the other hand, do not (**Figure** 13.11). They are generally bordered by hills or low rises, so that the water is blocked from flowing directly downhill. They represent yet another important resource for humans and another area in need of conservation.

Though the word **pond** refers to water that does not constantly flow downhill, there is disagreement about the exact definition of a pond. It is generally agreed, however, that a pond is a small body of freshwater. You probably wouldn't need a boat to get across it, and you might be able to stand up in it. Little or no surface water would escape from the pond through streams, and they are often fed by underground springs.

Lakes are larger bodies of freshwater formed by some natural process like tectonic plate movement, landslides, or human actions , such as building a dam. Almost all lakes are freshwater, and water usually leaves the lake through a river or a stream. All lakes lose some water to evaporation.

Some lakes are so large that they have their own tidal systems and currents, and can affect weather patterns. The Great Lakes in the United States, for example, contain 22% of the world's fresh surface water (**Figure** 13.12). The largest of the Great Lakes, Lake Superior, has a tide that rises and falls several centimeters each day. The Great Lakes are large enough to change the entire weather system in the Northeast region of the United States, in what is known as the "lake effect." They are home to countless species of fish and wildlife as well.

Lakes can be formed in a variety of different ways. Some lakes, like The Great Lakes fill depressions eroded as glaciers scraped soil and rock out from the landscape. Lakes known as crater lakes, formed in volcanic calderas that have filled up with precipitation. Rift lakes are formed in cracks created by tectonic faults. And subglacial lakes are found below a frozen ice cap. As a result of geologic history and the arrangement of land masses on the Earth, most lakes are in the Northern Hemisphere. In fact, over 60% of all the world's lakes are in Canada — most of these lakes were formed by the glaciers that covered most of Canada in

Figure 13.10: The famous Horseshoe Falls at Niagara Falls drops over 1,800 cubic meters of water per second, down a cliff nearly 50 meters (170 feet) in height. The falls are fed by Lake Erie and the Niagara River. (6)

Figure 13.11: Ponds are small, enclosed bodies of water. (20)

Figure 13.12: The Great Lakes are the largest lakes in the world. They are found along the border of the United States of America and Canada. (1)

the last Ice Age.

Limnology is the study of all bodies of freshwater and the organisms that live there. The ecosystem of a lake is divided into three distinct sections (**Figure** 13.13):

1. The littoral zone, which is the sloped area closest to the edge of the water.
2. The open-water zone (also called the photic or limnetic zone), where sunlight is abundant.
3. The deep-water zone (also called the aphotic or profundal zone), where little or no sunlight can reach.

Much life is found in the littoral zone, because sunlight allows the growth of plants on the lake bed. These plants in turn, provide food and shelter to animals like snails, insects, and fish. Other plants and fish such as bass and trout live in the open-water zone. The deep-water zone does not allow for plants to grow, so fewer organisms live there. In this zone, most organisms are scavengers like crabs and catfish, which feed on dead organisms that fall to the bottom. Fungi and bacteria aid in the decomposition of those dead organisms, too. Though different creatures live in the oceans, ocean waters also have these same divisions based on sunlight with similar types of creatures that live in each of the zones.

Lakes are not always permanent features of a landscape. Some **intermittent lakes** come and go with the seasons, as water levels rise and fall. Over a longer time period, lakes can disappear when they are filled in with sediments, if the springs or streams that fill them diminish, or if their outlets grow due to erosion. When the climate of an area alters, lakes can either expand or shrink, and lakes may disappear altogether if precipitation significantly diminishes.

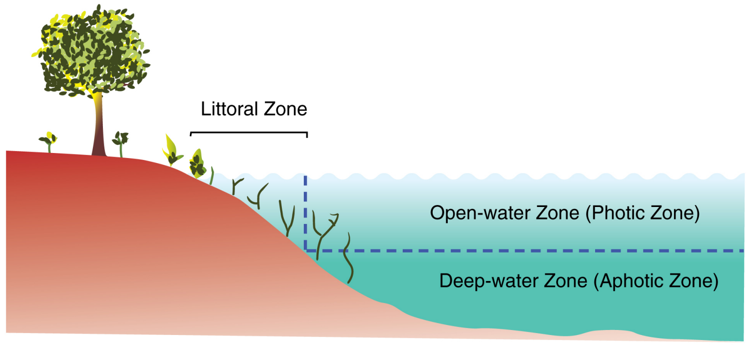

Figure 13.13: The three primary zones of a lake are the littoral, open-water, and deep-water zones. (12)

Wetlands

The word **wetland** is well-named. It refers to land that holds a great deal of water for significant periods of time, and that contains specialized plants able to grow in these wet conditions. Wetlands are created where bodies of water and bodies of land meet. They can be large flat areas or relatively small and steep areas. Wetlands tend to create unique ecosystems that rely on both the land and the water for survival. Wetlands are important regions of biological diversity, yet they can also be fragile systems that are sensitive to the amounts and quality of water.

Types of Wetlands

A marsh is a type of wetland usually around lakes, ponds, streams, or the ocean where grasses and reeds are common but trees are not (**Figure** 13.14). Animals present in marshes usually include frogs, turtles, muskrats, and many varieties of birds. The water in a marsh is generally shallow and may be either freshwater or saltwater.

A swamp is a wetland characterized by lush trees and vines in a low-lying area beside slow-moving rivers (**Figure** 13.15). Like marshes, they are frequently or always inundated with water. Since the water in a swamp moves slowly, oxygen in the water is often scarce, so plants and animals must be adapted for these low-oxygen conditions. Swamps can be freshwater, saltwater, or a mixture of both.

An estuary is an area where saltwater from the sea mixes with freshwater from a stream or river (**Figure** 13.16). These semi-enclosed areas are home to plants and animals that can tolerate the sharp changes in salt content that the constant motion and mixing of waters creates. Estuaries contain brackish water, which has more salt than freshwater but less than sea water. Because estuaries contain areas of water with many different levels of dissolved salt, they tend to have many different habitats for plants and animals. As a result, estuaries

Figure 13.14: A marsh is a treeless wetland. (5)

Figure 13.15: A swamp is characterized by trees in still water. (10)

have extremely high biodiversity.

Figure 13.16: Chesapeake Bay, surrounded by Maryland and Virginia, is the largest estuary in the United States. (11)

Ecological Role of Wetlands

As mentioned above, wetlands are homes to many different species of organisms. Though they make up only 5% of the area of the United States, wetlands contain more than 30% of the plant types found in the United States. Many endangered species live in wetlands, and therefore many wetlands are protected from human use.

Wetlands also play a key biological role by removing pollutants from water. For example, they can trap and use fertilizer that has rushed off a farmer's fields, and therefore prevent that fertilizer from contaminating another body of water. Since wetlands naturally purify water, preserving wetlands also helps to maintain clean supplies of water.

Floods

Floods are a natural part of the water cycle, but they can be terrifying forces of destruction. Put most simply, a flood is an overflow of water in one place. Floods can occur for a variety of different ways, and their effects can be minimized in several different ways. Perhaps unsurprisingly, floods tend to affect low-lying areas most severely.

Causes of Floods

Floods usually occur when precipitation occurs more quickly than that water can be absorbed into the ground or carried away by rivers or streams. Flooding may be sudden and unexpected, in the case of a flash flood, when very intense rainfall occurs in an area (**Figure** 13.17). This strong rainfall will fall too fast to be absorbed into the ground, and will overflow the banks of the streams and rivers. Alternately, floods can occur more slowly, when a long period of rainfall fills the ground with water and the levels of rivers and streams gradually rises. Less commonly, floods can occur when a dam breaks along a reservoir — as you might expect, this type of flooding can be catastrophic. In California, floods commonly occur when rainfall far exceeds annual averages, such as during an El Nino year. High water levels have also caused small dams to break, wreaking havoc downstream.

Figure 13.17: A flash flood in England in 2004 was caused by three and a half inches of rain that fell in just 60 minutes. It devastated two villages. (14)

Vegetation is an important factor in determining whether a flood occurs. Plants tend to slow down the water that runs over the land, giving it time to enter the ground. Even if the ground is too wet to absorb more water, plants still slow the water's passage across the earth, increasing the time between rainfall and the water's arrival in a stream. For the same reason, wetlands also play a key role in minimizing the impacts of floods; they act as a buffer between land and high water levels. Flooding is therefore less common in areas that are heavily vegetated, and can be more severe in areas that have been recently logged.

Effects of Floods

The most recent catastrophic flooding in United States history occurred in New Orleans in 2005, in the aftermath of Hurricane Katrina (**Figure** 13.18). This flooding occurred because of the failure of the city's **levees**, raised structures designed to hold back a river or lake. The New Orleans levees were poorly designed, and broke in multiple places after the storm, allowing water to pour into the city (**Figure** 13.19). Ultimately, over 80% of the city was submerged, 90% of city residents evacuated, and over 1800 people died in the disaster.

Figure 13.18: Hurricane Katrina in 2005 was one of the deadliest storms in United States history. (7)

Not all the consequences of flooding are negative. Floods deposit sediment in their floodplains, and these sediments are nutrient rich and good for farming. Therefore, many farmers today grow crops in the floodplains of major rivers. This pattern of rain and flooding was also important to such peoples as the ancient Egyptians along the Nile River.

Figure 13.19: Levees that held back flood water were broken in many key areas around the city of New Orleans. (2)

Floods are also responsible for moving large amounts of sediments about within streams. These sediments provide habitats for animals, and the periodic movement of sediment is crucial to the lives of several types of organisms. Many plants and fish along the Colorado River, for example, depend on seasonal flooding to rearrange sand bars.

Lesson Summary

- One way water returns to the oceans is through rivers and streams.
- Streams begin in higher elevations, with many tributaries joining together as it flows to lower elevations.
- A mature river will develop a floodplain and may eventually form a delta where the river meets the ocean.
- Water temporarily resides in ponds and lakes, which are mostly freshwater.
- Scientists study lakes, wetlands and estuaries because they are biologically important areas.
- Flooding is part of the natural cycle of all rivers, which enriches floodplains with important nutrients.
- Flooding produces difficulties for humans living on or near the floodplain and in coastal areas, particularly when levees break.

Review Questions

1. Where do streams originate?
2. Compare and contrast streams and rivers.
3. What is an advantage and disadvantage of living in floodplains?
4. Which of the 10 longest rivers has the greatest rate of flow?
5. Compare and contrast ponds and lakes.
6. What are 3 main types of wetlands?
7. Consider an animal common in swamps and an animal common in rivers. What natural adaptations do they each have to their habitat?
8. Deserts are places that get little rain. Why are they in danger of flash floods at times?

Vocabulary

aphotic zone The region in a freshwater body where no sunlight can reach. Also called the deepwater zone or the profundal zone.

brackish Water that is a mixture of freshwater and saltwater.

confluence The point where two streams join together.

divide A ridge that separates one water basin from another. Each water basin will be drained by streams into a different ocean.

estuary An area where saltwater from the sea mixes with freshwater from a stream or river. Estuaries often have high biodiversity.

floodplain A flat area covered by a stream or river when it floods. Often rich in nutrients and thus good places to farm.

intermittent lake A lake that appears and disappears seasonally, as water levels rise and fall.

lake A larger body of freshwater, usually drained by a stream. May be naturally occurring or humanmade.

levee A raised structure designed to hold back the waters of a stream or river in the case of a flood.

limnology The study of all freshwater bodies and the organisms that live in them.

littoral zone The region in a freshwater body closest to shore. Usually contains the most life in the body of water.

marsh A type of wetland around lakes, streams, or the ocean where grasses and reeds are common, but there are no trees. May be freshwater, saltwater, or brackish. Water is generally shallow.

mouth The point where a stream enters a larger body of water like a lake or an ocean.

photic zone The region in a freshwater body where sunlight is abundant. Also called the open-water zone or limnetic zone.

pond A small body of freshwater, with no stream draining it. Often fed by an underground spring.

pool A deep, slow-moving part of the stream. The stream is usually wider at the point where a pool is found.

source The place where a stream starts.

stream A body of moving water, contained within a bank (sides) and bed (bottom).

swamp A wetland in a low-lying area, where water moves very slowly. Oxygen levels are often low in swamps.

tributary The smaller of two streams that join together to make a larger stream.

wetland A region of land that holds a great deal of water for significant periods of time, and that contains specialized plants able to grow in these wet conditions.

Points to Consider

- What types of streams have you seen in your area?
- Why are bodies of water never really permanent?
- Is it possible that your home could be flooded? What would you do if it were flooded?

13.3 Ground Water

Lesson Objectives

- Define groundwater.
- Explain the location, use, and importance of aquifers.
- Define springs and geysers.
- Describe how wells work, and why they are important.

Introduction

Although lakes and rivers are visible sources of water, did you know that there is water present underground at almost every spot on Earth? Though this may be surprising, water beneath the ground is commonplace. It bubbles to the surface at times through springs and geysers. We also use wells to bring underground water to the surface, so that we can use this important resource in places where fresh surface water is not readily available.

Groundwater

As you have learned, most of the Earth's water is found in the oceans, with smaller amounts in frozen ice caps, and still smaller amounts present in lakes and rivers. Some water is found in the atmosphere in the form of water vapor or clouds. However the most common place to find fresh liquid water is under the Earth's surface, in a form called **groundwater** (**Figure** 13.20). Water from the surface seeps downward into the ground through tiny spaces or pores in the rock. At some point, though, it hits a layer of rock that no longer has pores, which stops the water from traveling downward. This rock is called **impermeable** because the water can no longer pass through it. The upper surface of the groundwater is called the **water table.** The water table will fall when there has been little rain in an area for a long time. The water table will also rise when it rains steadily for a long time. It is important to know how deep beneath the surface the water table is for anyone who intends to dig into the surface or make a well. Because groundwater involves interaction between the Earth and the water, the study of groundwater is called **hydrogeology.**

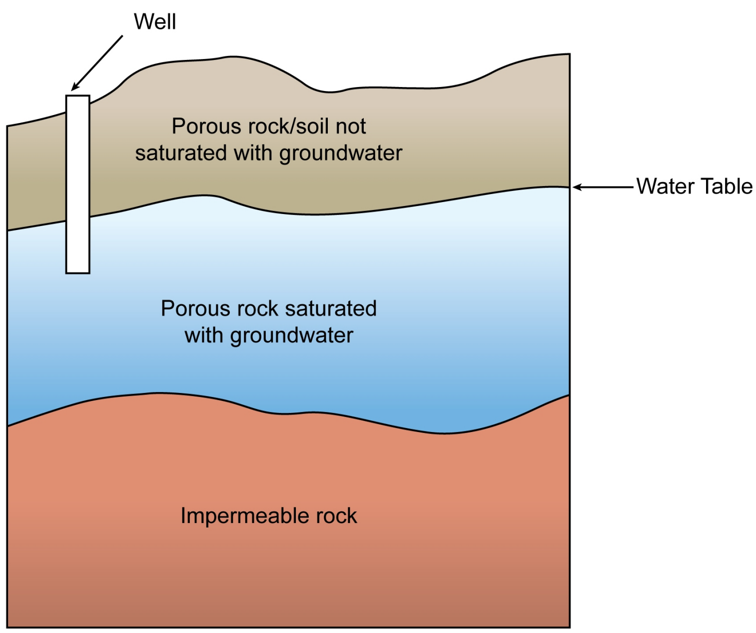

Figure 13.20: Groundwater is found beneath the solid surface. Notice that the water table roughly mirrors the slope of the land's surface. A well penetrates the water table. (9)

Aquifers

Large collections of groundwater can be found in **aquifers** (**Figure** 13.21). Aquifers are large regions of sediment or rock that can hold significant amounts of groundwater. Aquifers can be large, sustainable water resources when water pumped out of aquifers is replenished by the water cycle. However, some aquifers are overused; people pump out more water than can be replaced. As the water is pumped out, the water table slowly falls, requiring people to spend more energy pumping out the water from greater depths. In addition, some wells may go completely dry if they are not deep enough to reach into the lowered water table. Draining aquifers can lead to the ground sinking, sometimes under houses and other structures. And when coastal aquifers are overused, salt water from the ocean may enter the aquifer, contaminating the aquifer and making it less useful for drinking and irrigation.

Most land areas have some kind of aquifer beneath them. Aquifers can occur at different depths and different geographic locations. The closer aquifers are to the surface, the more likely they will be used by humans. However, closeness to the surface also increases the probability that the aquifers could be contaminated by surface pollution that seeps through the porous rock along with the water. Aquifers are usually not open spaces like caverns or swimming pools, but instead are porous rock and sediment. The spaces between the sediments or rock particles are filled in with water. Wet sand at the beach is a good model for the consistency of most aquifers.

The Ogallala Aquifer is one of the world's largest aquifers, and is a particularly important source of freshwater in the United States. It lies beneath eight United States states — South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas. It ranges from less than a meter deep to hundreds of meters deep and covers about 440,000 square kilometers! It is widely used by people for municipal and agricultural needs. However, its rate of replenishment is only about 10% of the rate at which it is being used. In other words, for every 100 liters of water that people withdraw from the aquifer, only 10 liters are being naturally replaced by precipitation. This overuse of the aquifer has created political controversies and disputes in those areas that depend on the aquifer.

Figure 13.21: Agricultural irrigation often depends on water from aquifers. (21)

Springs and Geysers

Whenever water beneath the ground meets the surface, a **spring** is created (**Figure** 13.22). This is a natural point where groundwater emerges on the Earth's surface. When water from a spring flows downhill, it can create a stream. If it does not move downhill, it may be termed a **seep,** and may create a pond or lake. Depending upon the source of water, the spring may be either constant, or may only flow at certain times of year.

Figure 13.22: Big Spring in Missouri lets out 12,000 liters of water per second(Left). Other springs are just tiny outlets like this one.(Right) (19)

Some minerals may become dissolved in groundwater, changing the water's flavor. Even carbon dioxide can dissolve in the groundwater, causing the water to be naturally carbonated. This water is sometimes sold as "mineral water."

Groundwater can be heated by magma below the Earth's surface. The heated water can create **hot springs**, springs with water that is naturally hot (**Figure** 13.23). Some hot springs are used as natural hot tubs and are considered therapeutic and spiritual by some people. However, hot springs can be dangerous, too. Their temperatures can be exceedingly hot, dissolved substances can be poisonous, and organisms like viruses and bacteria can spread disease. Be sure a hot spring is safe before entering one.

When heated groundwater is trapped in narrow spaces, the pressure builds up and causes water to actually rocket upward. A geyser is the result of such a pressurized spring. Most geysers do not erupt constantly, but rather in periodic spurts, because pressure decreases during an eruption and then increases again after an eruption. Old Faithful, probably the most famous geyser in the world, got its name for erupting in regular cycles lasting 90 minutes (**Figure** 13.24). Its eruptions last for a couple of minutes and discharge 15,000 to 30,000 liters of water during each eruption.

Wells

A well is an artificial structure created by digging or drilling in order to reach groundwater present below the water table. In **Figure** 13.25, you can see how a well penetrates the

Figure 13.23: Green Dragon Spring is a hot spring found at Yellowstone National Park. (4)

groundwater. When the water table is close to the surface, wells can be a very convenient method for extracting water. You may have made a very simple well by digging a hole in the sand at the beach until you see a pool of water at the bottom. When the water table is far below the surface, digging wells can be quite a challenge. Most wells use motorized pumps to bring water to the surface, but many wells still require people to use a bucket to draw water up.

Wells have been an important source of water for humans through the ages. Obviously, in places that have little precipitation, wells are vital to life. Using groundwater at a faster rate than it can be replenished by the water cycle, will cause the water table in an aquifer to fall. A well using that groundwater might therefore go dry, as the water that supplies the well gets used up. It is important to use water at a rate at which it can be naturally replenished. In addition, humans must be careful not to pollute groundwater, since pollution can make water supplies unusable by humans.

Lesson Summary

- Groundwater, water that infiltrates the ground, forms our largest source of readily available freshwater.
- The water table forms the top of the zone of saturation, where pore spaces in sediment or rock are completely filled with water.
- Aquifers are underground areas of sediment or rock that hold groundwater.
- In steep areas, where groundwater intersects the ground surface, a spring or seep can form.
- If groundwater is heated by magma, it can form hot springs and geysers.
- In order to access groundwater supplies, humans drill wells and pump water from the

Figure 13.24: Old Faithful Geyser during an eruption. (17)

Figure 13.25: An old-fashioned well that uses a bucket drawn up by hand. (18)

ground.

Review Questions

1. What is groundwater?
2. What is the water table?
3. What are aquifers and why are they so important?
4. Replenishing an aquifer is important because it makes the aquifer a resource that can last a long time. What do you think are ways to keep the amount of water used and the amount of water replenished the same?
5. Earthquakes can often change the frequency of eruptions or the amount of water released by geysers. Why do you think this is so?
6. Why can hot springs be dangerous?
7. How does a well work?
8. Groundwater is invisible to people on the surface of the Earth. Explain one way that you might monitor how humans are affecting the amount of groundwater in an aquifer.

Further Reading / Supplemental Links

- Inside Yellowstone http://www.nps.gov/archive/yell/insideyellowstone/0017oldfaithful3.htm
- Earth's water distribution video, University of Waikato, New Zealand http://www.sciencelearn.org.nz/contexts/h2o_on_the_go/sci_media/video/earth_s_water_

distribution

Vocabulary

groundwater Water present under the ground, between the spaces in sediment or rock. Impermeable rock lies beneath the groundwater.

hot spring A spring in which the water has been heated by magma.

hydrogeology The study of groundwater.

impermeable Something that water cannot penetrate.

seep A point where a small amount of groundwater moves up onto the Earth's surface. Seeps do not produce enough water to create a stream, but they may create a small pond or wetland.

spring A point on the Earth's surface, at which water groundwater bubbles up.

water table The upper surface of the groundwater.

Points to Consider

- Which fresh water source do you think would be cleaner: water from a river or water from a well? Why?
- Why is pollution and overuse of our natural resources always a big concern?
- What policies might people put in place to conserve water levels in lakes and aquifers?

Image Sources

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(5) *A marsh is a treeless wetland.*. Public Domain.

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(19) *http://en.wikipedia.org/wiki/File:Nacentemackinac.jpg*. (a) GNU-FDL (b)GNU-FDL.

(20) *Ponds are small, enclosed bodies of water.*. CC-BY 2.0.

(21) http://en.wikipedia.org/wiki/File:TravellingSprinkler.JPG. GNU-FDL.

(22) USGS. http://en.wikipedia.org/wiki/Water_cycle. GNU-FDL.

(23) *The divides of North America.*. GNU-FDL.

(24) http://en.wikipedia.org/wiki/File:Hoover_dam.jpg. GNU-FDL.

(25) *Liquid water.*. GNU-FDL.

Chapter 14

Earth's Oceans

14.1 Introduction to the Oceans

Lesson Objectives

- Describe how the oceans formed.
- Explain the significance of the oceans.
- Describe the composition of ocean water.
- Define the parts of the water column and oceanic divisions.

Introduction

Have you ever heard the Earth called the "Blue Planet"? This term makes sense, because over 70% of the surface of the Earth is covered with water. The vast majority of that water (97.2%) is in the oceans. Without all that water, our world would be a different place. The oceans are an important part of Earth: they help to determine the make-up of the air, they help determine the weather and temperature, and they support great amounts of life. The composition of ocean water is unique to its location and depth. Just as Earth's interior is divided into layers, the ocean separated into different layers, called the water column.

How the Oceans Formed

Scientists have developed a number of hypotheses about how the oceans formed. Though these hypotheses have changed over time, one idea now has the wide support of Earth scientists, called the volcanic outgassing theory. This means that water vapor given off by volcanoes erupting over millions or billions of years, cooled and condensed to form Earth's oceans.

Creation and Collection of Water

When the Earth was formed 4.6 billion years ago, it would never have been called the Blue Planet. There were no oceans, there was no oxygen in the atmosphere, and no life. But there were violent collisions, explosions, and eruptions. In fact, the Earth in its earliest stage was molten. This allowed elements to separate into layers within the Earth — gravity pulled denser elements toward the Earth's center, while less dense materials accumulated near the surface. This process of separation created the layers of the Earth as we know them.

As temperatures cooled, the surface solidified and an atmosphere was created. Volcanic eruptions released water vapor from the Earth's crust, while more water came from asteroids and comets that collided with the Earth (**Figure** 14.1). About 4 billion years ago, temperatures cooled enough for oceans to begin forming.

Figure 14.1: Volcanic activity was common in Earth's early stages, when the oceans had not yet begun to form. (11)

Present Ocean Formation

As you know, the continents were not always in the same shape or position as they are today. Because of tectonic plate movements, land masses have moved about the Earth since they were created. About 250 million years ago, all of the continents were arranged in one huge mass of land called Pangea (**Figure** 14.2). This meant that most of Earth's water was collected in a huge ocean called Panthalassa. By about 180 million years ago, Pangea had begun to break apart because of continental drift. This then separated the Panthalassa Ocean into separate but connected oceans that are the ocean basins we see today on Earth.

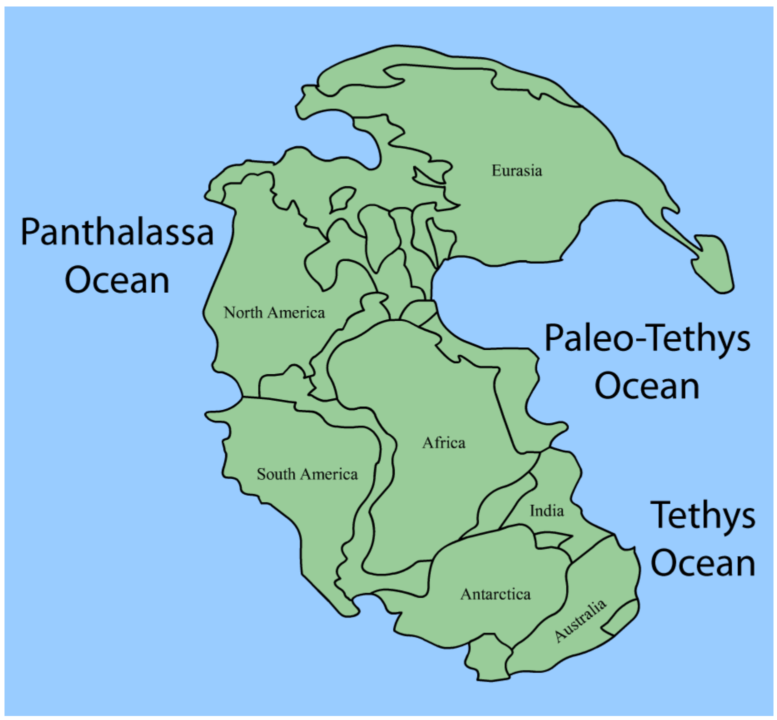

Figure 14.2: Pangea was the sole landform 250 million years ago, leaving a huge ocean called Panthalassa, along with a few smaller seas. (24)

Significance of the Oceans

The Earth's oceans play an important role in maintaining the world as we know it. Indeed, the ocean is largely responsible for keeping the temperatures on Earth fairly steady. It may get pretty cold where you live in the wintertime. Some places on Earth get as cold as -70ºC. Some places get as hot as 55ºC. This is a range of 125ºC. But compare that to the surface temperature on Mercury: it ranges from -180ºC to 430ºC, a range of 610ºC. Mercury has neither an atmosphere nor an ocean to buffer temperature changes so it gets both extremely hot and very cold.

On Earth, the oceans absorb heat energy from the Sun. Then the ocean currents move the energy from areas of hot water to areas of cold water, and vice versa. Not only does ocean circulation keep the water temperature moderate, but it also affects the temperature of the air. If you examine land temperatures on the Earth, you will notice that the more extreme temperatures occur in the middle of continents, whereas temperatures near the water tend to be more moderate. This is because water retains heat longer than land. Summer temperatures will therefore not be as hot, and winter temperatures won't be as cold, because the water takes a long time to heat up or cool down. If we didn't have the oceans, the temperature range would be much greater, and humans could not live in those harsh conditions.

The ocean is home to an enormous amount of life. This includes many kinds of microscopic life, plants and algae, invertebrates like sea stars and jellyfish, fish, reptiles, and marine mammals. The many different creatures of the ocean form a vast and complicated food web, that actually makes up the majority of all biomass on Earth. (**Biomass** is the total weight of living organisms in a particular area.) We depend on the ocean as a source of food and even the oxygen created by marine plants. Scientists are still discovering new creatures and features of the oceans, as well as learning more about marine ecosystems (**Figure** 14.3).

Finally, the ocean provides the starting point for the Earth's water cycle. Most of the water that evaporates into the atmosphere initially comes from the ocean. This water, in turn, falls on land in the form of precipitation. It creates snow and ice, streams and ponds, without which people would have little fresh water. A world without oceans would be a world without you and me.

Composition of Ocean Water

Water has oftentimes been referred to as the "universal solvent", because many things can dissolve in water (**Figure** 14.4). Many things like salts, sugars, acids, bases, and other organic molecules can be dissolved in water. Pollution of ocean water is a major problem in some areas because many toxic substances easily mix with water.

Perhaps the most important substance dissolved in the ocean is salt. Everyone knows that ocean water tastes salty. That salt comes from mineral deposits that find their way to the

Figure 14.3: Coral reefs are amongst the most densely inhabited and diverse areas on the globe. (2)

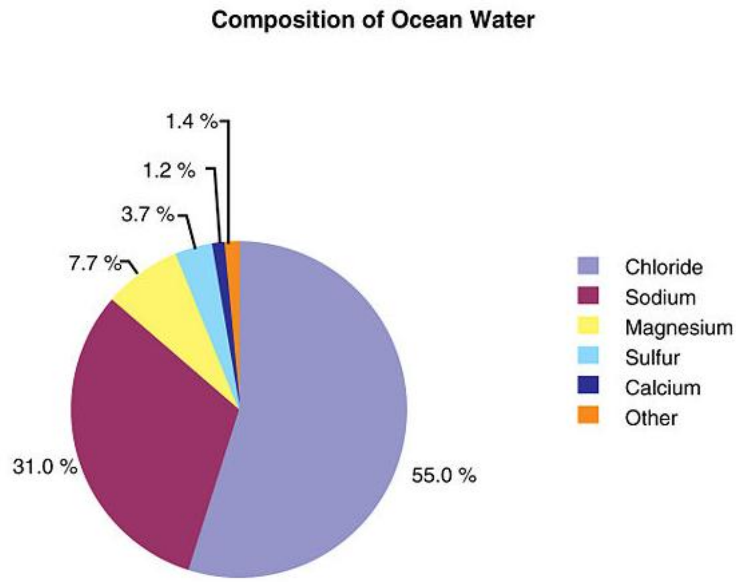

Figure 14.4: Ocean water is composed of many substances. The salts include sodium chloride, magnesium chloride and calcium chloride. (22)

ocean through the water cycle. Salts comprise about 3.5% of the mass of ocean water. Depending on specific location, the salt content or **salinity** can vary. Where ocean water mixes with fresh water, like at the mouth of a river, the salinity will be lower. But where there is is lots of evaporation and little circulation of water, salinity can be much higher. The Dead Sea, for example, has 30% salinity—nearly nine times the average salinity of ocean water. It is called the Dead Sea because so few organisms can live in its super salty water.

The density (mass per volume) of seawater is greater than that of fresh water because it has so many dissolved substances in it. When water is more dense, it sinks down to the bottom. Surface waters are usually lower in density and less saline. Temperature affects density too. Warm water is less dense and colder waters are more dense. These differences in density create movement of water or deep ocean currents that transport water from the surface to greater depths.

The Water Column

In 1960, one of the deepest parts of the ocean (10,910 meters) was reached by two men in a specially designed submarine called the *Trieste* (**Figure** 14.5). This part of the ocean has been named the Challenger Deep. In contrast, the average depth of the ocean is 3,790 meters — still an incredible depth for sea creatures to live at and for humans to travel. What makes it so hard to live at the bottom of the ocean? There are three major factors—the absence of light, low temperature, and extremely high pressure. In order to better understand regions of the ocean, the scientists define different regions by depth (**Figure** 14.6).

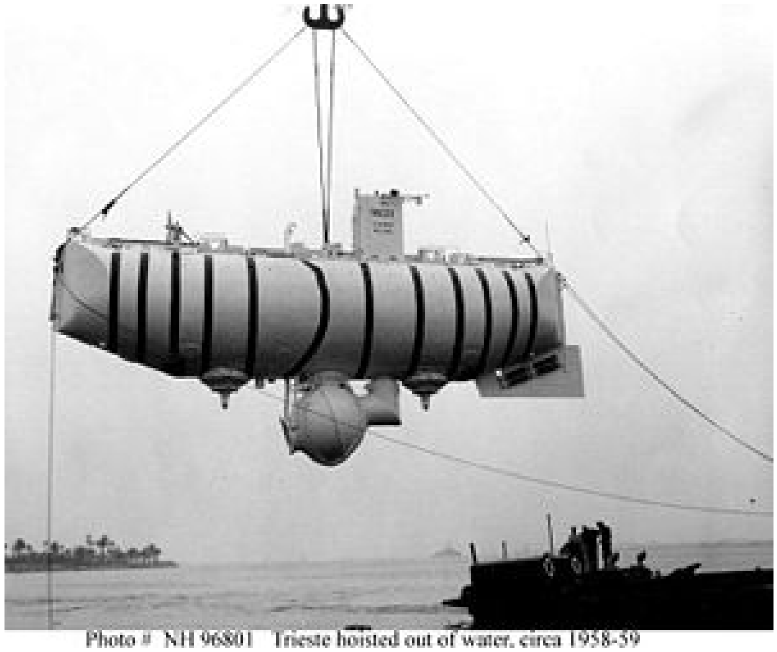

Figure 14.5: The Trieste made a record dive to the Challenger Deep in 1960. No craft exists today that can reach that depth. (7)

Sunlight only penetrates water to a depth of about 200 meters, a region called the **photic zone** (photic means light). Since organisms that photosynthesize depend on sunlight, they can only live in the top 200 meters of water. Such photosynthetic organisms supply almost all the energy and nutrients to the rest of the marine food web. Animals that live deeper than 200 meters mostly feed on whatever drops down from the photic zone.

Beneath the photic zone is the **aphotic zone,** where there is not enough light for photosynthesis. The aphotic zone makes up the majority of the ocean but a minority of its life forms. Descending to the ocean floor, the water temperature decreases while pressure increases tremendously. Each region is progressively deeper and colder, with the very deepest areas in ocean trenches.

The ocean can also be divided by horizontal distance from the shore. Nearest to the shore lies the **intertidal zone**. In this region, you might find waves, changes in tide, and constant motion in the water that exposes the water to large amounts of air. Organisms that live in this zone are adapted to withstand waves and exposure to air in low tides, by having strong attachments and hard shells. The **neritic zone** includes the intertidal zone and the part of the ocean floor that very gradually slopes downward, the continental shelf. Lots of oceanic plants live in this zone, since some sunlight still penetrates to the bottom of the ocean floor in the neritic zone. Beyond the neritic zone is the **oceanic zone**, where the sloping sea floor takes a much even steeper dive and sunlight does not reach. Animals such as sharks, fish, and whales can be found in this zone. They feed on materials that sink from upper levels, or consume one another. At hydrothermal vents, areas of extremely hot water with lots of dissolved materials allow rare and unusual producers to thrive.

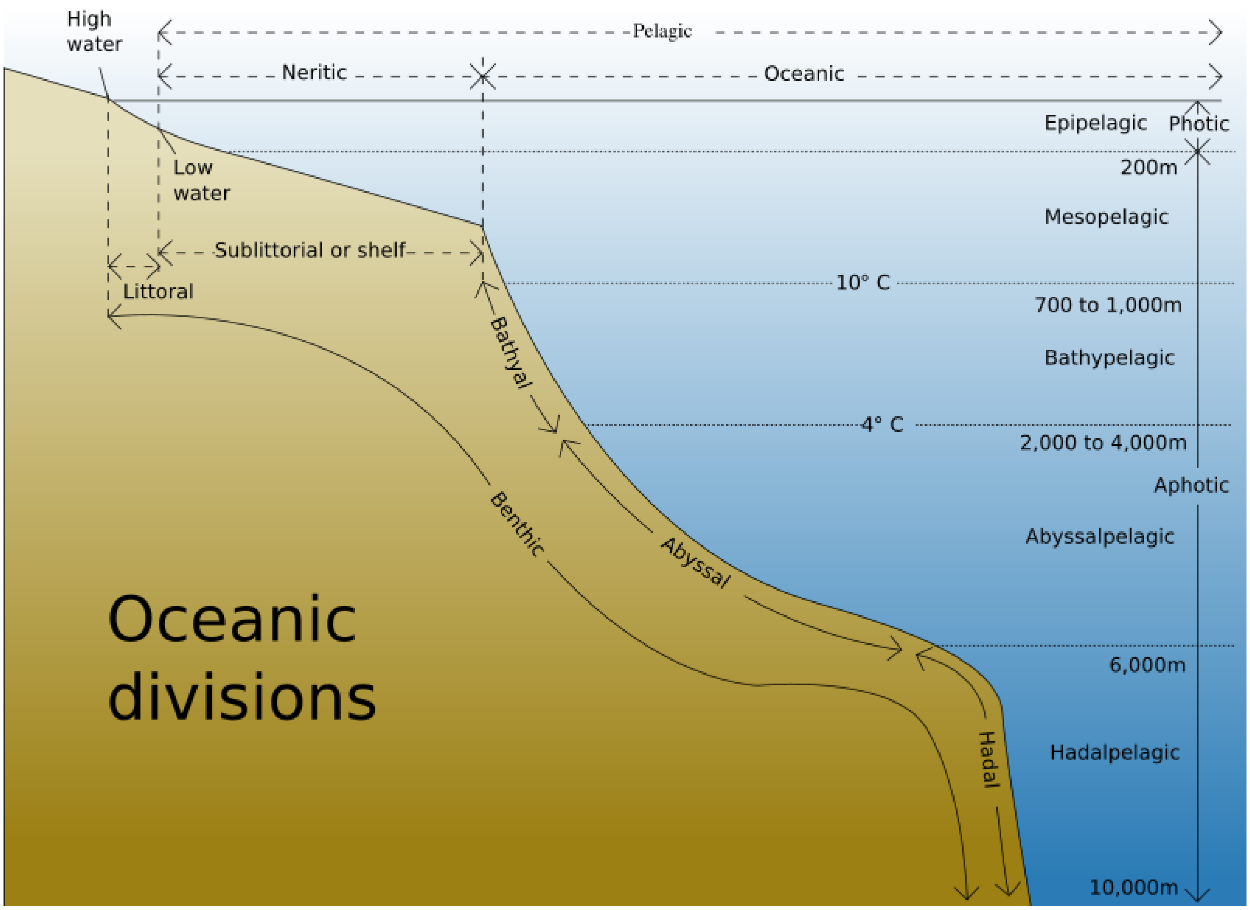

Figure 14.6: The ocean environment is divided into many regions based on factors like availability of light and nutrients.Organisms adapt to the conditions and resources in the regions in which they live. (18)

Lesson Summary

- Our oceans originally formed as a water vapor released by volcanic outgassing cooled and condensed.
- The oceans serve the very important role of helping to moderate Earth's temperatures.
- The oceans are home to a tremendous diversity of life, and algae which are all photosynthetic organisms.
- The main elements dissolved in seawater are chlorine, sodium, magnesium, sulfate and calcium.

- Usual salinity for the oceans is about 3.5% or 35 parts per thousand.
- Some regions in areas of high evaporation, like the Dead Sea, have exceptionally high salinities.
- The photic zone is the surface layer of the oceans, down to about 200m, where there is enough available light for photosynthesis.
- Below the photic zone, the vast majority of the oceans lies within the aphotic zone, where there is not enough light for photosynthesis.
- On average, the ocean floor is about 3,790m but there are ocean trenches as deep as 10,910m.
- The ocean has many biological zones determined by availability of different abiotic factors.
- Neritic zones are nearshore areas, including the intertidal zone. Oceanic zones are offshore regions of the ocean.

Review Questions

1. What was the name of the single continent that separated to form today's continents?
2. From what three sources did water originate on Earth?
3. What percent of the Earth's surface is covered by water?
4. How do the oceans help to moderate Earth's temperatures?
5. Over time, the Earth's oceans have become more and more salty. Why?
6. What is the most common substance that is dissolved in ocean water?
7. What is density?
8. Compare and contrast the photic and aphotic zones.
9. Describe the types of organisms found in the intertidal, neritic, and oceanic zones. Give examples of a life form you think might be found in each.

Vocabulary

aphotic zone

The zone in the water column deeper than 200 m. Sunlight does not reach this region of the ocean.

biomass The total mass of living organisms in a certain region.

current The movement of water in a stream, lake, or ocean.

density Mass per volume. The units for density are usually g/cm^3 or g/mL.

intertidal zone The part of the ocean closest to the shore, between low and high tide.

neritic zone The part of the ocean where the continental shelf gradually slopes outward from the edge of the continent. Some sunlight can penetrate this region of the ocean.

oceanic zone The open ocean, where the seafloor is deep. No sunlight reaches the floor of the ocean here.

Pangea The supercontinent that tectonically broke apart about 200 million years ago, forming the continents and oceans that we see today on Earth.

photic zone The topmost region of the water column, extending from the surface down to about 200 m in depth. Sunlight easily penetrates this region of the water column.

salinity A measure of the amount of dissolved salt in water.

water column A vertical column of ocean water, which is divided into different zones according to their depth.

Points to Consider

- What creates the movement of water like tides and waves?
- Is it possible to have a river in the middle of the ocean?
- What other factors affect the movement of ocean water? How do these factors affect to the world's climate and the ocean's ecosystem?

14.2 Ocean Movements

Lesson Objectives

- Define waves and explain their formation.
- Describe what causes tides.
- Describe how surface currents form and how they affect the world's climate.
- Describe the causes of deep currents.
- Relate upwelling areas to their impact on the food chain.

Introduction

Ocean water is constantly in motion (**Figure** 14.7). From north to south, east to west, and up and down the shore, ocean water moves all over the place. These movements can be explained as the result of many separate forces, including local conditions of wind, water, the position of the moon and Sun, the rotation of the Earth, and the position of land formations.

Figure 14.7: Ocean waves transfer energy through the water over great distances. (34)

Waves

A *wave* is a disturbance that transfers energy through matter or empty space. Sound waves move through the air, earthquakes send powerful waves through solid earth, spacecraft radio waves travel across millions of miles through the vacuum of empty space, and ocean waves move through water. All of these types of waves are able to transfer energy over great distances. The size of a wave and the distance it travels depends on the amount of energy that the wave carries.

The most familiar waves occur on the ocean's surface. It is upon these waves that surfers play and boogie boarders ride. These waves are mostly created by the wind. There are three factors wind that determine the size of the wave: 1) the speed of the wind, 2) the distance over which the wind has blown, and 3) the length of time that the wind has blown. The greater each of these factors, the bigger the wave.

Waves can be measured by their amplitude, a distance measured vertically from the **crest** (the top of the wave) to the **trough** (the bottom of the wave). They can also be measured by their **wavelength**, which is the horizontal distance between crests (**Figure** 14.8). When wind blows across the water surface, energy is transferred to the water. The transfer of that energy may create tiny ripples that disappear when the wind dies down, or it may create larger waves that continue until they reach the shore. Most waves reach the shore.

Scientists sometimes describe waves by measuring the speed of a wave. A wave's speed is determined by measuring the time it takes for one wavelength to pass by. Interestingly, particles in the ocean are not significantly moved by waves; although they are bobbled around by the waves, the particles tend to stay where they are.

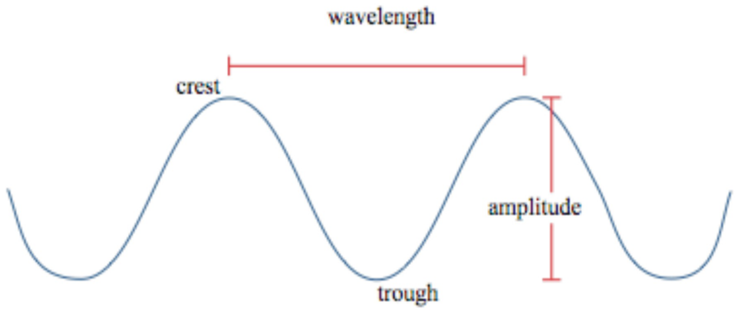

Figure 14.8: Waves are measured by their amplitude and by their wavelength. (14)

Waves can also form when a rapid shift in ocean water is caused by underwater earthquakes, landslides, or meteors that hit the ocean. These waves, called **tsunami** (**Figure** 14.9), can travel at speeds of 800 kilometers per hour (500 miles per hour). Tsunami have small, often unnoticeable wave heights in the deep ocean. However as a tsunami approaches the continental shelf, wave height increases. The wave speed is also slowed by friction with the shallower ocean floor, which causes the wavelength to decrease, creating a much taller wave. Many people caught in a tsunami have no warning of its approach. Tsunami warning systems are important for protecting for coastal areas and low-lying countries.

Waves break when they get close to the shore. That is due to the wave's interaction with the sea floor. When the wave hits the shore, the energy at the bottom of the wave is transferred to the ocean floor, which slows down the bottom of the wave. The energy at the top of the wave, in the crest, continues at the same speed, however. Since the top of this wave is going faster than the bottom, the crest falls over and crashes down.

Tides

Wind is the primary force that causes ocean surface waves, but it does not cause the tides. Tides are the daily changes in the level of the ocean water at any given place. The main factors that causes tides are the gravitational pull of the Moon and the Sun (**Figure** 14.10).

How does the Moon affect the oceans? Since the Moon is a relatively large object in space that is very close to the Earth, its gravity actually pulls Earth's water towards it. Wherever the moon is, as it orbits the Earth, there is a high tide 'bulge' that stays lined up with the Moon. The side of the Earth that is furthest from the Moon also has a high tide 'bulge'. This is because the Earth is closer to the moon the water on its far side. The Moon's gravity pulls more on the planet than the water on the opposite side. These two water bulges on opposite sides of the Earth aligned with the Moon are the **high tides**. Since ocean water is

Figure 14.9: An undersea earthquake caused the Boxing Day Tsunami in 2004 which devastated Indonesia, Sri Lanka, India, Thailand, and Myanmar. In this photo, the tsunami hits the Maldives in the Indian Ocean. (17)

Figure 14.10: High tide (left) and low tide (right) at Bay of Fundy on the Gulf of Maine in North America. The Bay of Fundy has one of the greatest tidal ranges on Earth. (31)

pulled higher in the areas of the two high tides, there is less water in between the two high tides. These areas are the **low tides** (**Figure** 14.11).

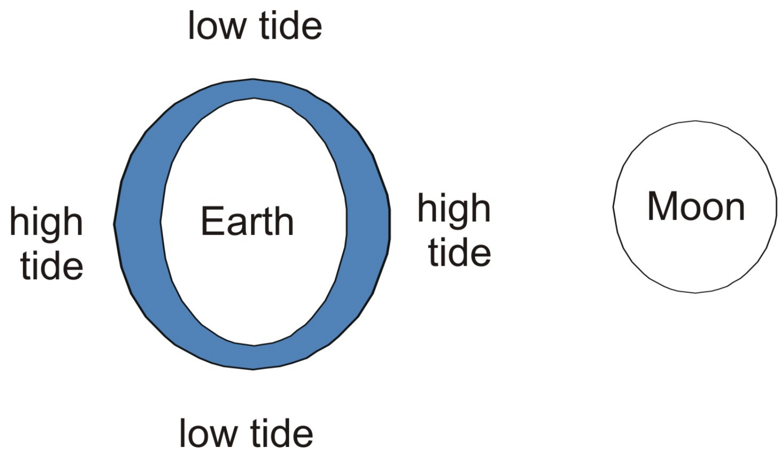

Figure 14.11: High tide is created by the gravitational pull of the moon which pulls water toward it. Water on the opposite side of the Earth is pulled least by the moon so the water bulges away from the moon. High tide occurs where the water is bulging. Low tide occurs where it is not. (35)

The **tidal range** is the difference between the ocean level at high tide and the ocean at low tide (**Figure** 14.12). Some places have a greater tidal range than others. High tides occur about twice a day, about every 12 hours and 24 minutes.

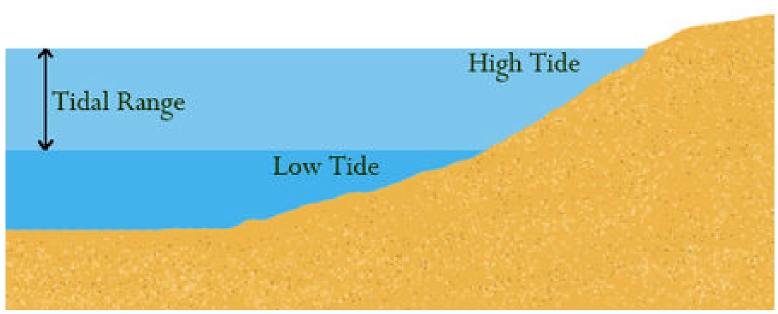

Figure 14.12: The tidal range is the difference between the ocean level at high tide and low tide. (26)

The Moon's gravity is mostly responsible for our tides, but the Sun also plays a role (**Figure** 14.13). The Sun is much larger than our Moon. It has a mass about 27,500,000 times greater than the Moon. A very large object like the Sun would produce tremendous tides if it were as near to Earth as the Moon. However it is so far from the Earth that its effect on the tides is only about half as strong as the Moon's. When both the Sun and Moon are aligned, the effect of each is added together, producing higher than normal tides called **spring tides**.

Spring tide are tides with the greatest tidal range. Despite their name, spring tides don't just occur in the spring; they occur throughout the year whenever the Moon is in a new-moon or full-moon phase, or about every 14 days.

Here is a link to see these tides in motion: http://oceanservice.noaa.gov/education/kits/tides/media/tide06a_450.gif *License:* GNU-FDL)

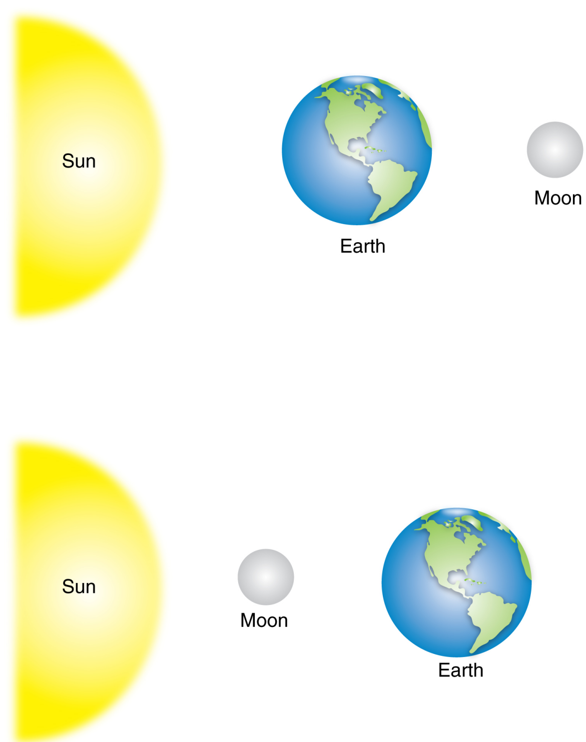

Figure 14.13: Spring tides occur when the Earth, the Sun, and the Moon are aligned, increasing the gravitational pull on the oceans. Sometimes, the Sun and Moon are on opposite sides of the Earth while at other times, they are on the same side. (29)

Neap tides are tides that have the smallest tidal range, and occur when the Earth, the Moon, and the Sun form a 90° angle (**Figure** 14.14). They occur exactly halfway between the spring tides, when the Moon is at first or last quarter. This happens because the Moon's high tide occurs in the same place as the Sun's low tide and the Moon's low tide is added to by the Sun's high tide.

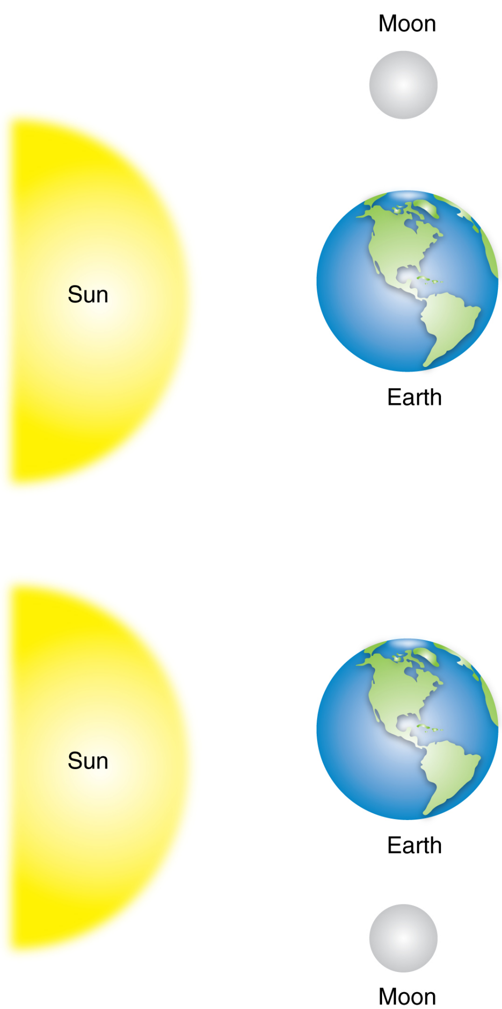

Figure 14.14: Neap tides occur when the Earth, the Sun, and the Moon form a right angle, at first and last quarters for the Moon. The two possible angles are shown below. (28)

Surface Currents

Wind that blows over the ocean water creates waves. It also creates **surface currents,** which are horizontal streams of water that can flow for thousands of kilometers and can reach depths of hundreds of meters. Surface currents are an important factor in the ocean because they are a major factor in determining climate around the globe.

Causes of Surface Currents

Currents on the surface are determined by three major factors:the major overall global wind patterns, the rotation of the Earth, and the shape of ocean basins.

When you blow across a cup of hot chocolate, you create tiny ripples on its surface that continue to move after you've stopped blowing. The ripples in the cup are tiny waves, just like the waves that wind forms on the ocean surface. The movement of hot chocolate throughout the cup forms a stream or current, just as oceanic water moves when wind blows across it.

But what makes the wind start to blow? When sunshine heats up air, the air expands, which means the density of the air decreases and it becomes lighter. Like a balloon, the light warm air floats upward, leaving a slight vacuum below, which pulls in cooler, denser air from the sides. The cooler air coming into the space left by the warm air is wind.

Because the Earth's equator is warmed by the most direct rays of the Sun, air at the equator is hotter than air further north or south. This hotter air rises up at the equator and as colder air moves in to take its place, winds begin to blow and push the ocean into waves and currents.

Wind is not the only factor that affects ocean currents. The 'Coriolis Effect' describes how Earth's rotation steers winds and surface currents (**Figure** 14.15). The Earth is a sphere that spins on its axis in a counterclockwise direction when seen from the North Pole. The further towards one of the poles you move from the equator, the shorter the distance around the Earth. This means that objects on the equator move faster than objects further from the equator. While wind or an ocean current moves, the Earth is spinning underneath it. As a result, an object moving north or south along the Earth will appear to move in a curve, instead of in a straight line. Wind or water that travels toward the poles from the equator is deflected to the east, while wind or water that travels toward the equator from the poles gets bent to the west. The Coriolis Effect bends the direction of surface currents.

The third major factor that determines the direction of surface currents is the shape of ocean basins (**Figure** 14.16). When a surface current collides with land, it changes the direction of the currents. Imagine pushing the water in a bathtub towards the end of the tub. When the water reaches the edge, it has to change direction.

Figure 14.15: The Coriolis Effect causes winds and currents to form circular patterns. The direction that they spin depend on the hemisphere that they are in. (19)

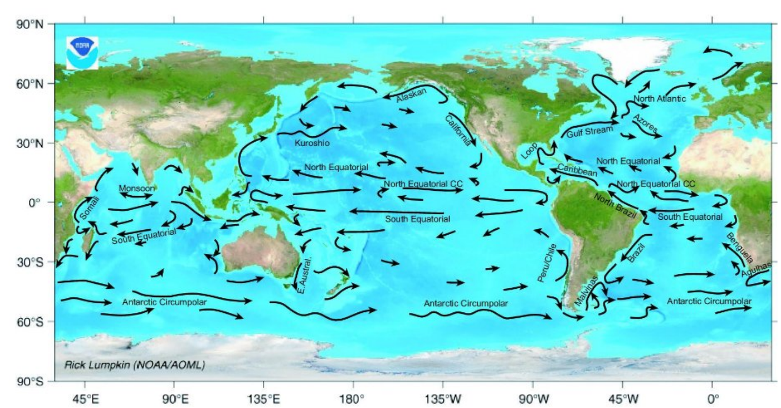

Figure 14.16: This map shows the major surface currents at sea. Currents are created by wind, and their directions are determined by the Coriolis effect and the shape of ocean basins. (6)

Effect on Global Climate

Surface currents play a large role in determining climate. These currents bring warm water from the equator to cooler parts of the ocean; they transfer heat energy. Let's take the Gulf Stream as an example; you can find the Gulf Stream in the North Atlantic Ocean in **Figure** 14.15. The Gulf Stream is an ocean current that transports warm water from the equator past the east coast of North America and across the Atlantic to Europe. The volume of water it transports is more than 25 times that of all of the rivers in the world combined, and the energy it transfers is more than 100 times the world's energy demand. It is about 160 kilometers wide and about a kilometer deep. The Gulf Stream's warm waters give Europe a much warmer climate than other places at the same latitude. If the Gulf Stream were severely disrupted, temperatures would plunge in Europe.

Deep Currents

Surface currents occur close to the surface of the ocean and mostly affect the photic zone. Deep within the ocean, equally important currents exist that are called **deep currents**. These currents are not created by wind, but instead by differences in density of masses of water. Density is the amount of mass in a given volume. For example, if you take two full one liter bottles of liquid, one might weigh more, that is it would have greater mass than the other. Because the bottles are both of equal volume, the liquid in the heavier bottle is denser. If you put the two liquids together, the one with greater density would sink and the one with lower density would rise.

Two major factors determine the density of ocean water: salinity (the amount of salt dissolved in the water) and temperature (**Figure** 14.17). The more salt that is dissolved in the water, the greater its density will be. Temperature also affects density: the colder the temperature, the greater the density. This is because temperature affects volume but not mass. Colder water takes up less space than warmer water (except when it freezes). So, cold water has greater density than warm water.

More dense water masses will sink towards the ocean floor. Just like convection in air, when denser water sinks, its space is filled by less dense water moving in. This creates convection currents that move enormous amounts of water in the depths of the ocean. Why is the water temperature cooler in some places? Water cools as it moves from the equator to the poles via surface currents. Cooler water is more dense so it begins to sink. As a result, the surface currents and the deep currents are linked. Wind causes surface currents to transport water around the oceans, while density differences cause deep currents to return that water back around the globe (**Figure** 14.18).

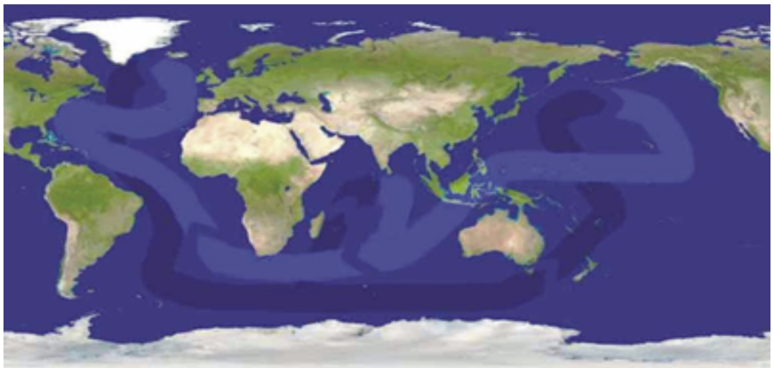

Figure 14.17: Thermohaline currents are created by differences in density due to temperature (thermo) and salinity (haline). The dark arrows are deep currents and the light ones are surface currents. (20)

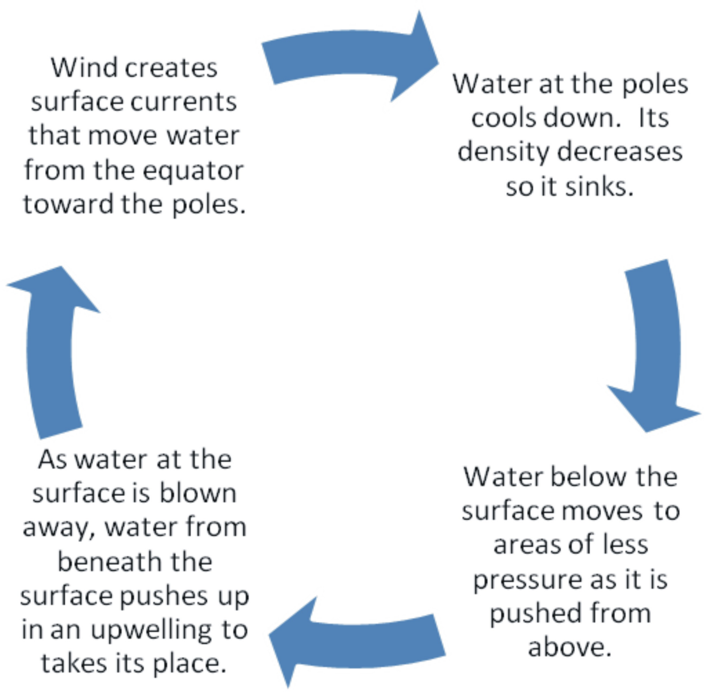

Figure 14.18: Surface and deep currents together form convection currents that circulate water from one place to another and back again. A water particle in the convection cycle can take 1600 years to complete the cycle. (10)

Upwelling

As you have seen, water that has greater density usually sinks to the bottom. However, in the right conditions, this process can be reversed. Denser water from the deep ocean can come up to the surface in an **upwelling** (**Figure** 14.19). Generally, an upwelling occurs along the coast when wind blows water strongly away from the shore. As the surface water is blown away from the shore, colder water from below comes up to take its place. This is an important process in places like California, South America, South Africa, and the Arabian Sea because the nutrients brought up from the deep ocean water support the growth of plankton which, in turn, supports other members in the ecosystem. Upwelling also takes place along the equator between the North and South Equatorial Currents.

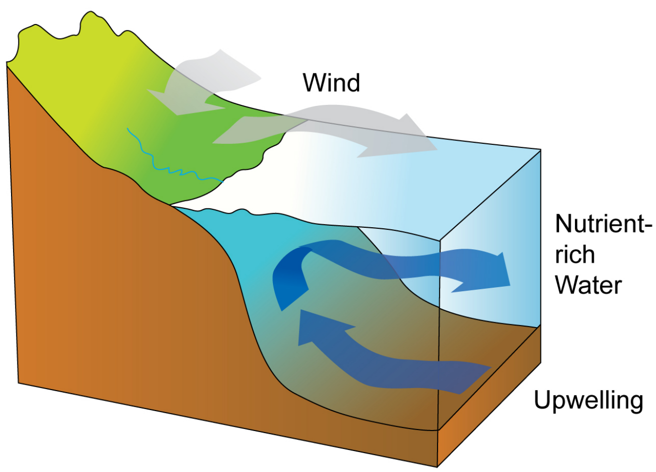

Figure 14.19: An upwelling forces denser water from below to take the place of less dense water at the surface that is pushed away by the wind. (9)

Lesson Summary

- Ocean waves are energy traveling through the water.
- The highest portion of a wave is the crest and the lowest is the trough.
- The horizontal distance between two wave crests is the wave's length.
- Most waves in the ocean are wind generated waves. Tsunami are exceptionally long wavelength waves often caused by earthquakes.
- Tides are produced by the gravitational pull of the Moon and Sun on Earth's oceans.
- Spring tides happen at full and new moons, when the Earth, Moon, and Sun are all aligned.

- Neap tides are tides of lower than normal tidal range that occur at first and last quarter moons, when the Moon is at right angles to the Sun.
- Ocean surface currents are produced by major overall patterns of atmospheric circulation, the Coriolis Effect and the shape of each ocean basin.
- Each half of each ocean basin has a major circular pattern of surface water circulation called a gyre.
- Ocean surface circulation brings warm equatorial waters towards the poles and cooler polar water towards the equator.
- Deep ocean circulation is density driven circulation produced by differences in salinity and temperature of water masses.
- Upwelling areas are biologically important areas that form as ocean surface waters are blown away from a shore, causing cold, nutrient rich waters to rise to the surface.

Review Questions

1. What factors of wind determine the size of a wave?
2. Define the *crest* and *trough* of a wave.
3. Why does a hurricane create big waves?
4. Tsunami are sometimes incorrectly called "tidal waves." Explain why this is not an accurate term for tsunami.
5. What is the principle cause of the tides?
6. What is a tidal range?
7. Why do you think that some places have a greater tidal range than other places?
8. Which has a greater tidal range, spring tides or neap tides? Explain.
9. What is the most significant cause of the surface currents in the ocean?
10. How do ocean surface currents affect climate?
11. What is the Coriolis Effect?
12. Some scientists have hypothesized that if enough ice in Greenland melts, the Gulf Stream might be shut down. Without the Gulf Stream to bring warm water northward, Europe would become much colder. Explain why melting ice in Greenland might affect the Gulf Stream.
13. What process can make denser water rise to the top?
14. Why are upwelling areas important to marine life?

Further Reading / Supplemental Links

- Learn About Ocean Currents, 5 min Life Videopedia http://www.5min.com/Video/Learn-about-Ocean-Currents-117529352

Vocabulary

amplitude The vertical height of a wave, measured from trough to crest.

Coriolis effect the apparent deflection of a moving object like water or air caused by Earth's rotation.

crest The highest point in a wave.

deep current A current deep within the ocean, which moves because of density differences (caused by differences in water temperature and salinity).

high tide The maximum height reached by a tide in the course of a day.

low tide The minimum height reached by a tide in the course of a day.

neap tide A tide that occurs when the Moon, Sun, and Earth are at 90° angles to one another. Tides have the smallest tidal range during a neap tide.

rip current A strong surface current of water that is returning to the ocean from the shore.

spring tide A tide that occurs when the Moon, Sun, and Earth area all in a line. Tides will have the greatest tidal range during a spring tide.

surface current A horizontal movement of ocean water, caused by surface winds.

tidal range The difference between the high and low tide.

tide The daily rise and fall in the level of the ocean water.

trough The lowest point in a wave.

tsunami A seismic sea wave generated by vertical movement of the ocean floor underwater earthquake, underwater volcanic eruption or landslide or meteorite impact.

upwelling Cold, nutrient-rich water that rises from oceanic depths usually near the continents, when wind blows the overlying surface away or along the equator.

wave A change in the shape of water caused by energy moving through the water.

wavelength The horizontal distance between two troughs, or two crests in a wave.

Points to Consider

- What is the bottom of the ocean like?
- How is the seafloor studied?
- How does the ocean floor contribute to the ocean's ecosystem?

Going Further - Applying Math

Tide Generating Force

In this chapter, you have learned some of the fundamental forces that influence tides. You can also learn some more about tides by using an equation to calculate the tide generating force. Like the force of gravity, the pull of the tide generating force is directly related to the masses of the astronomical objects involved and inversely related to the square of the distance between them. Tides are caused by both the gravitational pull of the Moon and the gravitational pull of the Sun on the layer of water that covers the Earth. Unlike the gravitational force, the tide generating force varies with the distance between the Moon (or the Sun) and the Earth cubed. So the equation for the tide generating force is as follows: $T = G (m_1 \cdot m_2 / d^3)$ where T is the tide generating force, G is the universal gravitational constant, m_1 and m_2 are the mass of the Earth and the mass of the Moon (or the mass of the Earth and the mass of the Sun), and d is the distance between them.

If we plug in values for the gravitational constant, the mass of the Earth and the mass of the Moon, we can calculate the tide generating force when the Moon is at apogee (farthest from the Earth in its orbit). Use $G = 6.673 \times 10^{-11} m^3 / kg \cdot s^2$; $m_1 = 7.35 \times 10^{22}$ kg for the mass of the Moon, $m_2 = 5.974 \times 10^{24}$ kg for the mass of the Earth; and d = 405,500 km for the distance from the Earth to the Moon at apogee.

You could use all the same values but substitute in d = 363,300 km for the distance from the Earth to the Moon when the Moon is at perigee (point when the Moon is closest to the Earth) and compare the tide generating force each distance.

Tsunami Tag

Often students ask if they could simply outrun a tsunami as it approaches them. How fast would you have to run to do this? You can calculate how fast a tsunami travels in the ocean using the equation for the speed of a shallow water wave, which is: V = the square root of g x d, where V = wave speed (velocity), g = the acceleration of gravity: 9.8 meters / s ^{2}, and d = the depth of the water. If you use d = 3,940m (the average depth of the Pacific Ocean), how fast does a tsunami travel? Do you think you could outrun this wave?

14.3 The Seafloor

Lesson Objectives

- Describe the obstacles to studying the seafloor and methods for doing so.
- Describe the features of the seafloor.
- List the living and non-living resources that people use from the seafloor.

Introduction

The ocean surface is vast and hides an entire world underneath it. The ocean floor is sometimes called the final frontier of the modern era. Though people have traveled on the ocean for millennia, people have explored only a tiny fraction of the ocean floor. We know very little about the vast expanse of our oceans. Today's technology has allowed us to learn more about the seafloor, including both its physical properties and its effects on living organisms.

Studying the Seafloor

Ancient myth says that Atlantis was a powerful undersea city whose warriors conquered many parts of Europe. There is little proof that such a city existed, but human fascination with the world under the oceans certainly has existed for centuries. Not much was known about the aphotic zone of the ocean until scientists developed a system modeled after the way that bats and dolphins use echolocation to navigate in the dark (**Figure** 14.20). Prompted by the need to find submarines during World War II, scientists learned to bounce sound waves through the ocean to detect underwater objects. The sound waves bounce back like an echo off of whatever object may be in the ocean. The distance of the object can be calculated based on the time that it takes for the sound waves to return. Finally, scientists were able to map the ocean floor.

Three main obstacles have kept us from studying the depths of the ocean: absence of light, very cold temperatures, and high pressure. As you know, light only penetrates the top 200 meters of the ocean; the depths of the ocean can be as much as 11,000 meters deep. Most places in the ocean are completely dark, which makes it impossible for humans to explore without bringing a source of light with them. Secondly, the ocean is very cold; colder than 0°C (32°F) in many places. Such cold temperatures pose significant obstacles to human exploration of the oceans. Finally, the pressure in the ocean increases tremendously as you go deeper. Scuba divers can rarely go deeper than 40 meters due to the pressure. The pressure on a diver at 40 meters would be 4 kilograms/square centimeter (60 lbs/sq in). Even though we don't think about it, the air in our atmosphere has weight. It presses down on us with a force of about 1 kilogram per square centimeter (14.7 lbs/ sq in). In the ocean,

Figure 14.20: Dolphins and whales use echolocation, a natural sonar system, to navigate the ocean. (15)

for every 10 meters of depth, the pressure increases by nearly 1 atmosphere! Imagine the pressure at 10,000 meters; that would be 1,000 kilograms per square centimeter (14,700 lbs/ sq in). Today's submarines usually dive to only about 500 meters; to go deeper than this they must be specially designed for greater depth (**Figure** 14.21).

In the 19th century, explorers mapped ocean floors by painstakingly dropping a line over the side of a ship to measure ocean depths, one tiny spot at a time. SONAR, which stands for *So*und *N*avigation *A*nd *R*anging, has enabled modern researchers to map the ocean floor much more quickly and easily. Researchers send a pulse of sound down to the ocean floor and calculate the depth based on how long it takes the sound to return. Of course, some scientific research requires actually traveling to the bottom of the ocean to collect samples or directly observe the ocean floor, but this is more expensive and can be dangerous.

In the late 1950s, the bathyscaphe (deep boat) *Trieste* was the first manned vehicle to venture to the deepest parts of the ocean, a region of the Marianas Trench named the Challenger Deep. It was built to withstand 1.2 metric tons per square centimeter and plunged to a depth of 10,900 meters. No vehicle has carried humans again to that depth, though robotic submarines have returned to collect sediment samples from the Challenger Deep. *Alvin* is a submersible used by the United States for a great number of studies; it can dive up to 4,500 meters beneath the ocean surface (**Figure** 14.22).

In order to avoid the expense, dangers and limitations of human missions under the sea, remotely operated vehicles or ROV's, allow scientists to study the ocean's depths by sending vehicles carrying cameras and special measuring devices. Scientists control them electronically with sophisticated operating systems (**Figure** 14.23).

Features of the Seafloor

Before scientists invented sonar, many people believed the ocean floor was a completely flat surface. Now we know that the seafloor is far from flat. In fact, the tallest mountains and

Figure 14.21: Submarines are built to withstand great pressure under the sea, up to 680 atmospheres of pressure (10,000 pounds per square inch). They still rarely dive below 400 meters. (25)

deepest canyons are found on the ocean floor; far taller and deeper than any landforms found on the continents. The same tectonic forces that create geographical features like volcanoes and mountains on land create similar features at the bottom of the oceans.

Look at (**Figure** 14.24). If you follow the ocean floor out from the beach at the top left, the seafloor gently slopes along the **continental shelf.** The sea floor then drops off steeply along the **continental slope,** the true edge of the continent. The smooth, flat regions that make up 40% of the ocean floor are the **abyssal plain.** Running through all the world's oceans is a continuous mountain range, called the **mid-ocean ridge** ("submarine ridge" in **Figure** 14.24). The mid-ocean ridge is formed where tectonic plates are moving apart from each other, allowing magma to seep out in the space where the plates pulled apart. The mid-ocean ridge system is 80,000 kilometers in total length and mostly underwater except for a few places like Iceland. Other underwater mountains include undersea volcanoes (called **seamounts**), which may rise more than 1,000 meters above the ocean floor. Those that reach the surface become volcanic islands, such as the Hawaiian Islands. Deep oceanic **trenches** are created where a tectonic plate dives beneath (subducts) another plate.

Resources From the Seafloor

The seafloor provides important living and non-living resources, which must be managed sustainably in order to maintain these resources. It is important for us to use the resources in a renewable way and to be careful not to contaminate the ocean because pollution affects the very resources that we need.

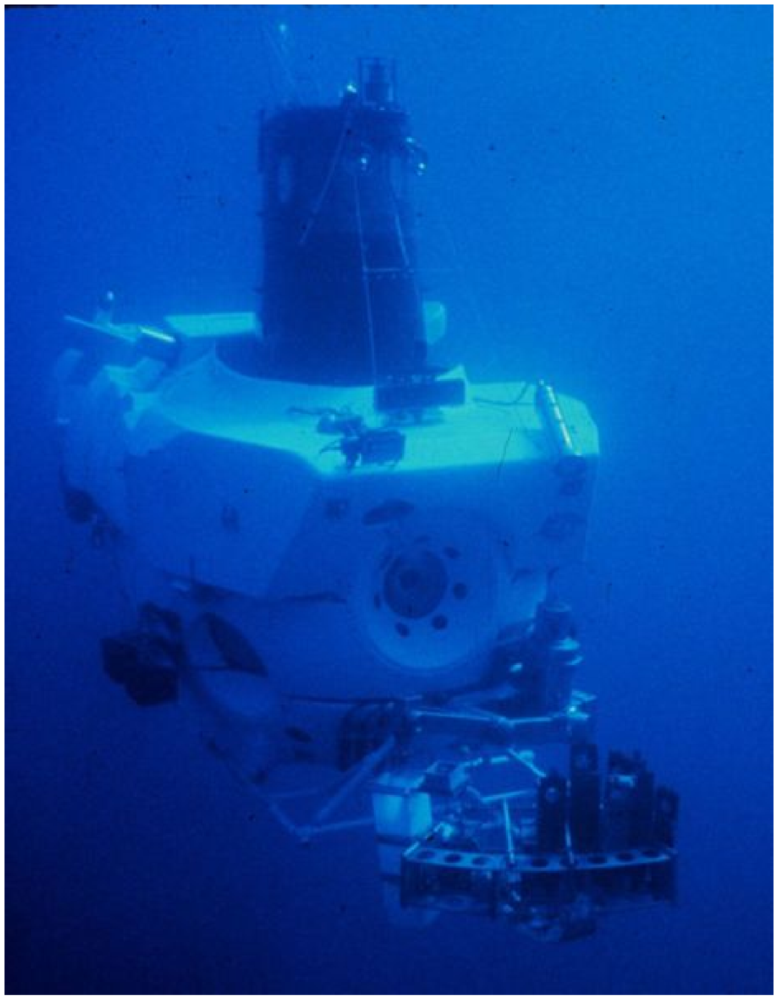

Figure 14.22: Alvin allows for a nine hour dive for up to two people and a pilot. It was commissioned in the 1960's. (8)

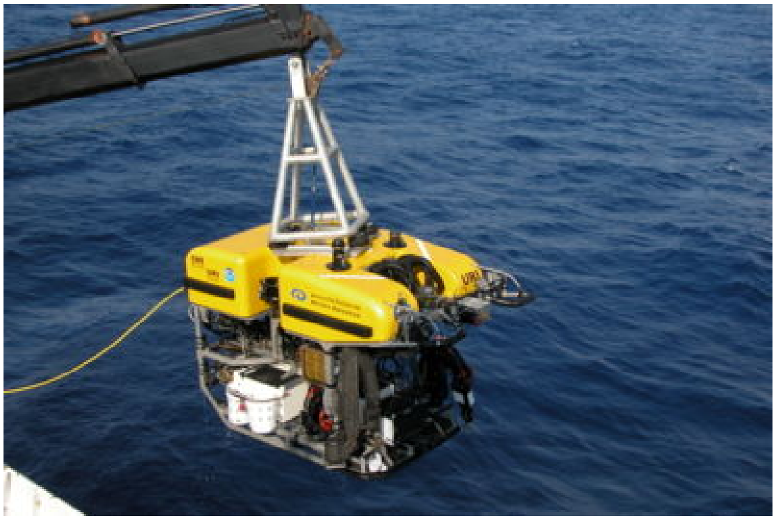

Figure 14.23: Remotely-operated vehicles like this one allow scientists to study the seafloor. (30)

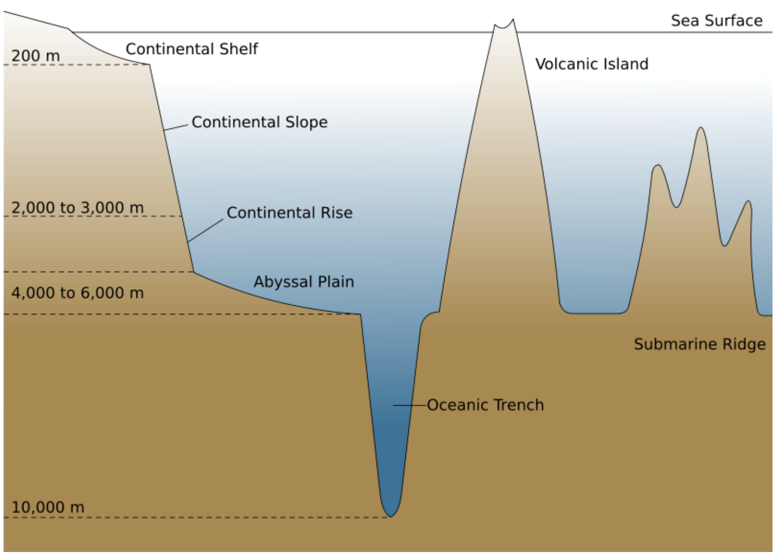

Figure 14.24: The seafloor is as varied a landscape as the continents. (4)

Living Resources

Although most fish are caught as they swim in the open waters of the ocean, **bottom trawling** is a method of fishing that involves towing a weighted net across the seafloor to harvest fish from the ocean floor. In many areas where bottom trawling is done, ecosystems are severely disturbed by the large nets and other fishing gear that people use. Many species of fish are being overharvested, which means their rate of reproduction cannot keep up with the rate at which people consume them. For this reason, a few areas in the world have laws that limit bottom trawling to waters not more than 1,000 meters deep or waters far from protected and sensitive areas. Still, recent reports on fishing resources tell us that urgent action is required to restore species of fish that have been taken in too great numbers.

The seafloor is home to many types of sea creatures, like clams, abalone, sea snails, and slugs. Some of these animals are used as food by people. Like the rich range of life in the rainforests, coral reefs in the ocean are sites of great biological diversity (**Figure** 14.25). Some of the organisms found in the ocean provide us with medications. The ocean floor also indirectly supports most life in the oceans, since upwelling currents bring important nutrients from the seafloor to plankton. These plankton in turn, provide food for most other creatures in the oceanic food web.

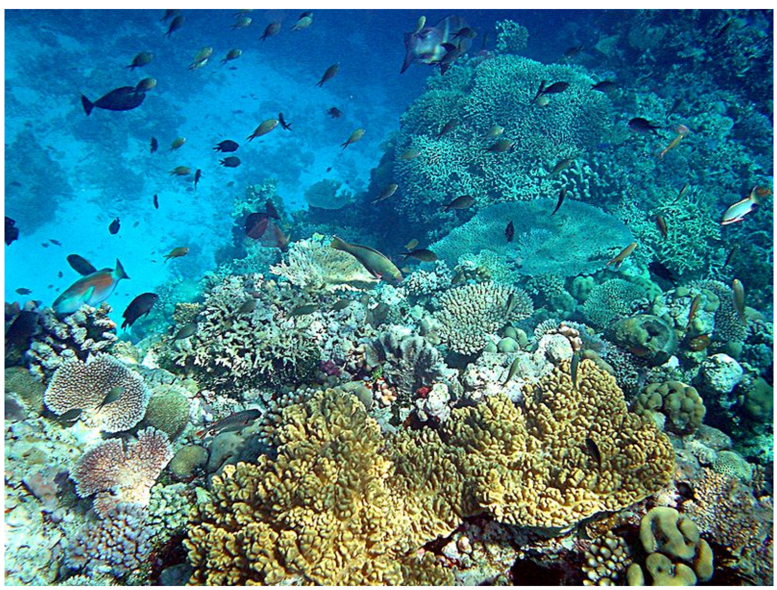

Figure 14.25: The seafloor in the coral reefs of Papua New Guinea is home to many important species. (33)

Non-living Resources

The most valuable non-living resources found in the ocean are oil and natural gas. Of course, these resources are below the seafloor, and require drilling to reach. Oil platforms can hosts dozens of oil wells that are drilled in places where the ocean is sometimes 2,000 meters deep (**Figure** 14.26). Working on oil platforms is dangerous for workers, who are exposed to harsh ocean conditions and gas explosions. Oil rigs also pose a threat to the ocean ecosystem, as a result of oil leaks and disruption of the natural environment.

Figure 14.26: Oil platforms like this one of the coast of the Gulf of Mexico can be fixed or they can float. They are generally used on the continental shelf but new technology allows them to be in deeper places. (5)

Many minerals are found on the ocean floor. They can form crystallized spheres called *nodules* that one day may be collected or mined from the bottom of the ocean (**Figure**

14.27). The nodules may be as small as a pea or as large as a basketball. Common mineral resources found in these nodules include manganese, iron, copper, nickel, phosphate, and cobalt. These minerals have many uses in the industrial world. It is estimated that there may be as much as 500 billion tons of nodules on the seafloor. Currently, there is not significant mineral mining on the seafloor, in part because of expense and concerns about how this mining would disrupt the seafloor.

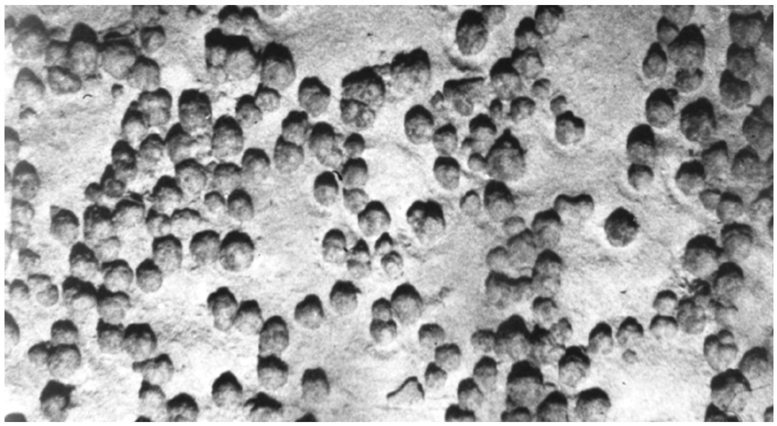

Figure 14.27: Manganese nodules from the seafloor are often rich in metals like manganese, iron, nickel, copper, and cobalt. (32)

Lesson Summary

- Until the development of sonar, we knew very little about the ocean floor.
- The deep ocean is dark, very cold and has tremendous pressure from the overlying water.
- Scuba divers can explore only to about 40 meters, while most submarines dive only to about 500 meters. Scientific research submersibles have explored the ocean's deepest trenches, but most are designed to reach only the ocean floor.
- Today much of our exploration of the oceans happens using sonar and remotely operated vehicles.
- Features of the ocean include the continental shelf, slope and rise. The ocean floor is called the abyssal plain. Below the ocean floor, there are a few small deeper areas called ocean trenches. Features rising up from the ocean floor include seamounts, volcanic islands and the mid-oceanic ridges and rises.
- The oceans provide us with both living and non-living resources.
- Living oceanic resources include fish that are harvested for food as well as the photosynthetic algae which begin the food chain in the surface waters of the ocean.
- Non-living resources include oil and natural gas found on our continental shelves and mineral resources like manganese nodules found on the deep ocean floor.

(*Source:* http://www.cdr.isa.org.jm/servlet/page?_pageid=326, *License:* GNU-FDL)

Review Questions

1. What are three obstacles to studying the seafloor?
2. The atmospheric pressure is about 1 kilogram per centimeter squared (14.7 pounds per square inch or 1 atmosphere) at sea level. About what is the pressure if you are 100 meters deep in the ocean?
3. What invention gave people the ability to map the ocean floor?
4. Which parts of the ocean floor would you expect there to be the greatest amount of living organisms?
5. How much deeper did the Trieste submerge than Alvin?
6. Compare and contrast the continental shelf and the abyssal plain.
7. Why do you think mapping the seafloor is important to the Navy? Explain.
8. If the mid-ocean ridge is created where the tectonic plates separate, why is a mountain range formed there?
9. Why is bottom trawling damaging to the seafloor?
10. Many people rely on the ocean to live because it provides them with food or work. As the world population grows, the resources in the ocean are used more and more. What can we do to make sure that people use the resources in the ocean at a rate that can be replenished?
11. What is a mineral nodule?

Vocabulary

abyssal plain The flat bottom of the ocean floor; the deep ocean floor.

bottom trawling Fishing by dragging deep nets along the ocean floor, so that they gather up living creatures along the bottom of the ocean.

continental shelf The shallow, gradually sloping seabed around the edge of a continent. Usually less than 200 meters in depth. The continental shelf can be thought of as the submerged edge of a continent.

continental slope The sloped bottom of the ocean that extends from the continental shelf down to the deep ocean bottom.

mid ocean ridge Mountain range on the ocean floor where magma upwells and new ocean floor is formed.

seamount A mountain rising from the seafloor that does not reach above the surface of the water. Usually formed from volcanoes.

trench Deepest areas of the ocean; found where subduction takes place.

Points to Consider

- What types of organisms are found in the ocean?
- How does ocean life differ in different regions of the ocean?
- How do ocean organism interact?

14.4 Ocean Life

Lesson Objectives

- Describe the different types of ocean organisms.
- Describe the interactions among different ocean organisms.

Introduction

The ocean covers an area of about 361 million square kilometers, about 71% of the Earth. For that reason, it is a home to a large portion of all life on Earth. The life in the ocean includes many different species. Some species seem bizarre, others are enormous, some are delicious to eat, and others are dangerous. Living organisms can be found throughout the ocean, even in the most remote and harsh parts.

Types of Ocean Organisms

There is a great variety of ocean life that ranges from the smallest animals on Earth to the largest. Some of these organisms breathe air from the atmosphere, while others can extract oxygen from the water. There are those that mostly float on the surface and those found in the ocean's depths. Some animals eat other organisms, while other creatures generate food from sunlight. The abundance of life in the oceans can seem endless. However pollution, acidification of the oceans, and overfishing can greatly reduce the diversity and abundance of ocean life. By studying and understanding the creatures of the ocean, humans can better preserve these organisms. With this in mind, we'll learn about the life forms in the ocean by dividing them into seven basic groups.

Plankton

The most abundant life forms in the ocean are **plankton**; most are so small that you can't even see them (**Figure** 14.28). These include many types of algae, copepods, and jellyfish. Because exploring the oceans is much harder than studying the land, many marine organisms haven't been extensively studied by humans. Scientists believe many species of marine organisms haven't even been discovered yet. The plankton are one group of organisms that have been studied extensively. The word "plankton," which comes from the Greek for wanderer, describes how these organisms live. All plankton float freely or drift, wandering at the ocean's surface.

The first link in all marine food chains are the **phytoplankton**, or 'plant' plankton, which use sunlight to make sugars from carbon dioxide and water (photosynthesis). Because they need sunlight, they can only live in the photic zone. Through photosynthesis, phytoplankton make food for themselves and give off oxygen, which is a waste product for them but essential for all animals on Earth. Phytoplankton produce all the food at the bottom of the ocean food chain, so they are called primary producers. Most of the photosynthesis on Earth happens in the oceans and phytoplankton produce a large share of the oxygen in the air we breathe. **Zooplankton**, or animal plankton eat phytoplankton as their source of food. They can be found in all parts of the ocean.

Figure 14.28: Plankton are perhaps the most important part of the food chain because they supply food for most aquatic life. (23)

Plants and Algae

There are only a few true plants in the oceans; these include salt marsh grasses and mangrove trees. But large algae, or seaweed, also use photosynthesis to make food, just as plants do on land. These organisms have to live in the photic zone, because they require sunlight for photosynthesis. For that reason, most plants, seaweeds and algae in the ocean are found near the ocean surface or close to the shore. The large algae *kelp* grows in the neritic zone (**Figure** 14.29). Kelp tends to grow in forests, and can reach over 50 meters long. Kelp forests sustain an abundance of life, like the otter that lives in their swaying stems. It is thought that land plants adapted from ocean organisms some 500 million years ago.

Figure 14.29: Kelp is common off the shores of California. Kelp is a crucial organism in many food webs near the coast. (12)

Marine Invertebrates

The ocean includes a great variety of animals. One major group of animals is the **invertebrates**. Invertebrates are animals with no spinal column. Marine invertebrates include sea slugs, sea anemones, starfish, octopi, clams, sponges, sea worms, crabs and lobsters. Most of these animals are found close to the shore, but they can be found throughout the ocean. In fact, scientists were amazed to discover invertebrates that thrived in the deep ocean near hydrothermal(hot water) vents, including giant tube worms, crabs, and shrimps (**Figure** 14.30).

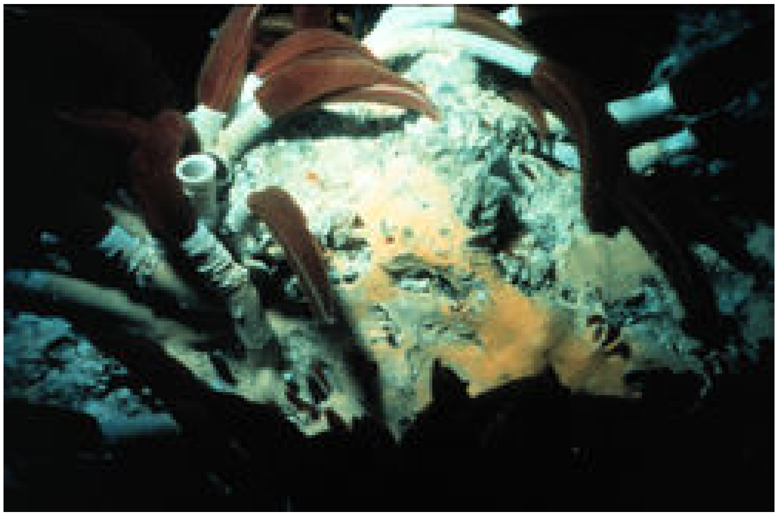

Figure 14.30: Giant tube worms have been found a mile deep in the ocean. They can grow up to 8 feet long and can withstand the very high water temperatures heated by hydrothermal vents. (3)

Fish

Like us, fish are **vertebrates** that have a spinal column and a hard skull. They are animals that have adapted to life in the water. Most fish are "cold-blooded" animals that have fins with which to move and steer, scales that protect them, gills with which to extract oxygen from the water, and a swim bladder that lets them float at particular depths within the ocean. Included among the fish are sardines, salmon, and eels, as well as the sharks and rays (which lack swim bladders)(**Figure** 14.31).

Reptiles

Reptiles are air-breathing, "cold-blooded" vertebrates. A few groups of reptiles have adapted to life at sea. These include sea turtles, sea snakes, a few saltwater crocodiles, and the marine

Figure 14.31: The Great White Shark is a fish that preys on other fish and marine mammals. (13)

iguana, which is found only at the Galapagos Islands (**Figure** 14.32). Most sea snakes bear live young in the ocean and do not need to come on land to breed. But turtles, crocodiles, and marine iguanas all lay their eggs on land, which makes both eggs and adults vulnerable to predation. For example, people use sea turtles or their eggs for food, for their shells, and for the medicinal purposes that some cultures believe they possess. Sea turtles are endangered species, so they are protected in many countries around the world.

Seabirds

Everybody loves penguins, a type of bird adapted to the sea (**Figure** 14.33). They do not fly; rather they are adapted to swimming and may spend half of their time at sea looking for food. There are many other kinds of seabirds, though, like gulls, gannets, pelicans, and petrels. Seabirds are adapted to catching fish by diving or by grabbing them at the surface with their claws.

Marine Mammals

Mammals are warm-blooded vertebrates that feed their young with milk. Most mammals have hair, ears, a jaw bone with teeth, and give birth to developed young. There are five types of marine mammals. The first type is termed Cetaceans which include whales, dolphins, and porpoises. The second type is called Sirenians which include the manatee and the dugong. Seals, sea lions, and walruses comprise the Pinniped group. Sea otters are the ocean members of the fourth group, the Mustelids, which also includes skunks, badgers and

Figure 14.32: Sea turtles are found all over the oceans, but their numbers are diminishing. (27)

weasels (**Figure** 14.34). The final type of ocean marine mammal is the polar bear, which depends heavily on the ocean for survival and is adapted to a life around the sea.

Interactions Among Ocean Organisms

To best understand how ocean organisms interact, it is necessary to consider the particular environments in which they live. There are four main ocean habitats: the intertidal zone and shore, reefs, the open ocean, and the deep sea including trenches. Most organisms have some adaptations specific to their preferred habitat.

A great abundance of life can be found in the intertidal zone. Many intertidal animals can live in or out of the water; some spend one part of their lives in the water and another out of the water. They must be adapted to frequent shifting of water levels and wave impacts. In response, many have hard shells and strong attachments that keep them safe. Some animals, like marine mussels, cling steadily to a rock for their entire lives (**Figure** 14.35). Many young organisms get their start in estuaries, which are special ecosystems affected by the tides, where freshwater and salt water come together.

Reefs are built up by corals and other animals that deposit the mineral calcium carbonate to make rock formations near the shore. They support a complex ecosystem of ocean organisms that live within the coral reef. These diverse organisms have complex interactions with one another; some species help each other to survive. When reefs are destroyed or polluted, certain species can be affected more than others. Harm to one species may have a *domino*

Figure 14.33: Many penguins live in and around Antarctica, but some penguins live farther north on islands such as the Galapagos Islands (near the Equator). The Southern Rockhopper Penguin lives in the Falkland Islands off the coast of Argentina, a long way from the ice. (21)

Figure 14.34: The sea otter is an marine mammal that depends on the ocean for survival. (16)

Figure 14.35: Marine mussels live in the intertidal zone. How are they adapted for life in the intertidal zone? (1)

effect on other species. This may cause the entire ecosystem to collapse. Coral reefs are particularly sensitive to certain threats like temperature change and oil spills.

The open ocean refers to the large open expanses of ocean water. This vast area is the primary habitat for relatively few animals. Most of the food in the ocean is found nearer to shore, so most of these animals are just passing through. Some larger animals like whales and giant groupers may live their entire lives in the open water.

As you know, scientists were surprised to find life in ocean trenches, the deepest parts of the ocean. How can animals survive at that depth? They have adapted to the resources available there, and some bacteria can even use inorganic compounds as energy sources instead of relying on the sun as a source of energy. This is called **chemosynthesis**. Shrimp, clams, fish, and giant tube worms have been found in these extreme places.

Still other animals can live on floating rafts of algae or in frozen places, like the North and South Poles. No matter where you might look in the grand ocean, some creature has found a way to live there. Almost all of these creatures depend on each other. Certainly all creatures depend on producers that convert sunlight into biomass. Our oceans are currently threatened by global warming, overuse and pollution. These imbalances in the ecosystems may someday devastate the delicate web of life on which humans depend.

Lesson Summaries

- Our oceans are home to a tremendous diversity of life including the very smallest bacteria to the very largest baleen whale.
- Some marine organisms float at the surface using the sun's energy, some exist at great ocean depths transforming chemicals in the water into food.
- Plankton are freely floating organisms that include the photosynthetic phytoplankton as well as the animals that eat them, the zooplankton.
- Virtually every phyla on Earth is represented in the ocean including invertebrate and vertebrate organisms, fish, reptiles, seabirds and even air breathing mammals.
- Many creatures in the ocean live in cooperation with other organisms, like coral animals that live symbiotically with dinoflagellates in their tissues.

Review Questions

1. What are seven categories of life in the ocean?
2. What does "invertebrate" mean?
3. What is the group of organisms are the primary producers in the ocean, on which all other life depends?
4. If fish require oxygen to live, why can't they survive on land?
5. Some people argue that polar bears are not really marine mammals because they don't live in the ocean itself. They would say polar bears are land animals like all other

bears. What is your opinion? Explain.

6. What are four major habitats of ocean organisms?
7. Describe adaptations that an organism that lives in a reef might have. How might these adaptations be different from an organism that lives in the open ocean?
8. Describe the importance of maintaining the ecosystem in the ocean.

Vocabulary

chemosynthesis Using inorganic compounds to produce food.

invertebrates Animals with no spinal column.

phytoplankton Plankton that can photosynthesize and therefore create oxygen and sugars.

plankton A diverse group of tiny animals and plants that freely drift in the water.

reef A large underwater structure created from the calcium carbonate skeletons of coral.

vertebrates Animals with a spinal column.

zooplankton Plankton that are tiny animals; they usually consume phytoplankton or other zooplankton as food.

Points to Consider

- How does the ocean interact with the atmosphere?
- How is energy transferred around the planet and how does this affect life on Earth?
- What does global warming mean for the oceans and how might this affect the entire globe?

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Chapter 15

Earth's Atmosphere

15.1 The Atmosphere

Lesson Objectives

- Describe the importance of the atmosphere to our planet and its life.
- Outline the role of the atmosphere in the water cycle.
- List the major components of the atmosphere and know their functions.
- Describe how atmospheric pressure changes with altitude.

Introduction

Earth's atmosphere is a thin blanket of gases and tiny particles—together called air. Without air, the Earth would just be another lifeless rock orbiting the Sun. Although we are rarely aware of it, air surrounds us. We are most aware of air when it moves, creating wind. Like all gases, air takes up space. These gases that make up our air are packed closer together near the Earth's surface than at higher elevations.

All living things need some of the gases in air for life support. In particular, all organisms rely on oxygen for respiration — even plants require oxygen to stay alive at night or when the Sun is obscured. Plants also require carbon dioxide in the air for photosynthesis. All weather happens in the atmosphere. The atmosphere has many other important roles as well. These include moderating Earth's temperatures and protecting living things from the Sun's most harmful rays.

Significance of the Atmosphere

Without the atmosphere, planet Earth would be much more like the Moon than like the planet we live on today. The Earth's atmosphere, along with the abundant liquid water on the Earth's surface, are keys to our planet's unique place in the solar system. Much of what makes Earth exceptional depends on the atmosphere. Let's consider some of the many reasons we are lucky to have an atmosphere.

Atmospheric Gases Are Indispensable for Life on Earth

Without the atmosphere, Earth would be lifeless. Carbon dioxide (CO_2) and oxygen (O_2) are the most important gases for living organisms. CO_2 is vital for use by plants in **photosynthesis**, in which plants use CO_2 and water to convert the Sun's energy into food energy. This food energy is in the form of the sugar glucose ($C_6H_{12}O_6$). Plants also produce O_2. Photosynthesis is responsible for nearly all of the oxygen currently found in the atmosphere.

The chemical reaction for photosynthesis is:

$6CO_2 + 6H_2O + \text{solar energy} \rightarrow C_6H_{12}O_6 + 6O_2$

By creating oxygen and food, plants have made an environment that is favorable for animals. In **respiration**, animals use oxygen to convert sugar into food energy they can use. Plants also go through respiration and consume some of the sugars they produce.

The chemical reaction for respiration is:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{useable energy}$

Notice that respiration looks like photosynthesis in reverse. In photosynthesis, CO_2 is converted to O_2 and in respiration, O_2 is converted to CO_2.

The Atmosphere is a Crucial Part of the Water Cycle

Water moves from the atmosphere onto the land, into soil, through organisms, to the oceans and back into the atmosphere in any order. This movement of water is called the water cycle or **hydrologic cycle** (**Figure** 15.1).

Water changes from a liquid to a gas by **evaporation**. **Water vapor** is the name for water when it is a gas. When the Sun's energy evaporates water from the ocean surface or from lakes, streams, or puddles on land, it becomes water vapor. The water vapor remains in the atmosphere until it **condenses** to become tiny droplets of liquid. The tiny droplets may come together to create **precipitation**, like rain and snow. Snow may become part of the ice in a glacier, where it may remain for hundreds or thousands of years. Eventually, the snow or ice will melt to form liquid water. A water droplet that falls as rain, could become part of a stream or a lake, or it could sink into the ground and become part of **groundwater**.

At the surface, the water will eventually undergo evaporation and reenter the atmosphere. If the water is taken up by a plant and then evaporates from the plant, the process is called **evapotranspiration**.

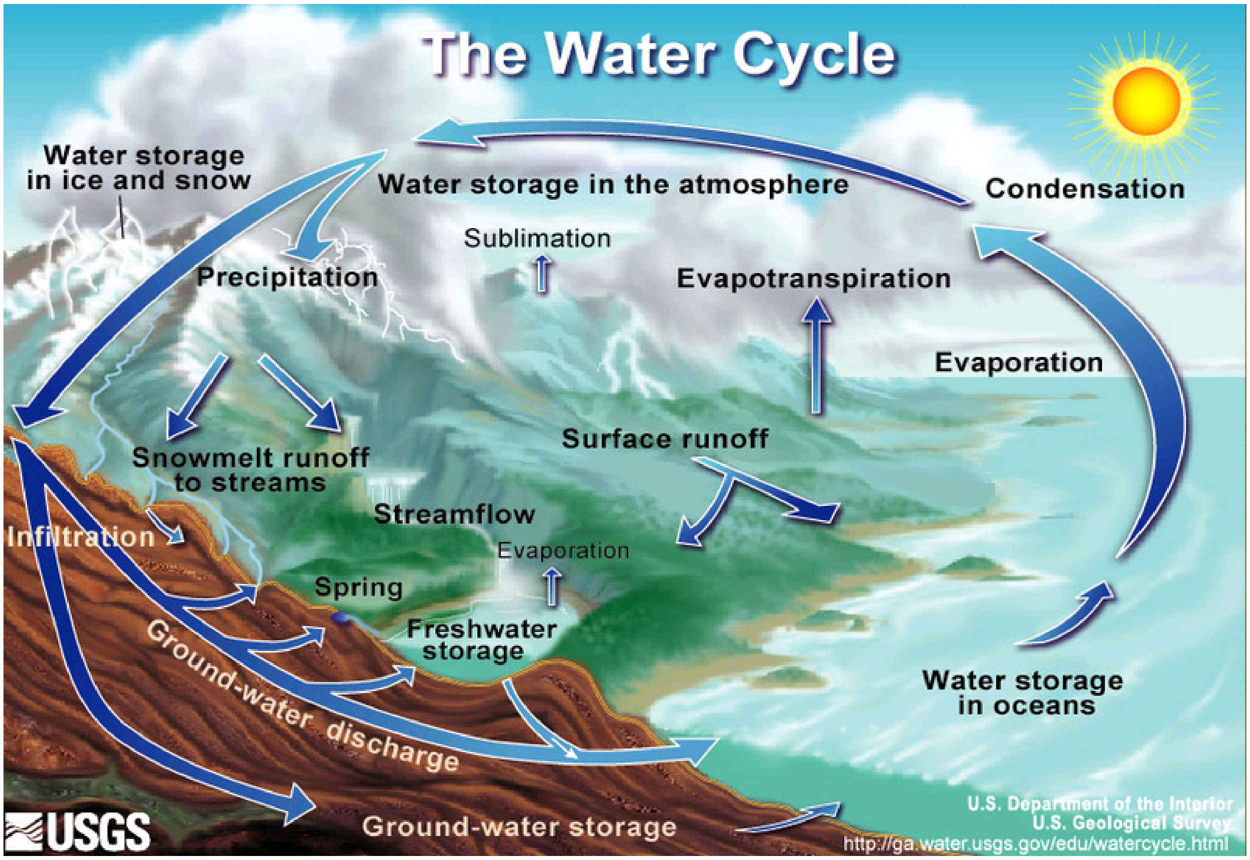

Figure 15.1: The Water Cycle. (20)

All **weather** takes place in the atmosphere, virtually all of it in the lower atmosphere. Weather describes what the atmosphere is like at a specific time and place, and may include temperature, wind and precipitation. It is the changes we experience from day to day. **Climate** is the long-term average of weather in a particular spot. Although the weather for a particular winter day in Tucson, Arizona may include snow, the climate of Tucson is generally warm and dry.

The physical and chemical changes that happen on Earth's surface due to precipitation, wind and reactions with the gases in our atmosphere are called **weathering**. Weathering alters rocks and minerals and shapes landforms at the Earth's surface. Without weathering, Earth's surface would not change much at all. For example, the Moon has no atmosphere, water or winds, so it does not have weathering. The footprints that astronauts made on the Moon decades ago will remain there until someone (human or alien) smooths them out! You would only need to spend a few minutes at the beach to know that Earth's surface is changing all the time.

Ozone in the Upper Atmosphere Makes Life on Earth Possible

Ozone is a molecule composed of three oxygen atoms, (O_3). Ozone in the upper atmosphere absorbs high energy **ultraviolet radiation** (UV) coming from the Sun. This protects living things on Earth's surface from the Sun's most harmful rays. Without ozone for protection, only the simplest life forms would be able to live on Earth.

The Atmosphere Keeps Earth's Temperature Moderate

Our atmosphere keeps Earth's temperatures within an acceptable range; the difference between the very coldest places on Earth and the very hottest is about 150°C (270°F). Without our atmosphere, Earth's temperatures would be frigid at night and scorching during the day. Our daily temperatures would resemble those seen on the Moon, where the temperature range is 310°C (560°F) because there is no atmosphere. **Greenhouse gases** trap heat in the atmosphere. Important greenhouse gases include carbon dioxide, methane, water vapor and ozone.

Atmospheric Gases Provide the Substance for Waves to Travel Through

The atmosphere is made of gases, mostly nitrogen and oxygen. Even though you can't see them, gases take up space and can transmit energy. Sound waves are among the types of energy that can travel though the atmosphere. Without an atmosphere, we could not hear a single sound. Earth would be as silent as outer space. Of course, no insect, bird or airplane would be able to fly since there would be no atmosphere to hold it up!

Composition of Air

Air is made almost entirely of two gases. The most common gas is nitrogen, and the second most common gas is oxygen (O_2). Nitrogen and oxygen together make up 99% of the planet's atmosphere. All other gases together make up the remaining 1%. Although each of these trace gases are only found in tiny quantities, many such as ozone, serve important roles for the planet and its life. One very important minor gas is carbon dioxide, CO_2, which is essential for photosynthesis and is also a very important greenhouse gas (**Table** (15.1)).

Table 15.1: **Concentrations of Atmospheric Gases**

Gas	Symbol	Concentration (%)
Nitrogen	N_2	78.08
Oxygen	O_2	20.95
Argon	Ar	0.93
Neon	Ne	0.0018
Helium	He	0.0005
Hydrogen	H	0.00006
Xenon	Xe	0.000009
Water vapor	H_2O	0 to 4
Carbon dioxide	CO_2	0.038
Methane	CH_4	0.00017
Krypton	Kr	0.00011
Nitrous oxide	N_2O	0.00005
Ozone	O_3	0.000004
Particles (dust, soot)		0.000001
Chlorofluorocarbons (CFCs)		0.00000002

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In nature, air is never completely dry. Up to 4% of the volume of air can be water vapor. **Humidity** is the amount of water vapor in air. The humidity of the air varies from place to place and season to season. This fact is obvious if you compare a summer day in Atlanta,Georgia where humidity is very high, with a winter day in Phoenix, Arizona where humidity is very low. When the air is very humid, it feels heavy or sticky. Your hair might get really curly or frizzy when it is very humid outside. Most people feel more comfortable when the air is dry. The percentage of water vapor in our atmosphere is listed with a wide range of values in the table above because air can be both very humid or dry.

Argon, neon, helium, xenon, and krypton are **noble gases**. They are colorless, odorless, tasteless, and they do not become part of ordinary chemical reactions because they are chemically inert. The noble gases simply exist in the atmosphere.

Some of what is in the atmosphere is not a gas. Particles of dust, soil, fecal matter, metals, salt, smoke, ash and other solids make up a small percentage of the atmosphere. This percentage is variable, as anyone who has spent a windy day in the desert knows (**Figure** 15.2). Particles are important because they provide starting points (or nuclei) for water vapor to condense on, which then forms raindrops. Some particles are pollutants, which are discussed in the chapter on human actions and the atmosphere.

Figure 15.2: A dust storm in Al Asad, Iraq. (6)

Pressure and Density

The atmosphere has different properties at different elevations above sea level, or **altitudes**. The **density** of the atmosphere (the number of molecules in a given volume) decreases the higher you go. This is why explorers who climb tall mountains, like Mt. Everest, have to set up camp at different elevations to let their bodies get used to the changes. What the atmosphere is made of, or the composition of the first 100 kilometers of the atmosphere stays the same with altitude, with one exception: the ozone layer at about 20 - 40 kilometers above the Earth. In the ozone layer, there is a greater concentration of ozone than in other portions of the atmosphere (**Figure** 15.3).

The molecules in gases are able to move freely. If no force acted on a gas at all, it would just escape or spread out forever. Gravity pulls gas molecules in towards the Earth's surface, pulling stronger closer to sea level. This means that atmospheric gases are denser at sea level, where the gravitational pull is greater. Gases at sea level are also compressed by the weight of the atmosphere above them. The weight of the atmosphere on a person's shoulders is equal to more than one ton. The force of the air weighing down over a unit of area is known as its atmospheric pressure, or **air pressure**. People and animals are not crushed because molecules inside our bodies are pushing outward to compensate. Air pressure is felt from all directions, not just from above.

The atmosphere has lower atmospheric pressure and is less dense at higher altitudes. There is less pull from gravity and there is less gas to push down from above. Without as much weight above them, the gases expand, so the air is lighter. For each 6 km (3.7 mile) increase in altitude, the air pressure decreases by half. At 5,500 meters (18,000 feet) above sea level, the air pressure is just less than half of what it is at sea level. This means that the weight of the air on a person's shoulders at that altitude is only one-half ton. At a high enough

Figure 15.3: The difference in air pressure between 2,000 meters and sea level caused this bottle to collapse. The bottle was originally at higher elevation, where air pressure is lower. When it was brought down to sea level, the higher air pressure at sea level caused the bottle to collapse. (25)

altitude, there is no gas left. The density of the atmosphere at 30 km (19 miles) above sea level is only 1% that of sea level. By 700 km (435 miles) from the planet's surface, the air pressure is almost the same as that in the vacuum of deep space.

If your ears have ever 'popped,' you have experienced a change in air pressure. This occurs when you go up or down in altitude quickly, such as flying in an airplane or riding in a car as it goes up or down a mountain. Gas molecules are found inside and outside your ears. When you change altitude quickly, your inner ear keeps the density of molecules at the original altitude. The popping occurs when the air molecules inside your ear suddenly move through a small tube in your ear equalizing the pressure. This sudden rush of air is felt as a popping sensation.

Colder, drier places on Earth usually have higher air pressure, while warmer, more humid places usually have lower air pressure. This happens because large areas of air move up or down by convection. Air pressure also often changes over time, as low and high pressure systems change locations. These phenomena will be discussed when we learn about weather.

Lesson Summary

- Without its atmosphere, Earth would be a very different planet. Gases in the atmosphere allow plants to photosynthesize and animals and plants to engage in respiration.
- Water vapor, which is an atmospheric gas, is an essential part of the water cycle.
- All weather takes place in the atmosphere.
- While the amount of gases do not vary relative to each other in the atmosphere, there is one exception: the ozone layer. Ozone in the upper atmosphere protects life from the Sun's high energy ultraviolet radiation.
- Air pressure varies with altitude, temperature and location.

Review Questions

1. What gas is used and what gas is created during photosynthesis? What gas is used and what gas is created during respiration?
2. Describe two reasons why photosynthesis is important.
3. Briefly describe the movement of water through the water cycle.
4. What is evapotranspiration?
5. What will happen if the humidity of the atmosphere increases?
6. Is weathering more effective in a humid or a dry climate?
7. On an unusual February day in Portland, Oregon, the temperature is 18°C (65°F) and it is dry and sunny. The winter climate in Portland is usually chilly and rainy. How could you explain a warm, dry day in Portland in winter?
8. What important role do greenhouse gases play in the atmosphere?
9. Why do your ears pop when you are in an airplane and the plane descends for a

landing?

10. If air pressure at sea level is one ton and at 5,500 m (18,000 feet) is one-half ton, what is air pressure at 11,000 m (36,000 feet)?

Vocabulary

air pressure The force of air pressing on a given area.

altitude Distance above sea level.

climate The long-term average of weather.

condenses Changes state from a gas to a liquid; in the case of water, from water vapor to liquid water.

evaporation The change in state of a substance from a liquid to a gas; in the case of water, from liquid water to water vapor.

evapotranspiration Water loss by plants to the atmosphere.

greenhouse gases Gases that trap heat in the atmosphere; these include water vapor, carbon dioxide, methane and ozone.

groundwater Fresh water found beneath the ground surface.

humidity The amount of water vapor held in the air; usually refers to relative humidity, meaning the amount of water the air holds relative to the total amount it could hold.

noble gases Gases that usually do not react chemically and have no color, taste, or odor; these are helium, neon, argon, xenon and krypton.

ozone A molecule made of three oxygen atoms; ozone in the lower atmosphere is a pollutant, but in the upper atmosphere it filters out the sun's most harmful ultraviolet radiation.

photosynthesis The process in which plants produce simple sugars (food energy) from solar energy; the process of photosynthesis changes carbon dioxide to oxygen.

precipitation Condensed moisture including rain, sleet, hail, snow, frost or dew.

respiration The process in which animals and plants use oxygen and produce carbon dioxide; in respiration, organisms convert sugar into food energy they can use.

water vapor The gas form of water.

weather The temporary state of the atmosphere in a region; the weather in a location depends on the air temperature, humidity, precipitation, wind and other features of the atmosphere.

Points to Consider

- How would Earth be different if it did not have an atmosphere?
- What are the most important components of the atmosphere?
- How does the atmosphere vary with altitude?

15.2 Atmospheric Layers

Lesson Objectives

- List the major layers of the atmosphere and their temperatures.
- Discuss why all weather takes place in the troposphere.
- Discuss how the ozone layer protects the surface from harmful radiation.

Introduction

The atmosphere is layered, and these layers correspond with how the atmosphere's temperature changes with altitude. By understanding the way temperature changes with altitude, we can learn a lot about how the atmosphere works. For example, the reason that weather takes place in the lowest layer is that the Earth's surface is the atmosphere's primary heat source. Heating the lowest part of the atmosphere places warm air beneath colder air, an unstable situation that can produce violent weather. Interesting things happen higher in the atmosphere, like the beautiful aurora, which light up the sky with brilliant flashes, streaks and rolls of white or colored light.

Air Temperature

Warm air rises: that's a saying just about everyone has heard. But maybe not everyone knows why this is true. Gas molecules are free to move around, and the molecules can take up as much space as they need. When the molecules are cool, they are sluggish and do not move as much, so they do not take up as much space. When the molecules are warm, they move vigorously and take up more space. With the same number of molecules in this larger volume, the air is less dense and air pressure is lower. This warmer, lighter air is more buoyant than the cooler air above it, so it rises. The cooler air then sinks down, since it is more dense than the air beneath it. The rising of warmer air and sinking of cooler air is a very important concept for understanding the atmosphere.

As you learned in the previous section, the composition of gases is mostly the same throughout the first 100 km of our atmosphere. This means if we measure the percentages of different gases throughout the atmosphere, it will stay basically the same. However the density of the gases and the air pressure do change with altitude; they basically decrease with increasing altitude. The property that changes most strikingly with altitude is air temperature. Unlike the change in pressure and density, changes in air temperature are not regular. A change in temperature with distance is called a **temperature gradient**.

The atmosphere is divided into layers based on how the temperature in that layer changes with altitude, the layer's temperature gradient (**Figure** 15.4). The temperature gradient of each layer is different. In some layers, temperature increases with altitude and in others it decreases. The temperature gradient in each layer is determined by the heat source of the layer. The different temperature gradients in each of the four main layers create the thermal structure of the atmosphere.

There are several layers of the atmosphere. The first layer is the **troposphere**. It is the closest to the ground and is sometimes referred to as the lower atmosphere. The second layer is the **stratosphere**, and is sometimes referred to as the upper atmosphere. Most of the important processes of the atmosphere take place in one of these two layers.

Troposphere

About three-fourths of the gases of the atmosphere are found in the troposphere because gravity pulls most of the gases close to the Earth's surface. As with the rest of the atmosphere, 99% of the gases are nitrogen and oxygen.

The thickness of the troposphere varies around the planet. Near the equator, the troposphere is thicker than at the poles, since the spinning of the Earth tends to shift air towards the equator. The thickness of the troposphere also varies with season. The troposphere is thicker in the summer and thinner in the winter all around the planet. At the poles in winter, the atmosphere is uniformly very cold and the troposphere cannot be distinguished from other layers. The importance of this feature of the atmosphere will become clear when we learn about ozone depletion.

Earth's surface is a major source of heat for the troposphere. Where does the heat come from? Nearly all the heat comes from the sun, either directly or indirectly. Some incoming sunlight warms the gases in the atmosphere directly. But more sunlight strikes the Earth's

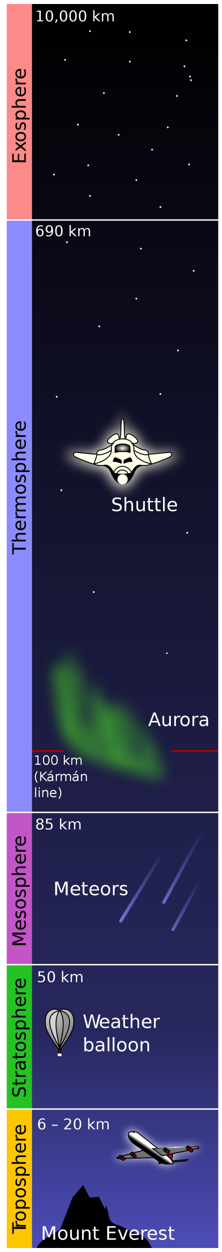

Figure 15.4: The layers of the atmosphere with altitude. (10)

rock, soil, and water, which radiate it back into the atmosphere as heat, further warming the troposphere. The temperature of the troposphere is highest near the surface of the Earth and declines with altitude. On average, the temperature gradient of the troposphere is 6.5°C per 1,000 m (3.6°F per 1,000 feet) of altitude.

Notice that in the troposphere, warm air is beneath cold air. Since warm air is less dense and tries to rise, this condition is unstable. So the warm air at the base of the troposphere rises and cool air higher in the troposphere sinks. For this reason, air in the troposphere does a lot of mixing. This mixing causes the temperature gradient to vary with time and place. For reasons that will be discussed in the next section, rising air cannot rise above the top of the troposphere. The rising and sinking of air in the troposphere means that all of the planet's weather takes place in the troposphere.

When there is a temperature **inversion**, air temperature in the troposphere *increases* with altitude and warm air sits over cold air. This is called an inversion because the usual situation is reversed or inverted. Inversions are very stable and they often last for several days or even weeks. Inversions commonly form over land at night or in winter. At these times, the ground is cold because there is little solar energy reaching it. At night, the Sun isn't out and in winter, the Sun is at a low angle, so little solar radiation reaches the ground. This cold ground cools the air that sits above it, making this low layer of air denser than the air above it. An inversion also forms on the coast where cold seawater cools the air above it. When that denser air moves inland, it slides beneath the warmer air over the land. Since temperature inversions are stable, they often trap pollutants and produce unhealthy air conditions in cities (**Figure** 15.5).

Figure 15.5: Smoke makes a temperature inversion visible. The smoke is trapped in cold dense air that lies beneath a cap of warmer air. (22)

At the top of the troposphere is a thin layer called the **tropopause**. Temperature in the tropopause does not change with height. This means that the cooler, denser air of the troposphere is trapped beneath the warmer, less dense air of the stratosphere. So the tropopause is a barrier that keeps air from moving from the troposphere to the stratosphere. Sometimes breaks are found in the tropopause and air from the troposphere and stratosphere can mix.

Stratosphere

The **stratosphere** rises above the tropopause. When a volcano erupts dust and gas that makes its way into the stratosphere, it remains suspended there for many years. This is because there is so little mixing between the stratosphere and troposphere. Pilots like to fly in the lower portions of the stratosphere because there is little air turbulence.

In the stratosphere, temperature increases with altitude. The reason is that the direct heat source for the stratosphere is the Sun. A layer of ozone molecules absorbs solar radiation, which heats the stratosphere. Unlike in the troposphere, air in the stratosphere is stable because warmer, less dense air sits over cooler, denser air. As a result, there is little mixing of air within the layer.

The stratosphere has the same composition of gases as the rest of the atmosphere, with the exception of the **ozone layer**. The ozone layer is found within the stratosphere at between 15 to 30 km (9 to 19 miles) altitude. The thickness of the ozone layer varies by the season and also by the latitude. The amount of ozone present in the ozone layer is tiny, only a few molecules per million air molecules. Still, the concentration of ozone is much greater than in the rest of the atmosphere. The ozone layer is extremely important because ozone gas in the stratosphere absorbs most of the Sun's harmful ultraviolet (UV) radiation.

How does ozone do this? High energy ultraviolet light, traveling through the ozone layer, breaks apart the ozone molecule, O_3 into one oxygen molecule (O_2) and one oxygen atom (O). This process absorbs the Sun's most harmful UV rays. Ozone is also reformed in the ozone layer: Oxygen atoms bond with O_2 molecules to make O_3. Under natural circumstances, the same amount of ozone is continually being created and destroyed and so the amount of ozone in the ozone layer remains the same.

The ozone layer is so effective that the highest energy ultraviolet, the UVC, does not reach the planet's surface at all. Some of the second highest energy ultraviolet, UVB, is stopped as well. The lowest energy ultraviolet, UVA, travels through the atmosphere to the ground. In this way, the ozone layer protects life on Earth. High energy ultraviolet light penetrates cells and damages DNA, leading to cell death (which we know as a bad sunburn). Organisms on Earth are not adapted to heavy UV exposure, which kills or damages them. Without the ozone layer to reflect UVC and UVB, most complex life on Earth would not survive long.

Above the stratosphere is the thin **stratopause**, which is the boundary between the stratosphere below and the mesosphere above. The stratopause is at about 50 km above the Earth's surface.

Mesosphere

Temperatures in the **mesosphere** decrease with altitude. Since there are very few gas molecules in the mesosphere to absorb the Sun's radiation, the heat source here is the stratosphere below. The mesosphere is extremely cold, especially at its top, about -90°C (-130°F).

The air in the mesosphere is extremely thin: 99.9% of the mass of the atmosphere is below the mesosphere. As a result, air pressure is very low. Although the amount of oxygen relative to other gases is the same as at sea level, there is very little gas and so very little oxygen. A person traveling through the mesosphere would experience severe burns from ultraviolet light since the ozone layer which provides UV protection is in the stratosphere below them. And there would be almost no oxygen for breathing! Stranger yet, an unprotected traveler's blood would boil at normal body temperature because the pressure is so low.

Despite the thin air, the mesosphere has enough gas that meteors burn as they enter the atmosphere (**Figure** 15.6). The gas causes friction with the descending meteor, producing its tail. Some people call them "shooting stars." Above the mesosphere is the **mesopause**. Astronauts are the only people who travel through the mesopause.

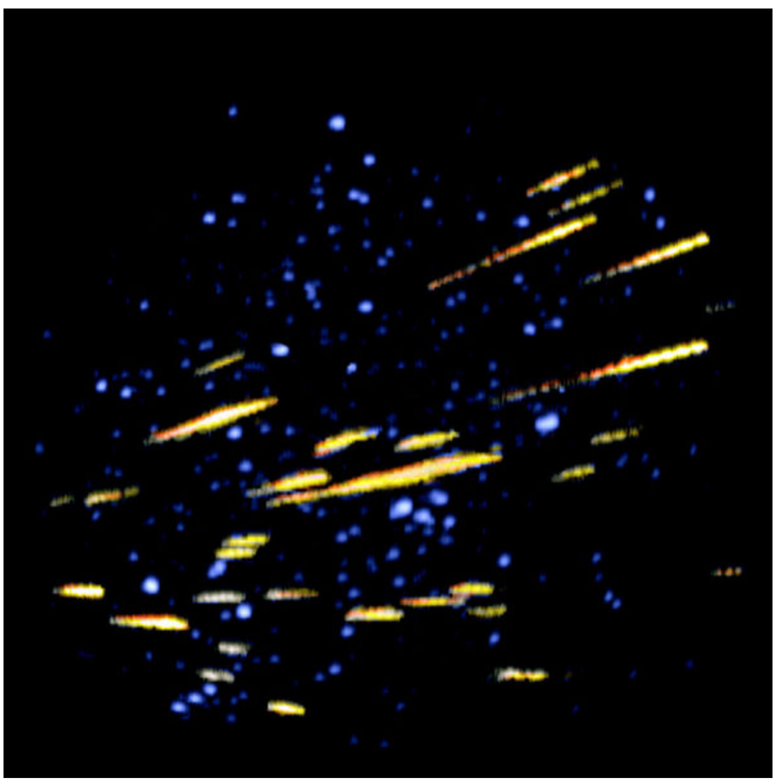

Figure 15.6: Meteors burn up as they hit the mesosphere. (23)

Thermosphere and Beyond

The **thermosphere** rises from the mesopause. The International Space Station (ISS) orbits within the upper part of the thermosphere, at about 320 to 380 km above the Earth (**Figure** 15.7).

Figure 15.7: The International Space Station. (18)

What does an astronaut experience in the thermosphere? Temperatures in the thermosphere can exceed 1000°C (1800°F) because oxygen molecules in the layer absorb short wavelength solar energy. Yet despite these high temperatures, the atmosphere outside the ISS feels cold. This is because gas molecules are so few and far between that they very rarely collide with other atoms and so little energy is transferred. The density of molecules is so low that one gas molecule can go about 1 km before it collides with another molecule.

Within the thermosphere is the **ionosphere**. The ionosphere gets its name because nitrogen and oxygen molecules are ionized by solar radiation. In the process of ionization, the neutrally-charged molecules absorb high-energy, short-wavelength energy from the Sun. This causes the molecules to lose one or more electrons and become positively-charged ions. The freed electrons travel within the ionosphere as electric currents. Because of the free ions, the ionosphere has many interesting characteristics.

Have you ever been out on an open road and found a radio station on the AM dial that is transmitted from hundreds of kilometers away? The reason radio waves can travel so far at night involves the ionosphere. During the day, the lower part of the ionosphere absorbs some of the energy from the radio waves and reflects some back to Earth. But at night the waves bounce off of the ionosphere, go back down to the ground, and then bounce back up again. This does not happen during the day due to ionization in the ionosphere. This bouncing up and down allows radio waves to travel long distances.

The most spectacular feature of the ionosphere is the nighttime **aurora**. Spectacular light displays with streamers, arcs, or foglike glows are visible on many nights in the polar regions. The lights can be white, green, blue, red or purple. The display is called the *aurora borealis* or northern lights in the Northern Hemisphere (**Figure** 15.8). It is called the *aurora australis* or southern lights in the Southern Hemisphere.

Figure 15.8: The Northern Lights above Bear Lake, Alaska. (7)

The aurora is caused by massive storms on the Sun that release great quantities of protons and electrons. These electrically charged particles fly through space and spiral in along lines of Earth's magnetic field. Earth's magnetic field guides the charged particles toward the poles, which explains why the auroras are seen primarily in the polar regions. When the protons and electrons enter the ionosphere, they energize oxygen and nitrogen gas molecules and cause them to light up. Each gas emits a particular color of light. Depending on where they are in the atmosphere, oxygen shines green or red and nitrogen shines red or blue. The frequency and intensity of the aurora increases when the Sun has more magnetic storms.

The outermost layer of the atmosphere is the **exosphere**. There is no real outer limit to the exosphere. If you continued traveling farther out from the Earth, the gas molecules would finally become so scarce that you would be in outer space. There is so little gravity holding gas molecules in the exosphere that they sometimes escape into outer space. Beyond the atmosphere is the **solar wind**. The solar wind is made of high-speed particles, mostly protons and electrons, traveling rapidly outward from the Sun.

Lesson Summary

- Different temperature gradients create different layers within the atmosphere. The lowest layer is the troposphere, where most of the atmospheric gases and all of the planet's weather are located.

- The troposphere gets its heat from the ground, and so temperature decreases with altitude. Warm air rises and cool air sinks and so the troposphere is unstable.
- In the stratosphere, temperature increases with altitude. The stratosphere contains the ozone layer, which protects the planet from the Sun's harmful UV. The higher layers contain few gas molecules and are very cold.

Review Questions

1. Why does warm air rise?
2. Why doesn't air temperature increase or decrease uniformly with altitude, just like air pressure decreases uniformly with altitude? Give examples of the different possible scenarios.
3. Where and when in the atmosphere is there no real layering at all? Why is this phenomenon important?
4. Describe how the ground acts as the heat source for the troposphere. What is the source of energy and what happens to that energy?
5. How stable is an inversion and why? How does an inversion form?
6. Why doesn't air from the troposphere and the stratosphere mix freely?
7. Where does the heat from the stratosphere come from and what is needed for that heat to be absorbed?
8. Describe the process of ozone creation and loss in the ozone layer. Under normal circumstances, does one occur more than the other?
9. How and where are 'shooting stars' created?
10. Why would an unprotected traveler's blood boil at normal body temperature in the mesosphere?

Further Reading / Supplemental Links

- http://www.youtube.com/watch?v=PaSFAbATPvk&feature=related

Vocabulary

aurora A spectacular light display that occurs in the ionosphere near the poles; called the aurora borealis or northern lights in the Northern Hemisphere, and the aurora australis or southern lights in the Southern Hemisphere.

exosphere The outermost layer of the atmosphere, where gas molecules are extremely far apart and some occasionally escape earth's gravity and fly off into outer space.

inversion A situation in the troposhere in which warm air lies above cold air.

ionosphere An ionized layer contained within the thermosphere; the second to the last layer of the atmosphere.

mesopause The thin transition layer in the atmosphere, the boundary between the mesosphere and the thermosphere.

mesosphere The layer of the atmosphere between the stratosphere and the thermosphere; temperature decreases with altitude.

ozone layer A layer of the stratosphere where ozone gas is more highly concentrated.

solar wind High-speed protons and electrons that fly through the solar system from the Sun.

stratopause The thin transitional layer of the atmosphere between the stratosphere and the mesosphere.

stratosphere The second layer of the atmosphere, where temperature increases with altitude due the presence of ozone.

temperature gradient The change in temperature with distance.

thermosphere The second to the last layer of the atmosphere where gases are extremely thinly distributed.

tropopause The thin transitional layer of the atmosphere between the troposphere and the stratosphere.

troposphere The lowermost layer of the atmosphere.

ultraviolet radiationn High energy radiation that comes from the Sun; there are three types of UV radiation, UVA, UVB and UVC. The shortest wavelength, and therefore the most dangerous, is UVC.

Points to Consider

- How does solar energy create the atmosphere's layers?
- How does solar energy create the weather?
- What would be the situation for life on Earth if there was less ozone in the ozone layer?

15.3 Energy in the Atmosphere

Lesson Objectives

- Describe how energy is transmitted.
- Describe the Earth's heat budget and what happens to the Sun's energy.
- Discuss the importance of convection in the atmosphere.
- Describe how a planet's heat budget can be balanced.
- Describe the greenhouse effect and why it is so important for life on Earth.

Introduction

Wind and precipitation, warming and cooling depend on how much energy is in the atmosphere and where that energy is located. Much more energy from the Sun reaches low latitudes (nearer the equator) than high latitudes (nearer the poles). These energy differences cause the winds, affect climate, and even drive ocean currents. Heat is held in the atmosphere by greenhouse gases.

Energy, Temperature, and Heat

Every material has **energy:** All the molecules within it vibrate. Gas molecules contain more energy than an equal number of liquid molecules (under the same temperature and pressure conditions) and move freely. Liquid molecules contain more energy than solids and move more freely than solids.

Energy travels through space or material. You know this because you can stand near a fire and feel the warmth. In this situation, energy is being transferred as invisible waves that can travel through air, glass, and even the vacuum of outer space. These waves have electrical and magnetic properties, so they are called **electromagnetic waves**. The transfer of energy from one object to another through electromagnetic waves is known as **radiation**. Different types of electromagnetic waves have different wavelengths. A wavelength is the horizontal distance from trough-to-trough or crest-to-crest of adjacent waves (**Figure** 15.9).

Humans are able to see some wavelengths of light, the wavelengths known as 'visible light.' These wavelengths appear to us as the colors of the rainbow (**Figure** 15.10). The longest wavelengths of visible light appear red and the shortest wavelengths appear violet. Wavelengths that are longer than visible red are infrared. Snakes can see infrared energy. We can record this with special equipment. Wavelengths that are shorter than violet are ultraviolet. Infrared and ultraviolet wavelengths of energy are just as important as the wavelengths in visible light; we just can't see them.

Some objects radiate electromagnetic waves in the visible light spectrum. Two familiar

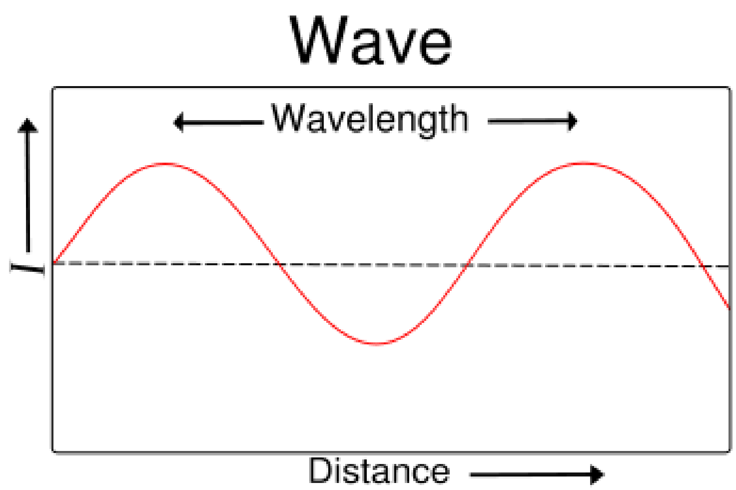

Figure 15.9: Waves. The high points are the crests, the low point is the trough. The wavelength is the distance from crest to crest. (27)

sources are the Sun and a light bulb. Some objects radiate electromagnetic waves at wavelengths that we cannot see. The glass of water sitting next to you does not radiate visible light, but it does radiate a tiny amount of heat.

You should be aware that some objects appear to radiate visible light, but they actually do not. The moon and the planets, for example, do not emit light of their own. They reflect the light of the Sun. **Reflection** is when light bounces back from a surface. **Albedo** is a measure of how well a surface reflects light. A surface that reflects a high percentage of the light that strikes it has high albedo and one that reflects a small percentage has low albedo.

One important fact to remember is that energy cannot be created or destroyed. It can only be changed from one form to another. In photosynthesis, for example, plants convert the Sun's energy into food energy. They do not create new energy. When energy is transformed, often some becomes heat. Heat transfers between materials easily, from warmer objects to cooler ones. If no more heat is added, eventually all of a material will reach the same temperature.

Temperature is a measure of how fast the atoms in a material are vibrating. High temperature particles vibrate faster than low temperature particles. Rapidly vibrating atoms smash together, which generates heat. As a material cools down, the atoms vibrate more slowly and collide less frequently. As a result, they emit less heat.

What is the difference between heat and temperature? Temperature measures how fast a material's atoms are vibrating. Heat measures the material's total energy. Think of a candle flame and a bathtub full of hot water. Which has a higher heat and which has a higher temperature? Surprisingly, the flame has a higher temperature, but much less heat because the hot region is very small. The bathtub has lower temperature but contains much more

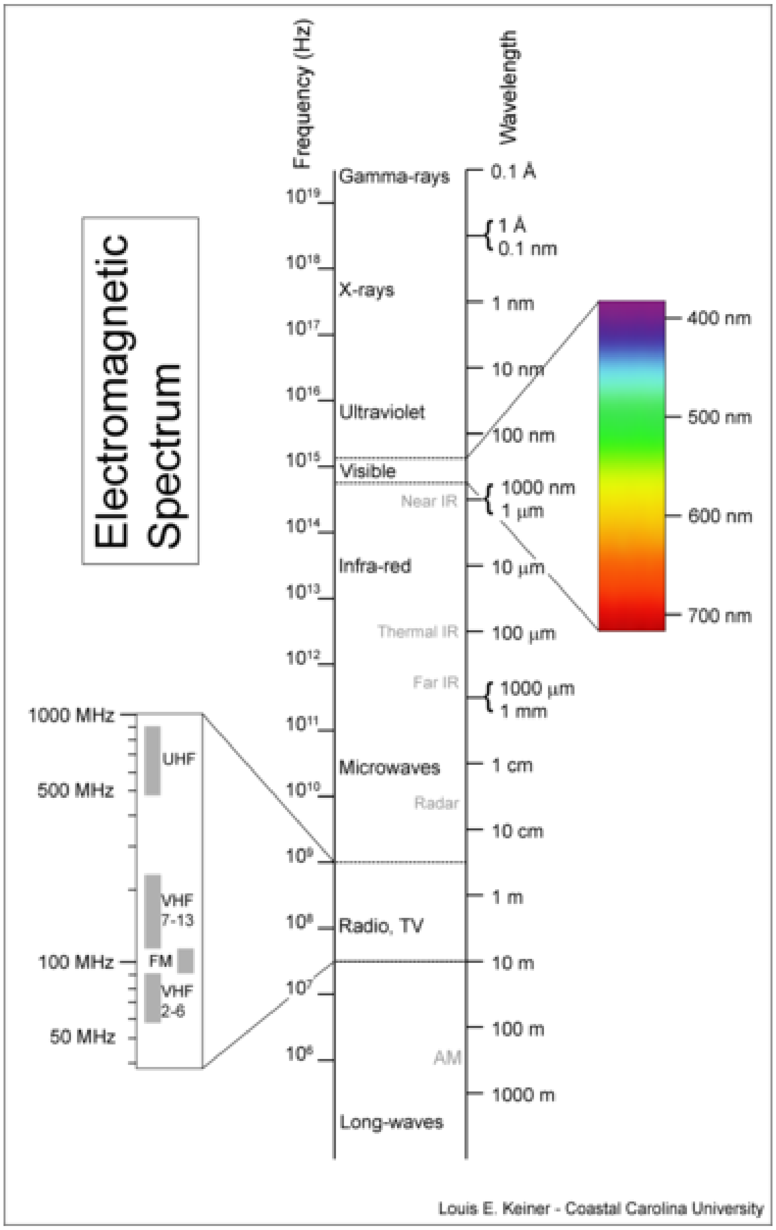

Figure 15.10: The electromagnetic spectrum showing the wavelengths of energy. Solar radiation that reaches the outer atmosphere includes radio waves, along with visible light plus the ultraviolet range nearest to violet and the near infrared. Other wavelengths of electromagnetic radiation are blocked by different parts of Earth's atmosphere. (2)

heat because it has many more vibrating atoms. Even though it's at a lower temperature, the bathtub has a greater total energy.

Heat is taken in or released when an object changes state, or changes from a gas to a liquid or a liquid to a solid. This heat is called **latent heat**. When a substance changes state, latent heat is released or absorbed. A substance that is changing its state of matter does not change temperature. All of the energy that is released or absorbed goes toward changing the material's state.

For example, imagine a pot of boiling water on the stove: that water is at 100ºC (212ºF). If a cook increases the temperature of the burner beneath the pot, more heat enters the water. But still the water remains at its boiling temperature. The additional energy goes into changing the water from liquid to gas. This allows the water to evaporate more rapidly. When water changes from a liquid to a gas it takes in heat. Since evaporation takes in heat, this is called evaporative cooling. Evaporative cooling is an inexpensive way to cool homes in hot, dry areas.

Substances also differ in their **specific heat,** the amount of energy needed to raise the temperature of one gram of the material by 1.0ºC (1.8ºF). Water has a very high specific heat, which means it takes a lot of energy to change the temperature of water. Let's compare a puddle and asphalt, for example. If you are walking barefoot on a sunny day, which would you rather walk across, the shallow puddle or an asphalt parking lot? Due to its high specific heat, the water stays cooler than the asphalt, even though it receives the same amount of solar radiation.

Energy From the Sun

Most of the energy that reaches the Earth's surface comes from the Sun. The Sun emits energy in a continuous stream of wavelengths (**Figure** 15.11). These wavelengths include visible light, infrared, ultraviolet radiation, and others. About 44% of solar radiation is in the visible light wavelengths. When viewed together, all of the wavelengths of visible light appear white. But a prism or water droplets, for example, can break the white light into different wavelengths so that you can see separate colors (**Figure** 15.12).

Only about 7% of solar radiation is in the ultraviolet (UV) wavelengths. Of the solar energy that reaches the outer atmosphere, UV wavelengths have the greatest energy. There are three types of UV energy: UVC has the shortest wavelengths and is the most energetic; UVA is the longest wavelengths and is the least energetic; and UBV is in the middle of the two. UV radiation will tan or burn human skin. The remaining solar radiation is the longest wavelength, infrared. Most objects radiate infrared energy, which we feel as heat (**Figure** 15.13).

Some of the wavelengths of solar radiation traveling through the atmosphere may be lost because they are absorbed by various gases (**Figure** 15.14). Ozone, for example, completely

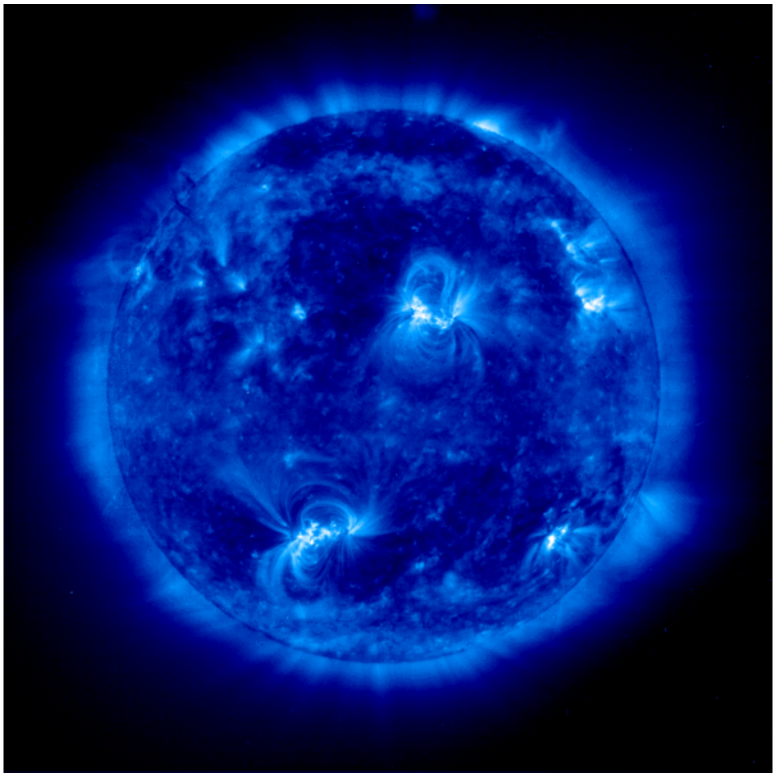

Figure 15.11: An image of the sun taken by the SOHO spacecraft. The sensor is picking up only the 17.1 nm wavelength, in the ultraviolet wavelengths. (9)

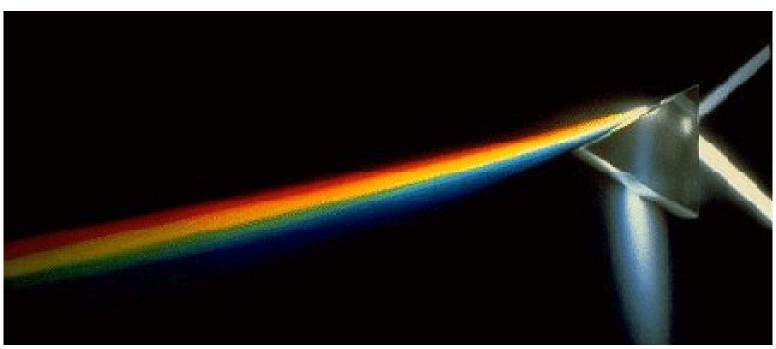

Figure 15.12: A prism breaks apart white light by wavelength so that you can see all the colors of the rainbow. (12)

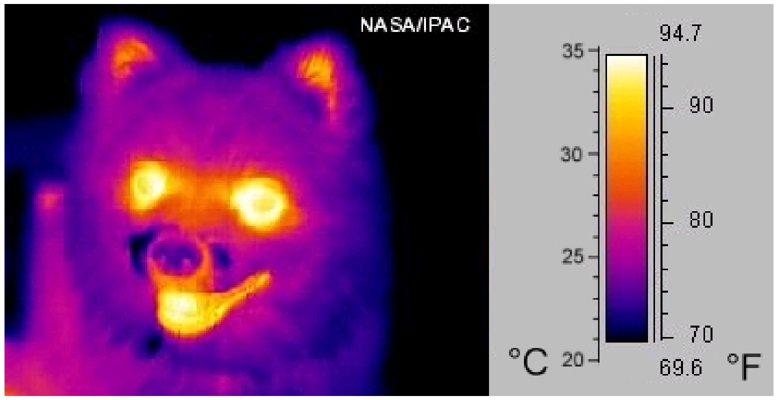

Figure 15.13: An image of a dog taken by an infrared sensor. The image shows the different amounts of heat radiating from the dog. (19)

removes UVC, most UVB and some UVA from incoming sunlight. O_2 , CO_2 and H_2O also filter out other wavelengths from solar energy.

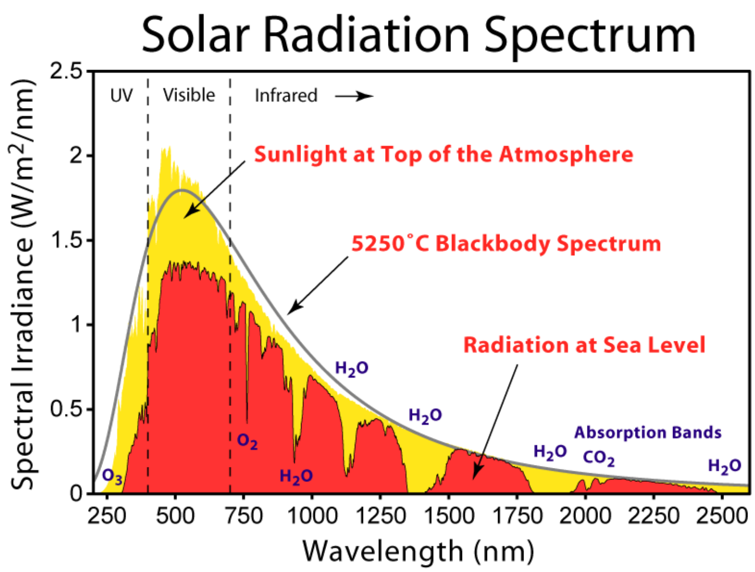

Figure 15.14: In the atmosphere, gases filter some wavelengths from incoming solar energy. The yellow field shows the wavelengths of energy that reach the top of the atmosphere. The red field shows the wavelengths that reach sea level. The amount of radiation is reduced overall as different gases filter out different wavelengths. Ozone filters out the shortest wavelength ultraviolet and oxygen filters out most infrared, at about 750 nm. (15)

Different parts of the Earth receive different amounts of solar radiation. This is because the Sun's rays strike the Earth's surface most directly at the equator. As you move away from the equator, you will notice that different areas also receive different amounts of sunlight in different seasons. But what causes the seasons?

The Earth revolves around the Sun once each year and spins on its axis of rotation once each day. This axis of rotation is tilted 23.5° relative to its plane of orbit around the Sun. The axis of rotation happens to be pointed to the star Polaris, or the North star. As the Earth orbits the Sun, the tilt of Earth's axis stays lined up with the North star. This means that the North Pole is tilted towards the Sun and the Sun's rays strike the Northern Hemisphere more directly in summer. At the summer solstice, June 21 or 22 of each year, the Sun's rays are hit the Earth most directly along the Tropic of Cancer. This is a circle of latitude exactly 23.5 ° north of the equator. When it is summer solstice in the Northern Hemisphere, it is winter solstice in the Southern Hemisphere. Winter solstice for the Northern Hemisphere happens on December 21 or 22. The tilt of Earth's axis points away from the sun in the winter and the Sun's rays strike most directly at the Tropic of Capricorn (**Figure** 15.15). The Tropic of Capricorn is a line of latitude exactly 23.5 ° south of the equator. The light from the Sun gets spread out over a larger area, so that area isn't heated as much. There are also fewer daylight hours in winter, so there is also less time for the Sun to warm that place. When it is winter in the Northern Hemisphere, it is summer in the Southern Hemisphere.

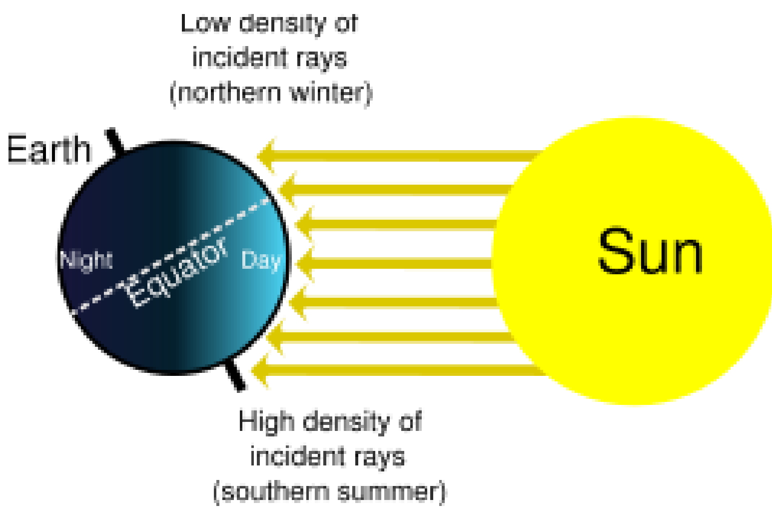

Figure 15.15: Arctic winter solstice. The sun's rays are directly overhead at the Tropic of Capricorn. Sunlight is striking the south pole, but it is spread out. No sunlight is getting to the North pole. (14)

Halfway between the two solstices, the Sun's rays shine most directly at the equator. We call these times an 'equinox' (**Figure** 15.16). The daylight and nighttime hours are exactly equal on an equinox. The autumnal equinox happens on September 22 or 23 and the *vernal* or spring equinox happens March 21 or 22 in the Northern Hemisphere. Thus the seasons are caused by the direction Earth's axis is pointing relative to the Sun.

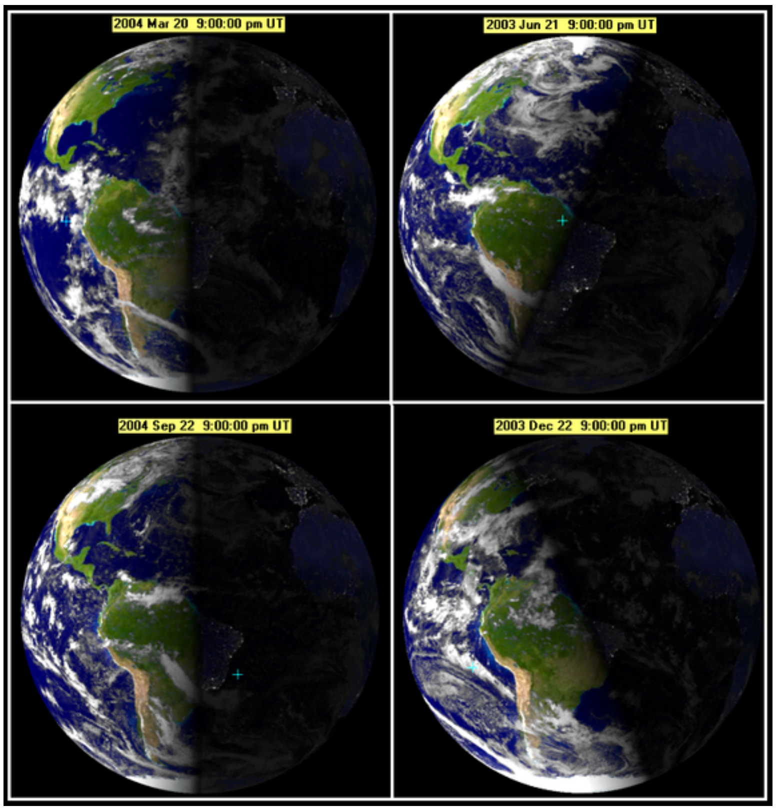

Figure 15.16: Where sunlight reaches on spring equinox, summer solstice, vernal equinox, and winter solstice. The time is 9:00 pm Universal Time, at Greenwich, England. (26)

Heat Transfer in the Atmosphere

Heat can move in three different ways. We've already examined radiation, in which electromagnetic waves transfer heat between two objects. **Conduction** is a type of heat transfer that occurs when heat moves from areas of more heat to areas of less heat by direct contact. Warmer molecules vibrate more rapidly than cooler molecules. They collide directly with other nearby molecules, giving them some of their energy, which transfers heat. When all the molecules are moving at the same rate, the substance is the same temperature throughout. Heat in the atmosphere is transferred by conduction. This is more effective at lower altitudes where air molecules are packed more densely together. Conduction can transfer heat upward to where the molecules are spread further apart. It can also transfer heat laterally from a warmer to a cooler spot, where the molecules are moving less vigorously.

The most important way heat is transferred in the atmosphere is by convection currents. Convection is the transfer of heat by movement of heated materials. The radiation of heat from the ground warms the air above it. This warmer air is less dense than the air above it and so it rises. As the heated air rises it begins to cool, since it is further from the heat source. As it cools, it contracts, becomes denser and sinks. Air moves horizontally between warm, rising air and cooler, sinking air. This entire structure is a **convection cell**.

Heat at Earth's Surface

Not all energy coming in from the Sun makes it to the Earth's surface. About half is filtered out by the atmosphere. Besides being absorbed by gases, energy is reflected by clouds or is scattered. Scattering occurs when a light wave strikes a particle and bounces off in some other direction. Of the energy that strikes the ground, about 3% is reflected back into the atmosphere. The rest warms the soil, rock or water that it reaches. Some of the absorbed energy radiates back into the air as heat. These infrared wavelengths can only be seen by infrared sensors.

It might occur to you that if solar energy continually enters the Earth's atmosphere and ground surface, then the planet must always be getting hotter. This is not true, because energy from the Earth escapes into space through the top of the atmosphere, just as energy from the Sun enters through the top of the atmosphere. If the amount that exits is equal to the amount that comes in, then there is no increase or decrease in average global temperature. This means that the planet's heat budget is in balance. If more energy comes in than goes out, the planet warms. If more energy goes out than comes in, the planet cools.

To say that the Earth's heat budget is balanced ignores an important point. The amount of incoming solar energy varies at different latitudes (**Figure** 15.17). This is partly due to the seasons. At the equator, days are about the same length all year and the Sun is high in the sky. More sunlight hits the regions around the equator and air temperatures are warmer. At the poles, the Sun does not rise for months each year. Even when the Sun is out all day and night in the summer, it is at a very low angle in the sky. This means that not much solar radiation reaches the ground near the poles. Because of this, during a large part of the year, the polar areas are covered with ice and snow. These brilliant white substances have a high albedo and reflect solar energy back into the atmosphere. For all of these reasons, the region around the equator is much warmer than the areas at the poles.

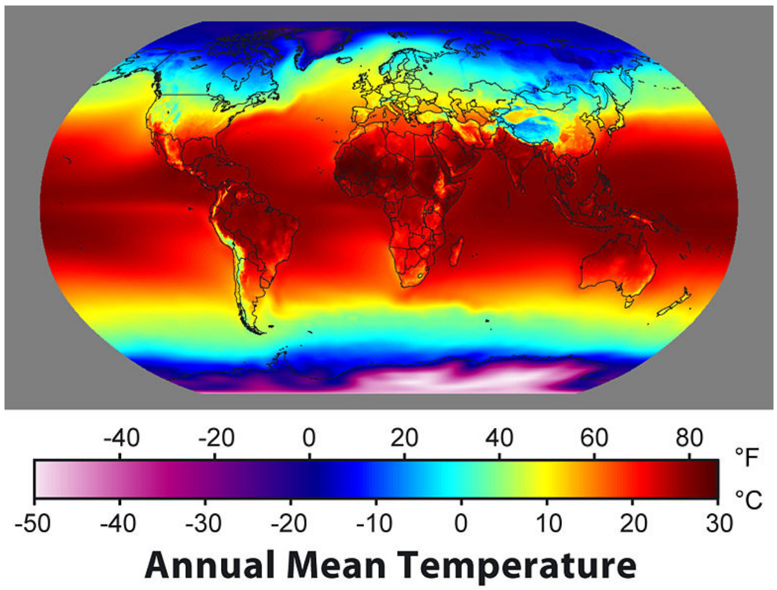

Figure 15.17: The average annual temperature of the Earth, showing that the equatorial region is much warmer than the polar regions. There is a roughly gradual temperature gradient from the low to the high latitudes. (4)

The difference in the amount of solar energy that the planet receives at different latitudes drives much of the activity that takes place at the Earth's surface. This includes the wind, water cycle, and ocean currents. The differences in solar energy around the globe drive the way the atmosphere circulates.

The Greenhouse Effect

The remaining factor in the Earth's heat budget s the role of greenhouse gases. Greenhouse gases warm the atmosphere by trapping heat. Sunlight strikes the ground, is converted to heat, and radiates back into the lower atmosphere. Some of the heat is trapped by greenhouse gases in the troposphere, and cannot exit into space. Like a blanket on a sleeping person, greenhouse gases act as **insulation** for the planet. The warming of the atmosphere due to insulation by greenhouse gases is called the **greenhouse effect** (**Figure** 15.18).

The greenhouse effect is very important, since without it the average temperature of the atmosphere would be about -18ºC (0ºF). With the greenhouse effect, the average temperature

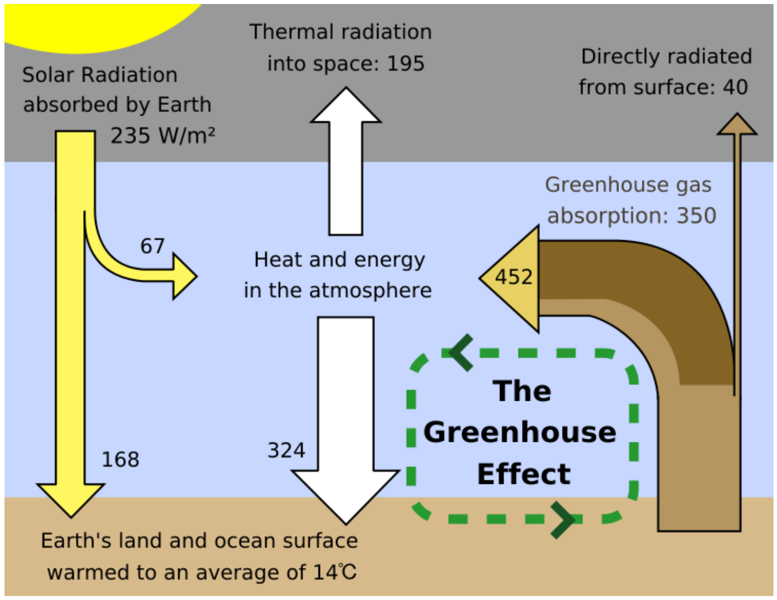

Figure 15.18: The Earth's heat budget, showing the amount of energy coming into and going out of the Earth system and the importance of the greenhouse effect. The numbers are the amount of energy that is found in one square meter of that location. (11)

of the atmosphere is a pleasant 15°C (59°F). Without insulation, daytime temperatures would be very high and nighttime temperatures would be extremely low. This is the situation on all of the planets and moons that have no atmosphere. If the Earth did not have insulation, temperatures would likely be too cold and too variable for complex life forms.

There are many important greenhouse gases in the atmosphere including CO_2, H_2O, methane, O_3, nitrous oxides (NO and NO_2), and chlorofluorocarbons (CFCs). All of these gases are a normal part of the atmosphere except CFCs, which are human-made. However, human activity has significantly raised the levels of many of these gases; for example, methane levels are about 2 1/2 times higher as a result of human activity. **Table** 15.2 shows how each greenhouse gas naturally enters the atmosphere.

Different greenhouse gases have different abilities to trap heat. For example, one methane molecule can trap 23 times as much heat as one CO_2 molecule. One CFC-12 molecule (a type of CFC) can trap 10,600 times as much heat as one CO_2. Still, CO_2 is a very important greenhouse gas because it is much more abundant in the atmosphere than the others.

Table 15.2:

Greenhouse Gas	Where It Comes From
Carbon dioxide	Respiration, volcanic eruptions, decomposition of plant material; burning of fossil fuels

Table 15.2: (continued)

Greenhouse Gas	Where It Comes From
Methane	Decomposition of plant material under some conditions, biochemical reactions in stomachs
Nitrous oxides	Produced by bacteria
Ozone	Atmospheric processes
Chlorofluorocarbons	Not naturally occurring; made by humans

The greenhouse effect is very important for another reason. If greenhouse gases in the atmosphere increase, they trap more heat and warm the atmosphere. If greenhouse gases in the atmosphere decrease, less heat is trapped and the atmosphere cools. The increase or decrease of greenhouse gases in the atmosphere affect climate and weather the world over.

Lesson Summary

- All materials contain energy, which can radiate through space as electromagnetic waves. The wavelengths of energy that come from the Sun include visible light, which appears white but can be broken up into many colors.
- Ultraviolet waves are very high energy. The highest energy UV, UVC and some UVB, gets filtered out of incoming sunlight by ozone.
- More solar energy reaches the low latitudes and the redistribution of heat by convection drives the planet's air currents.

Review Questions

1. What is the difference between temperature and heat?
2. Give a complete description of these three categories of energy relative to each other in terms of their wavelengths and energy: infrared, visible light, and ultraviolet.
3. Why do the polar regions have high albedo?
4. Give an example of the saying "energy can't be created or destroyed.
5. Describe what happens to the temperature of a pot of water and to the state of the water as the dial on the stove is changed from no heat to the highest heat.
6. Describe where the Sun is relative to the Earth on summer solstice, autumnal equinox, winter solstice and spring equinox. How much sunlight is the North pole getting on June 21? How much is the South pole getting on that same day?
7. What is the difference between conduction and convection?
8. What is a planet's heat budget? Is Earth's heat budget balanced or not?
9. On a map of average annual temperature, why are the lower latitudes so much warmer than the higher latitudes?

10. Why is carbon dioxide the most important greenhouse gas?
11. How does the amount of greenhouse gases in the atmosphere affect the atmosphere's temperature?

Vocabulary

albedo The amount of light that reflects back off a surface; snow and ice have high albedo.

conduction Heat transfer between molecules in motion.

convection Heat transfer by the movement of currents.

convection cell A heat transfer unit in which warm material rises, cold material sinks, and material moves between the two to create a cell.

electromagnetic waves Radiation travels in electromagnetic waves; waves that have both electrical and magnetic properties.

energy The ability to work; energy is not created or destroyed but can be transferred from one form to another.

greenhouse effect The trapping of heat that is radiated out from the planet's surface by greenhouse gases in the atmosphere and moderates a planet's temperatures.

insulation A material that inhibits heat or electricity conduction so that the insulated object stays at its current temperature for longer.

latent heat The energy taken in or released as a substance changes state from solid to liquid or liquid to gas.

radiation The movement of energy through a material or through space, as carried by electromagnetic waves.

reflection The return of a wave from a surface, such as a light wave from a mirror.

specific heat The amount of energy needed to raise the temperature of 1 gram of material by 1°C (1.8°F).

Points to Consider

- How does the difference in solar radiation that reaches the lower and upper latitudes explain the way the atmosphere circulates?
- How does the atmosphere protect life on Earth from harmful radiation and from extreme temperatures?
- What would the consequences be if the Earth's overall heat budget were not balanced?

15.4 Air Movement

Lesson Objectives

- List the parts of an atmospheric convection cell and the properties of the air currents within it.
- Describe how high and low pressure cells create local winds and explain how several types of local winds form.
- Discuss how global convection cells lead to the global wind belts.

Preview Questions

1. How do high and low pressure zones determine where winds blow?
2. How are land and sea breezes related to monsoon winds?
3. What determines the directions in which the global wind belts blow?

Introduction

Knowing a few basic principles can give a person a good understanding of how and why air moves. Warm air rises, creating a low pressure region, and cool air sinks, creating a high pressure zone. Air flowing from areas of high pressure to low pressure creates winds. Air moving at the bases of the three major convection cells in each hemisphere north and south of the equator creates the global wind belts.

Air Pressure and Winds

Think back to what you learned about convection cells in the previous lesson. Warm air rises, creating an upward-flowing limb of a convection cell (**Figure** 15.19). Upward flowing air lowers the air pressure of the area, forming a **low pressure zone.** The rising air sucks in air from the surrounding area, creating wind.

Figure 15.19: Papers being held up by rising air currents above a furnace demonstrate the important principle that warm air rises. (16)

At the top of the troposphere, the air travels horizontally from a high pressure zone to a low pressure zone. Since it is at the top of the troposphere, the air cools as it moves. This cold, dense air creates the downward flowing limb of the convection cell. Where the sinking air strikes the ground, air pressure is relatively high. This creates a **high pressure zone**. The sinking air is relatively cool, since it has traveled across the tropopause.

Air that moves horizontally between high and low pressure cells makes wind. The winds will race from the high to low zones if the pressure difference between them is large. If the difference is smaller, the winds will be slower.

Convection in the atmosphere creates the planet's weather. It's important to know that warm air can hold more moisture than cold air. When warm air near the ground rises in a low pressure zone, it cools. If the air is humid, it may not be able to hold all the water it contains as vapor. Some water vapor may condense to form clouds or even precipitation. Where cooler air descends at a high pressure zone, it warms. Since it can then hold more moisture, the descending air will evaporate water on the ground.

Air moving between large high and low pressure systems creates the global wind belts that profoundly affect regional climate. Smaller pressure systems create localized winds that affect the weather and climate of a local area.

Local Winds

Local winds are created when air moves from small high pressure systems to small low pressure systems. High and low pressure cells are created by a variety of conditions. Some of these winds have very important effects on the weather and climate of some regions.

Land and Sea Breezes

You learned that water has a very high specific heat: it maintains its temperature well. This means that water heats and cools more slowly than land. Sometimes there is a large temperature difference between the surface of the sea (or a large lake) and the land next to it. This temperature difference causes small high and low pressure regions to form, which creates local winds.

In the summer, and to a lesser degree in the day, a low pressure cell forms over the warm land and a high pressure cell forms over the cooler ocean. During warm summer afternoons, winds called **sea breezes** blow from the cooler ocean over the warmer land (**Figure** 15.20). Sea breezes often have a speed of about 10 to 20 km (6 to 12 miles) per hour and can lower air temperature much as 5 to 10°C (9 to 18°F). The effect of land and sea breezes is felt only about 50 to 100 km (30 to 60 miles) inland.

The opposite occurs in the winter, the land is colder than the nearby water due to its lower specific heat. The cold land cools the air above it. This causes the air to become dense and sink, which creates a high pressure cell. Meanwhile, the warmer ocean warms the air above it and creates a low pressure cell. This occurs to a smaller degree at night, since land cools off faster than the ocean. Winds called **land breezes** blow from the high to the low pressure cell. These local winds blow from the cooler land to the warmer ocean. Some warmer air from the ocean rises and then sinks on land, causing the temperature over the land to become warmer.

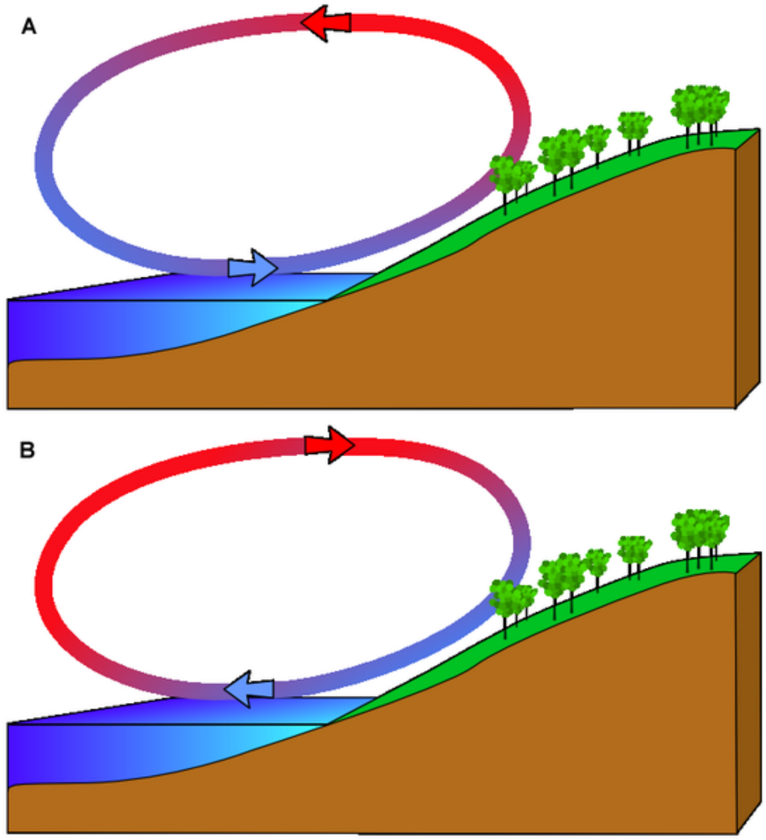

Figure 15.20: Sea and land breezes. (A) Sea breezes blow from the cooler sea to the warmer land. This cools the land near shore in summer and in the daytime and moderates coastal temperatures. (B) Land breezes blow from the cooler land to the warmer sea. This warms the land near shore in winter and at night and moderates coastal temperatures. (21)

Land and sea breezes are very important because they moderate coastal climates. In the hot summer, sea breezes cool the coastal area. In the cold winter, land breezes blow cold air seaward. These breezes moderate coastal temperatures. Land and sea breezes create the pleasant climate for which Southern California is known.

Monsoon Winds

Monsoon winds are larger scale versions of land and sea breezes; they blow from the sea onto the land in summer and from the land onto the sea in winter. Monsoon winds are incredibly strong because they occur in coastal areas with extremely high summer temperatures. Monsoons are common wherever very hot summer lands are next to the sea. The southwestern United States has summer monsoon rains when relatively cool moist air sucked in from the Gulf of Mexico and the Gulf of California meets air that has been heated by scorching desert temperatures (**Figure** 15.21).

Figure 15.21: The Arizona summer monsoon. (5)

The most important monsoon in the world occurs each year over the Indian subcontinent. More than two billion residents of India and southeastern Asia depend on monsoon rains for their drinking and irrigation water. In the summer, air over the Indian subcontinent becomes extremely hot, so it rises. Warm, humid air from the northern Indian Ocean enters the region, and it too is heated and rises. As the rising wet air cools, it drops heavy monsoon rains. In the winter, cool air from over the land moves seaward. Back in the days of sailing ships, seasonal shifts in the monsoon winds carried goods back and forth between India and Africa.

Mountain and Valley Breezes

Temperature differences between mountains and valleys create mountain and valley breezes. During the day, air on mountain slopes is heated more than air at the same elevation over an adjacent valley. As the day progresses, warm air rises off the slopes and draws the cool air up from the valley. This uphill airflow is called a **valley breeze.** When the Sun goes down, the mountain slopes cool more quickly than the air in the nearby valley. This cool air sinks, which causes a **mountain breeze** to flow downhill.

Katabatic Winds

Katabatic winds also move up and down slopes, but they are stronger mountain and valley breezes. Katabatic winds form over a high land area, such as on a high plateau. The plateau is usually surrounded on almost all sides by mountains. In winter, the plateau grows cold, making the air above it extremely cold. This dense air sinks down from the plateau through gaps in the mountains. Wind speeds depend on the difference in air pressure over the plateau and over the surroundings. If a storm, which has low pressure, forms outside the plateau, there is a big difference in wind pressure and the winds will race rapidly downslope. Katabatic winds form over many continental areas. Extremely cold katabatic winds blow over Antarctica and Greenland.

Foehn Wind (Chinook Winds)

Foehn winds or **Chinook winds** develop when air is forced up over a mountain range. This takes place, for example, when the westerly winds bring air from the Pacific Ocean over the Sierra Nevada Mountains in California. As the relatively warm, moist air rises over the windward side of the mountains, it cools and contracts. If the air is humid, it may form clouds and drop rain or snow. When the air sinks on the leeward side of the mountains, it forms a high pressure zone. The windward side of a mountain range is the side that receives the wind; the leeward side is the side where air sinks.

The descending air warms and creates very strong, dry winds. Foehn winds can raise temperatures more than 20°C (36°F) in an hour and cause humidity to decrease. If there is snow on the leeward side of the mountain, it may disappear by quickly melting and evaporating in the dry winds. If precipitation falls as the air rises over the mountains, the air will be very dry as it sinks on the leeward size of the mountains. This dry, sinking air causes a **rain-shadow effect** (**Figure** 15.22). Many deserts are found on the leeward side of mountains due to rainshadow effect.

The name of these winds is a bit confusing. Some people refer to all of these winds as Foehn winds, others as Chinook winds, and still others as orogenic winds. The names Foehn and Chinook are sometimes used for any of these types of winds, but are also used regionally. Foehn winds are found in the European Alps, and Chinook winds are found in the Rocky Mountains of North America. Although the description is apt, Chinook does not mean "snow eater".

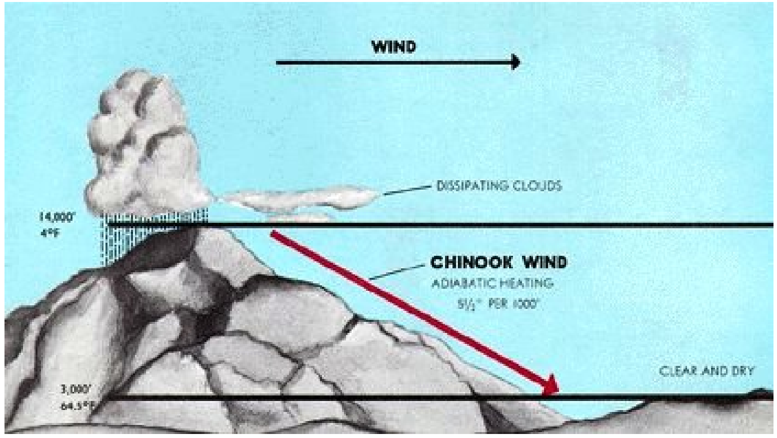

Figure 15.22: Air cools and loses moisture as it rises over a mountain. It descends on the leeward side and warms by compression. The resulting warm and dry winds are Foehn winds or Chinook winds. If the air loses precipitation over the mountain, the leeward side of the mountain will be dry, experiencing rainshadow effect. (13)

Santa Ana Winds

"Deadly" is a term often used to describe the **Santa Ana winds** in Southern California (**Figure** 15.23). These winds are created in the late fall and winter when the Great Basin east of the Sierra Nevada cools. The high pressure is created when the Great Basin cools forces winds downhill and in a clockwise direction. The air sinks rapidly, so that its pressure rises. At the same time, the air's temperature rises and its humidity falls. The winds blow across the Southwestern deserts and then race downhill and westward toward the ocean. Air is forced through canyons cutting the San Gabriel and San Bernadino mountains. The winds are especially fast through Santa Ana Canyon, which gives them their name.

The Santa Ana winds often arrive at the end of California's long summer drought season. The hot dry winds dry out the landscape even more. If a fire starts, it can spread quickly, causing large-scale devastation. In late October 2007, Santa Ana winds fueled many fires that together burned 426,000 acres of wild land and more than 1500 homes (**Figure** 15.24). The 2003 Santa Ana winds contributed to the loss of 721,791 acres to wild fires.

Desert Winds

The image of a lonely traveler battling a dust storm in the desert is one most people have seen, at least in cartoon form. Desert winds pick up dust because there is not as much vegetation to hold down the dirt and sand. Hot winds blow across many deserts and most are given local names. Across the Sahara there are winds known as leveche, sirocco and sharav.

Figure 15.23: Santa Ana winds blow dust and smoke westward over the Pacific from Southern California. (3)

Figure 15.24: The Harris Fire burning downward on Mount Miguel, San Diego County on October 23, 2007. The fire is being pushed along by Santa Ana winds. (1)

High summer temperatures on the desert create high winds, which are often associated with monsoon storms. A **haboob** forms in the downdrafts on the front of a thunderstorm (**Figure** 15.25). Air spins and lifts dust and sand into a cloud of dirt that may include dust devils or tornadoes. Haboobs cause many sandstorms.

Figure 15.25: A haboob in the Phoenix metropolitan area, Arizona. (24)

Dust devils, also called whirlwinds, may also form on hot, clear desert days. The ground becomes so hot that the air above it heats and rises. Air flows into the low pressure and begins to spin. Dust devils are small and short-lived but they may cause damage.

Atmospheric Circulation

You have already learned that more solar energy hits the equator than the polar areas. The excess heat forms a low pressure cell at the equator. Warm air rises to the top of the troposphere where half of the warmed air moves toward the North Pole and half toward the South Pole. The air cools as it rises and moves along the top of the troposphere. When the cooled air reaches a high pressure zone, it sinks. Back on the ground, the air then travels toward the low pressure at the equator. The air rising at the low pressure zone at the equator and sinking at a high pressure in the direction of the North or South Pole creates a convection cell.

If the Earth was just a ball in space and did not rotate, there would be only one low pressure zone and it would be at the equator. There would also be one high pressure at each pole. This would create one convection cell in the northern hemisphere and one in the southern. But because the planet does rotate, the situation is more complicated. The planet's rotation means that the Coriolis Effect must be taken into account.

The **Coriolis Effect** causes freely moving objects to appear to move right in the Northern

Hemisphere and to the left in the Southern Hemisphere. The objects themselves are actually moving straight, but the Earth is rotating beneath them, so they seem to bend or curve. An example might make the Coriolis Effect easier to visualize. If an airplane flies 500 miles due north, it will not arrive at the city that was due north of it when it began its journey. Over the time it takes for the airplane to fly 500 miles, that city moved, along with the Earth it sits on. The airplane will therefore arrive at a city to the west of the original city (in the Northern Hemisphere), unless the pilot has compensated for the change.

A common misconception of the Coriolis Effect is that water going down a drain rotates one way in the Northern Hemisphere and the other way in the Southern Hemisphere. This is not true because in a small container like a toilet bowl, other factors are more important. These factors include the shape of the bowl and the direction the water was moving when it first entered the bowl.

But on the scale of the atmosphere and oceans, the Coriolis Effect is very important. Let's look at atmospheric circulation in the Northern Hemisphere as a result of the Coriolis Effect (**Figure** 15.26). Air rises at the equator as described above. But as the air moves toward the pole at the top of the troposphere, it deflects to the right. (Remember that it just appears to deflect to the right because the ground beneath it moves.) At about 30ºN latitude, the air from the equator meets relatively cool air flowing toward the equator from the higher latitudes. This air is cool because it has come from higher latitudes. Both batches of air descend, creating a high pressure cell. Once on the ground, the air returns to the equator. This convection cell is called the Hadley Cell and is found between 0º and 30ºN.

There are two more convection cells in the Northern Hemisphere. The Ferrell cell is between 30ºN and 50º to 60ºN. This cell shares its southern, descending side with the Hadley cell to its south. Its northern rising limb is shared with the Polar cell located between 50ºN to 60ºN and the North Pole, where cold air descends.

There are three mirror image circulation cells in the Southern Hemisphere. In that hemisphere, the Coriolis effect makes objects appear to deflect to the left.

Global Wind Belts

Global winds blow in belts encircling the planet. The global wind belts are enormous and the winds are relatively steady (**Figure** 15.27). We will be able to figure out how the wind in these belts blows using the information you just learned about atmospheric circulation.

In between each convection cell, where air moves vertically, there is little wind. But where air moves horizontally along the ground between the high and low pressure zones, steady winds form. The air movement of each large circulation cell creates the major wind belts. The wind belts are named for the directions from which the winds come. The westerly winds, for example, blow from west to east. Some names remain from the days when sailing ships depended on wind for their power.

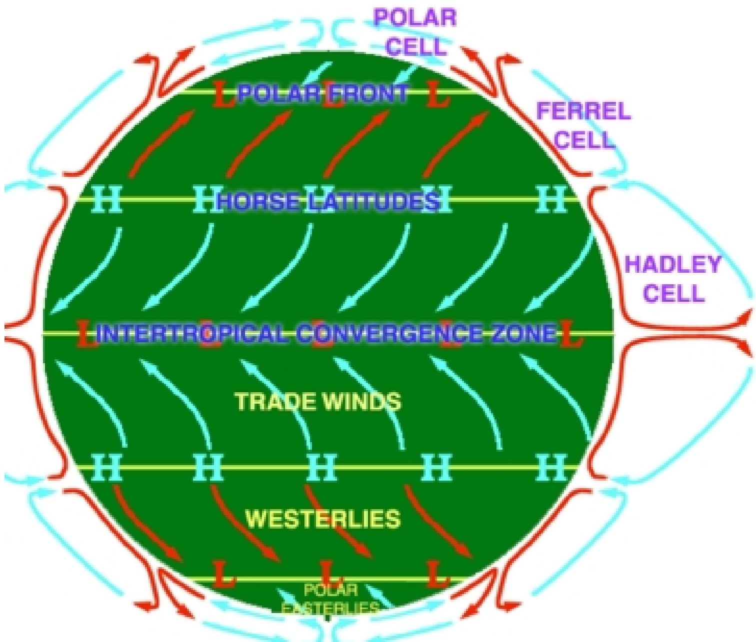

Figure 15.26: The atmospheric circulation cells, showing direction of winds at Earth's surface. (8)

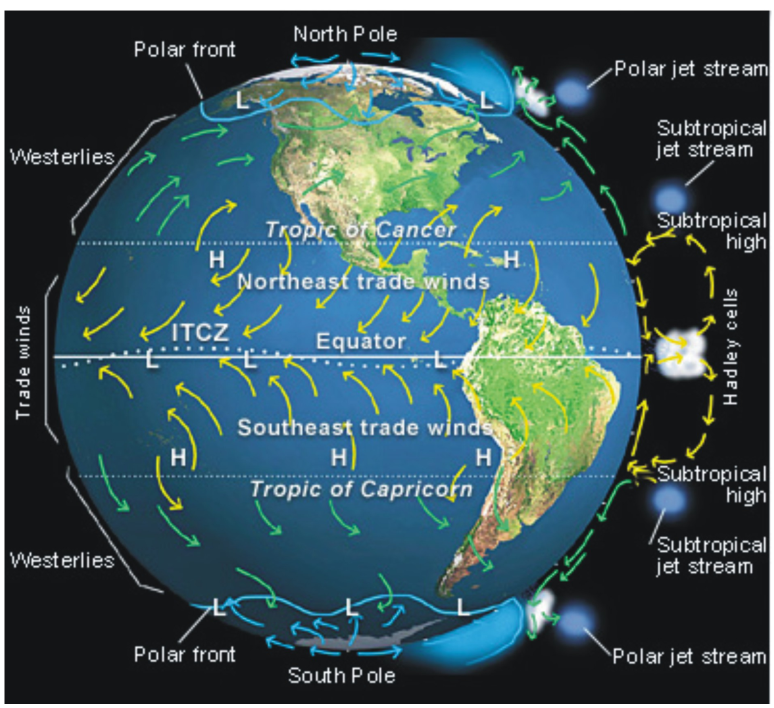

Figure 15.27: The major wind belts and the directions that they blow. (17)

Let's look at the global wind belts at the Earth's surface in the Northern Hemisphere. In the Hadley cell, air moves north to south, but is deflected to the right by the Coriolis Effect. These winds therefore blow from the northeast to the southwest. They are called the *trade winds* because at the time of sailing ships they were good for trade. Winds in the Ferrel cell blow from the southwest and are called the westerly winds or *westerlies.* The westerlies are the reason a flight across the United States from San Francisco to New York City takes less time than the reverse trip. On the outbound flight, the airplane is being pushed along by the westerlies, but on the reverse trip the airplane must fight against the air currents. In the Polar cell, the winds travel from the northeast and are called the *polar easterlies.* These names hold for the winds in the wind belts of the Southern Hemisphere as well.

The usual pattern of atmospheric circulation cells and the global wind belts determine normal global climate, but many other factors come into play locally. The high and low pressure areas created by the six atmospheric circulation cells generally determine the amount of precipitation a region receives. In low pressure regions, where air is rising, rain is common. In high pressure cells, the sinking air causes evaporation and the region is usually dry. More specific climate affects will be described in the chapter about climate.

The junction between the Ferrell and Polar cells is a low pressure zone. At this location, relatively warm, moist air that has circulated from the equator meets relatively cold, dry air that has come from the pole. The result is a place of extremely variable weather, known as the **polar front**. This weather is typical of much of North America and Europe.

The polar jet stream is found high up in the atmosphere where the two cells come together. A **jet stream** is a fast-flowing river of air at the boundary between the troposphere and the stratosphere. A jet stream can flow faster than 185 km/hr (115 mi/hr) and be thousands of kilometers long and a few hundred kilometers in width, but only a few kilometers thick. Jet streams form where there is a large temperature difference between two air masses. This explains why the polar jet stream is the world's most powerful.

Jet streams move seasonally as the angle of the Sun in the sky moves north and south. The polar jet stream moves south in the winter and north in the summer between about 30°N and 50° to 75°N. The location of the jet stream determines the weather a location on the ground will experience. Cities to the south of the polar jet stream will be under warmer, moister air than cities to its north. Directly beneath the jet stream, the weather is often stormy and there may be thunderstorms and tornadoes.

Lesson Summary

- Winds blow from high pressure zones to low pressure zones. The pressure zones are created when air near the ground becomes warmer or colder than the air nearby.
- Local winds may be found in a mountain valley or near a coast.
- Global wind patterns are long term, steady winds that prevail around a large portion of the planet.

- The location of the global wind belts has a great deal of influence on the weather and climate of an area.

Review Questions

1. Draw a picture of a convection cell in the atmosphere. Label the low and high pressure zones and where the wind is.
2. Under what circumstances will winds be very strong?
3. Given what you know about global-scale convection cells, where would you travel if you were interested in experiencing warm, plentiful rain?
4. Describe the atmospheric circulation for two places where you are likely to find deserts, and explain why these regions are relatively warm and dry.
5. How could the Indian and southeast Asian monsoons be reduced in magnitude? What effect would a reduction in these important monsoons have on that part of the world?
6. Why is the name "snow eater" an apt description of Chinook winds?
7. Why does the Coriolis Effect cause air (or water) to appear to move clockwise in the Northern Hemisphere? When would the Coriolis Effect cause air to appear to move counterclockwise?
8. Sailors once referred to a portion of the ocean as the doldrums. This is a region where there is frequently no wind, so ships would become becalmed for days or even weeks. Given what you know about atmospheric circulation, where do you think the doldrums might be in terms of latitude?
9. Imagine that the jet stream is located further south than usual for the summer. What will the weather be like in regions just north of the jet stream, as compared to a normal summer?
10. Give a general description of how winds form.

Further Reading / Supplemental Links

- High and Low Pressure Systems animations, Bureau of Meteorology, Australian Government http://www.bom.gov.au/lam/Students_Teachers/pressure.shtml

Vocabulary

Coriolis Effect The tendency of a freely moving object to appear to move right right in the Northern Hemisphere and left in the Southern Hemisphere.

Foehn winds (Chinook winds) Winds that form when low pressure draws air over a mountain range.

haboob Desert sandstorms that form in the downdrafts of a thunderstorm.

high pressure zone A region where relatively cool, dense air is sinking.

jet stream A fast-flowing river of air high in the atmosphere, where air masses with two very different sets of temperature and humidity characteristics move past each other.

katabatic winds Winds that move down a slope.

land breeze A wind that blows from land to sea in winter when the ocean is warmer than the land.

low pressure zone A region where relatively warm, less dense air is rising.

mountain breeze A wind that blows from up on a mountain down to the valley below in the late afternoon or at night when mountain air is cooler.

polar front The meeting zone between cold continental air and warmer subtropical air at around 50°N and 50°S.

Santa Ana winds Hot winds that blow east to west into Southern California in fall and winter.

sea breeze A wind that blows from sea to land in summer when the land is warmer than the ocean.

valley breeze An uphill airflow.

Points to Consider

- How do local winds affect the weather in an area?
- How do the global wind belts affect the climate in an area?
- What are the main principles that control how the atmosphere circulates?

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(19) http://en.wikipedia.org/wiki/Image:Infrared_dog.jpg. GNU-FDL.

(20) USGS. *The Water Cycle.*. GNU-FDL.

(21) http://en.wikipedia.org/wiki/Image:Diagrama_de_formacion_de_la_brisa-breeze.png. GNU-FDL.

(22) http://en.wikipedia.org/wiki/Image:SmokeCeilingInLochcarron.jpg. GNU-FDL.

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(24) http://en.wikipedia.org/wiki/Image:Haboob2.jpg. GNU-FDL.

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Chapter 16

Weather

16.1 Weather and Atmospheric Water

Lesson Objectives

- Discuss the difference between weather and climate.
- Describe the relationship between air temperature and humidity, including the concept of dew point.
- List the basics of the different cloud types and what they indicate about current and future weather.
- Explain how the different types of precipitation form.

Introduction

If someone across country asks you what the weather is like today, you need to consider several factors. Air temperature, humidity, wind speed, the amount and types of clouds and precipitation are all part of a thorough weather report. In this chapter, you will learn about these many of these features in more detail.

What is Weather?

Weather is what is going on in the atmosphere at a particular place at a particular time. Weather may be cold or hot, or wet or dry, and it changes rapidly. A warm sunny day may rapidly turn into a cold and stormy one, making you wish you had brought your jacket. There are many factors that influence the weather; a few examples include the air temperature over a region, whether there is a second air mass nearby, and how close high and low pressure cells are. A location's weather depends on air temperature, air pressure, humidity, cloud cover, precipitation, and wind speed and direction, which are all directly related to the amount of energy that is in the system and where that energy is. The ultimate source of this energy is the sun.

Climate is the average of a region's weather over time. The climate for a particular place is steady, and changes only very slowly. Portland, Oregon has a mild, moist climate and Fairbanks, Alaska has a frigid, dry one. Portland or Fairbanks may experience a warm sunny day in February, but that doesn't change their climate. Climate is determined by many factors, which are related to the amount of energy that is found in that location over time. Factors that determine the amount of energy include the angle of the sun, the likelihood of cloud cover, the air pressure, and many others.

Humidity

Humidity is the amount of water vapor in the air in a particular spot. We usually use the term to mean relative humidity, the percentage of water vapor a certain volume of air is holding relative to the maximum amount it can contain. If the humidity today is 80%, that does not mean that 80% of the molecules in the air are water vapor. It means that the air contains 80% of the total amount of water it can hold at that temperature. If the humidity increases to more than 100%, the excess water will condense from the air and form precipitation.

Humidity affects weather a great deal and is important for weather forecasting. When humidity is high, precipitation is more likely. The combination of high humidity and high temperatures can threaten people's health. People are more uncomfortable when both temperature and humidity are high. As people and some other animals sweat to cool themselves off; they lose heat as the sweat evaporates. But if the air is already saturated with water vapor, the sweat will not evaporate and the person will not cool. They will simply be hot and sweaty, and uncomfortable.

The National Weather Service has developed a **heat index** (HI). On an HI chart (**Table** 16.1), people can see what the temperature feels like, when the air temperature and humidity are known. For example, if the temperature is 85°F, but humidity is only 40%, the temperature feels like a pleasant 84°F. But if the temperature is 85°F, but the humidity is 90%, the air temperature feels like a very hot and sticky 101°F. This information is useful for people who are interested in outdoor activities. High humidity cause health problems, such as sunstroke or heatstroke, to occur more quickly.

Table 16.1: **Heat Index: Temperature (F) vs. Humidity (%)**

	90%	80%	70%	60%	50%	40%
80°F	85	84	82	81	80	79
85°F	101	96	92	90	86	84
90°F	121	113	105	99	94	90

Table 16.1: (continued)

	90%	80%	70%	60%	50%	40%
95°F		133	122	113	105	98
100°F			142	129	118	109
105°F				148	133	121
110°F						135

Since warm air can hold more water vapor than cool air, raising or lowering temperature can change air's relative humidity (**Figure** 16.1). The temperature at which air becomes saturated with water is called the air's **dew point.** This term makes sense, because water will condense from the air as dew, if the air cools down overnight and reaches 100% humidity.

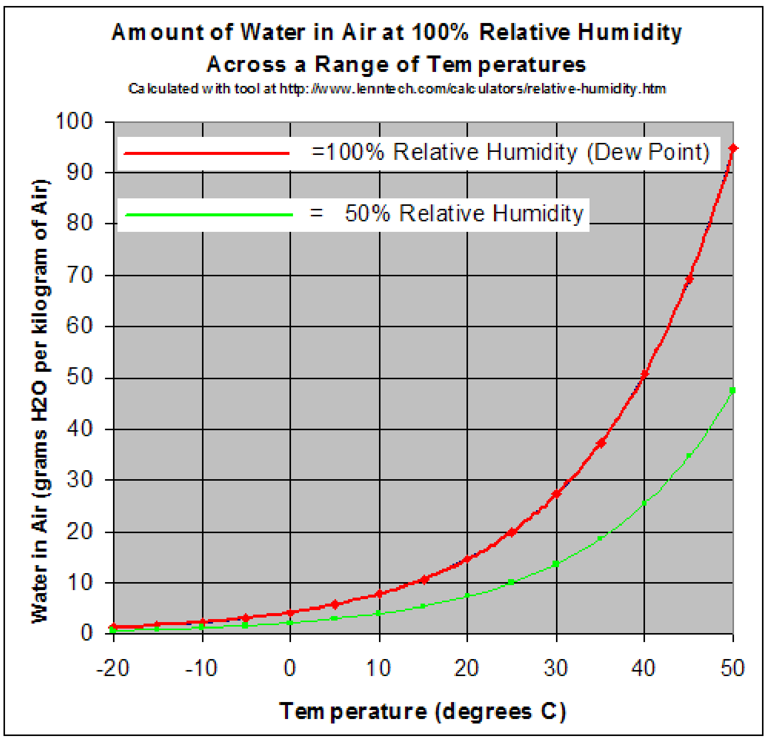

Figure 16.1: This diagram shows the amount of water air can hold at different temperatures. The temperatures are given in degrees Celsius. (25)

Clouds

Sometimes there are lots of clouds in the sky and sometimes you can't see a cloud anywhere. Either way, **clouds** have a big influence on weather. Clouds affect weather in three ways: (1)

preventing solar radiation from reaching the ground, (2) absorbing warmth that is re-emitted from the ground, and (3) as the source of precipitation. When there are no clouds, there is less insulation. As a result, cloudless days can be extremely hot, and cloudless nights can be very cold. For this reason, cloudy days tend to have a lower range of temperatures than clear days.

Clouds form when air reaches its **dew point**, the temperature when the air is saturated with water vapor. This can happen in two ways. First, the air temperature can stay the same while the humidity increases. This is common in locations that are warm and humid. Second, the humidity can remain the same, but the temperature decreases. When this happens, the air will eventually cool enough so that it reaches 100% humidity, and water droplets form. Air cools when it comes into contact with a cold surface or when it rises. There are three ways that rising air can create clouds: (1) It can be warmed at or near the ground level, (2) It can be pushed up over a mountain or mountain range, or (3) It can be thrust over a mass of cold, dense air.

Water vapor in the atmosphere is not visible, unless it condenses to become a cloud. Water vapor condenses around a nucleus, such as dust, smoke, or a salt crystal. This forms a tiny liquid droplet. Billions of these water droplets together make a cloud. If the atmosphere is very cold, the droplets freeze into ice. Most clouds appear white because sunlight reflects off the water droplets. If the clouds are thick, the droplets scatter or absorb the light and less solar radiation can travel through them. This is why storm clouds are dark black or gray.

Clouds have been classified in several ways. The most common classification used today divides clouds into four separate cloud groups, which are determined by their altitude (**Figure** 16.2). High clouds, which have the prefix 'cirro-,' are found above 6,000 m (20,000 feet) in altitude. Middle clouds, which have the prefix 'alto-,' are between 2,000 to 7,000 m (6,500 to 23,000 feet). Low clouds, which have the word 'stratus' in their names, occur beneath 2,000 m (6,500 feet). Each of the clouds that occur in these groups is layered, and they grow horizontally.

Another group of clouds, which have the prefix 'cumulo-,' describes clouds that grow vertically instead of horizontally. These impressive clouds have their bases at low altitude and their tops at high or middle altitude.

Table 16.2:

High clouds:	Cirrus (Ci)	Cirrostratus (Cs)	Cirrocumulus (Cc)
Middle clouds:	Altostratus (As)	Altocumulus (Ac)	
Low clouds:	Stratus (St)	Stratocumulus (Sc)	Nimbostratus (Ns)
Vertical clouds:	Cumulus (Cu)	Cumulonimbus (Cb)	

(*Source:* CK-12 Foundation, *License:* CC-BY-SA)

High clouds form where the air is extremely cold and can hold little water vapor. The

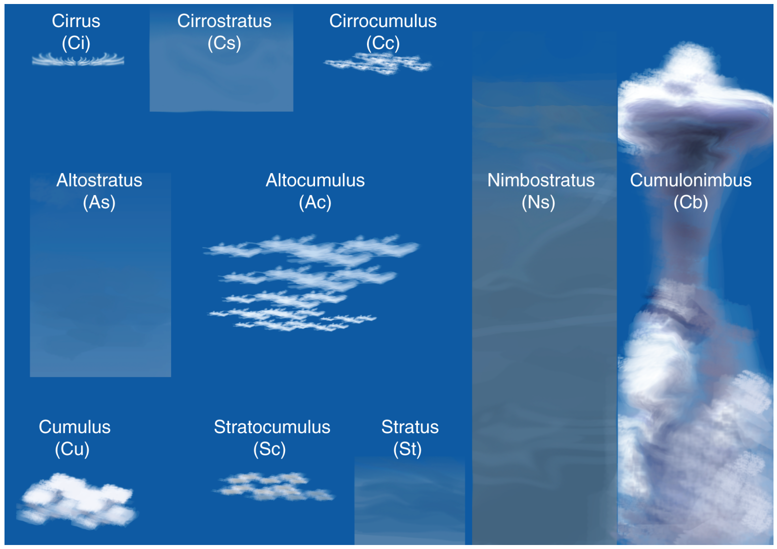

Figure 16.2: The four cloud types and where they are found in the atmosphere. The symbols are shown in **Table** 16.2: (45)

ice crystals that form create thin, wispy **cirrus** clouds (**Figure** 16.3). Cirrus clouds may indicate an oncoming storm.

Figure 16.3: Cirrus clouds are thin wisps of ice crystals found at high altitudes. (36)

Cirrocumulus clouds are small, white puffs that ripple across the sky, often in rows. **Cirrostratus** clouds are thin, white sheets of clouds, made up of ice crystals like cirrus clouds (**Figure** 16.4). Cirrostratus clouds are sometimes so thin that they cannot be seen, unless illuminated by the sun or moon.

Figure 16.4: Cirrostratus clouds are so thin they are sometimes invisible unless backlit by the Sun or Moon. (32)

Middle clouds may be made of water droplets, ice crystals or both, depending on the air temperatures. **Altocumulus** clouds appear as white to gray, puffy stripes rolling across the sky (**Figure** 16.5). These clouds often occur before thunderstorms. Thick and broad **altostratus** clouds are gray or blue-gray. They often cover the entire sky and usually mean a large storm, bearing a lot of precipitation is coming.

Low clouds usually hold droplets of liquid water, although they may also contain ice when temperatures are very cold. **Stratus** clouds are gray sheets that cover the entire sky (**Figure** 16.6). These clouds may produce a steady drizzle or mist, but do not carry hard rain. **Nimbostratus** clouds are thick and dark. They bring steady rain or snow. **Stratocumulus** clouds are rows of large, low puffs that may be white or gray. These clouds rarely bring precipitation. but

Clouds grow vertically when strong air currents are rising upward. **Cumulus** clouds resemble white or light gray cotton and have towering tops (**Figure** 16.7). On fair days, cumulus clouds may grow upward but produce no precipitation. On hot summer afternoons, though, cumulus clouds may mushroom into a form that looks like a head of cauliflower. These clouds may produce light showers.

If the vertical air currents are strong, a cumulus cloud will grow upward until it develops into a **cumulonimbus** cloud (**Figure** 16.8). Tall, dark and ominous cumulonimbus clouds are associated with lightning and intense thunderstorms.

Figure 16.5: Altocumulus clouds are white puffs found in the middle altitudes. (20)

Figure 16.6: Stratus clouds with the Alps in the distance. (7)

Figure 16.7: Anvil-shaped cumulus clouds floating over Australia. (42)

Figure 16.8: Cumulonimbus cloud lit up by lightning. (12)

Fog

Fogs are clouds located at or near the ground. When humid air near the ground cools below its dew point, fog is formed. Fogs develop differently from the way clouds form. There are several types of fog, each of which forms in a different way.

Radiation fogs form at night when skies are clear and the relative humidity is high. As the ground cools, the bottom layer of air cools also. Eventually the air temperature may be lowered below its dew point. If there is a light breeze, the fog will be carried upward. Radiation fog can grow to 30 meters (100 feet) thick. One to three hours after sunrise, radiation fog burns off as the ground warms. The Central Valley of California frequently experiences radiation fog, which is called tule fog in this area. Tule fog can be so thick that drivers cannot see the car in front of them and their headlights just reflect back off the sheet of water droplets.

San Francisco, California is famous for its summertime **advection fog** (**Figure** 16.9). Warm, moist air from over the Pacific Ocean blows over the cold California current just offshore. This cools the eastward moving air below its dew point and thereby creates fog. Advection fog is brought onshore by sea breezes. If the fog is accompanied by light wind, a thicker layer of air cools and the fog can grow to be up to 600 m (2,000 feet) thick.

Figure 16.9: Advection fog fills the gap where the Golden Gate Bridge spans the San Francisco Bay inlet. (16)

Steam fog appears in autumn or early winter and can make a pond or lake appear to be steaming. The "steam" forms when cool air moves over a lake that still holds some of its summer heat. Water evaporates from the lake surface and condenses as it cools in the overlying air. Steam fog is rarely very thick.

When warm humid air travels up a hillside and cools below its dew point it creates an **upslope fog** (**Figure** 16.10).

Figure 16.10: Upslope fog around the peaks of Mt. Lushan in China. (37)

Precipitation

As you know from your daily life, precipitation is an extremely important part of weather. Precipitation most commonly falls as rain or snow, but can also be sleet, hail, dew or frost. Sleet is a mixture of rain and snow, and often forms when snow partially melts as it falls. Dew forms when moist air comes into contact with a cold surface, like the ground or a car windshield, and cools below its dew point. Frost forms under similar conditions, but when the air cools to below freezing (**Figure** 16.11).

Figure 16.11: Hoar frost. (43)

The other types of precipitation come from clouds. Rain or snow droplets fall when they become heavy enough to escape from the rising air currents that hold them up in the cloud. The most common way for rain or snow to droplets to grow, occurs in cold clouds, where the temperature is -10°C(14°F) or less (**Figure** 16.12). Here the water vapor freezes directly into ice crystals, which continue to grow as more water vapor freezes onto them. When the ice crystals become heavy enough, they fall. Even as they fall, the ice crystals collect more moisture. If temperatures are cold, the ice will hit the ground as a snowflake. If temperatures near the ground are greater than 4° C(39°F), the ice crystal may melt and become a raindrop. One million cloud droplets will combine to make only one rain drop!

Water may also precipitate from warm clouds. Here too, water droplets get trapped in rising and falling air currents. As the droplet travels around the convection cell, it collides with other small droplets. At some point, the droplet is large enough to escape the convecting air currents and it falls to the ground as rain. If the air currents are very strong, the droplets must be very large before they fall.

If a raindrop falls through warm air but hits a layer of freezing air near the ground, it becomes frozen into a small clear ice pellet known as **sleet**. Sleet usually is mixed with liquid water drops that did not freeze as they descended from the cloud. If the layer of frigid air near the

Figure 16.12: Snow storm in Cleveland, Ohio. (46)

ground is not thick enough for the raindrop to freeze before it reaches the ground, the drop may freeze on the ground, forming **glaze**. The weight of glaze covering a tree branch can make the branch fall.

Hail forms in cumulonimbus clouds with strong updrafts. An ice particle falling through a cloud is captured by an updraft and continues to grow as it travels around the convection cell. When it finally becomes too heavy, it drops to the ground. Although hail is usually less than 1 cm (about one-half inch), it's not uncommon to find hail that is 5 to 10 cm (2 to 4 inch) in diameter (**Figure** 16.13). The largest hailstone ever measured, 14 cm (5.5 inches) in diameter and weighing 766 grams (27 ounces), was collected in Coffeyville, Kansas in 1970.

Lesson Summary

- Air temperature causes differences in pressure so that convection cells form.
- Air rising in a convection cell may cool enough to reach its dew point and form clouds or precipitation if the humidity is high enough.
- Clouds or fog may form if warmer air meets a colder ground surface. Air temperature and humidity also determine what sorts of clouds and precipitation form.
- These factors play a role in creating a pleasant or uncomfortable day, such as when it might be warm and dry or hot and humid.

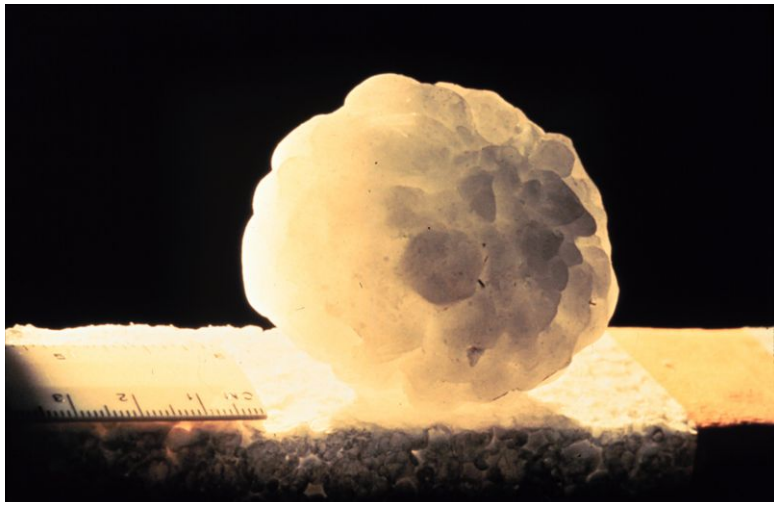

Figure 16.13: A large hail stone, about 6 cm (2.5 inches) in diameter. (15)

Review Questions

1. What factors need to be included in a thorough weather report?
2. If Phoenix, Arizona experiences a cool, wet day in June (when the weather is usually hot and dry), does that mean the region's climate is changing?
3. Look back at the table that shows heat index. Which day would most people find more pleasant: An 85°F day with 90% humidity or a 90°F day with 40% humidity?
4. What happens when a batch of air reaches its dew point? At what temperature does this occur?
5. What effect do clouds have on weather?
6. You are standing in a location which is clear in the morning, but in the afternoon there are thunderstorms. There is no wind during the day, so the thunderstorms build directly above you. Describe how this happens.
7. In what three ways can air rise to create clouds?
8. What are the four different cloud groups and how are they classified?
9. How does sleet form? How does glaze form?
10. What circumstances must be present for enormous balls of hail to grow and then fall to the ground?

Vocabulary

altocumulus Gray puffy stripes of globular clouds arranged in lines across the sky.

altostratus Thicker clouds than cirrostratus; like a gray veil, may completely hide Sun or Moon.

cirrocumulus High clouds that are small, white and puffy, arranged in groups or lines.

cirrostratus Thin, whitish, veil-like clouds that produce a halo around the Sun or Moon, but do not blur their outline.

cirrus High, wispy clouds made of ice crystals.

cloud Tiny water or ice particles that are grouped together in the atmosphere.

cumulonimbus Tall, dark clouds that produce thunderstorms.

dew point The temperature at which air is saturated with water vapor, or where the air has reached 100% humidity.

glaze A layer of smooth, transparent ice that forms when freezing rain or drizzle hit a cold surface.

hail Pellets of ice or ice and snow that form only in cumulonimbus clouds.

heat index A measurement that combine the effects of temperature and humidity; the heat index more accurately describes what weather will actually feel like.

humidity The amount of water vapor in the air, sometimes used synonymously with relative humidity.

nimbostratus Thick, dark, continuous, low clouds that brings continuous rain or snow.

radiation fog Fog caused by the radiation of heat on a cold, windless night.

relative humidity The amount of water vapor in the air relative to the maximum amount of water vapor that the air could contain at that temperature.

sleet Partly frozen rain or partly melted snow and ice.

stratocumulus Soft, globular, low clouds in groups or lines that rarely bring precipitation.

stratus Low clouds that are continuous and may produce drizzle but no hard rain.

upslope fog Fog that forms from winds that blow up a slope and cool.

Points to Consider

- When thinking about the weather, what factors do you consider important in the air that surrounds you?
- How do air temperature, humidity, and pressure differences create different sorts of weather?
- Think about the types of weather described in this lesson. Imagine types of weather that you have not experienced, look at photos, and ask friends and relatives who've lived in other places what their weather is like.

16.2 Changing Weather

Lesson Objectives

- Describe the characteristics air masses have and how they get those characteristics.
- Discuss what happens when air masses meet.
- List the differences between stationary, cold, warm, and occluded fronts.

Introduction

The weather in a location often depends on what type of air mass is over it. Another key factor revolves around whether or not the spot is beneath a **front,** the meeting place of two air masses. The characteristics of the air masses and their interactions can determine whether the weather is constant over an area, or whether there are rapid changes in air temperature, wind, precipitation and even thunderstorms.

Air Masses

An **air mass** is a batch of air that has nearly the same temperature and humidity (**Figure** 16.14). An air mass is created above an area of land or water known as its source region. Air masses come to have a distinct temperature and humidity when they remain over a region for several days or longer. The heat and moisture leave the ground and move into the air above it, until the overlying air takes on the temperature and humidity characteristics of that particular region.

Air masses are created primarily in high pressure zones. They most commonly form in polar and tropical regions, which have very distinctive temperature and humidity. The temperate zones are ordinarily too unstable for air masses to form. Instead, air masses move across them, making the middle latitudes the site of very interesting weather.

Air masses can be 1,600 km (1,000 miles) or more across and several kilometers thick.

Temperature and humidity may change a bit horizontally across the air mass, but not too much. An air mass may have more changes with altitude.

Meteorologists use symbols to describe the characteristics of an air mass. The first symbol tells whether the air mass had its origin over a continent (c) or over an ocean (m, for maritime). As you might expect, air masses that form over oceans contain more water vapor than those that form over land. The second symbol tells the general latitude where the air mass gained its temperature and humidity traits. The categories are arctic (A), polar (P,)tropical (T), and equatorial (E). Of course, air masses that form over polar areas are colder than those that form over tropical regions.

Globally, the major air masses are continental arctic or continental antarctic(cA or cAA); continental polar (cP); maritime polar (mP); continental tropical (cT); maritime tropical (mT); and maritime equatorial (mE). Maritime arctic and continental equatorial air masses rarely form.

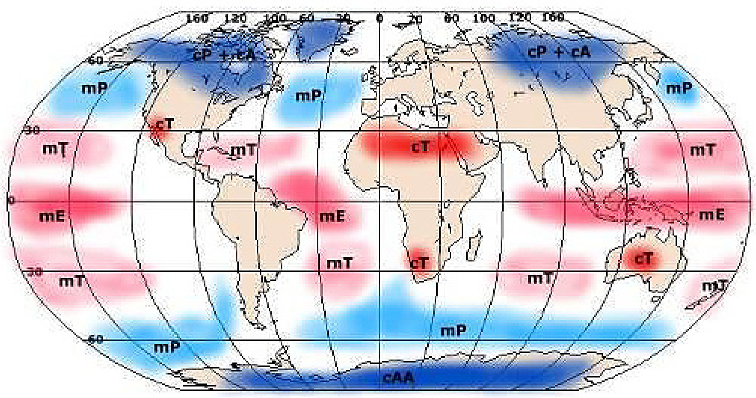

Figure 16.14: The source regions of air masses found around the world. (11)

A third symbol takes into account the properties of an air mass relative to the ground it moves over. If the air mass is colder than the ground, it is given the designation k, for cold. If it is warmer than the ground, it is given the designation w. For example, a cPk is an air mass with a continental polar source region that is colder than the region it is now moving over.

Air Mass Movement

Air masses are pushed along by high-level winds, although they move slower than the winds. An air mass gets its characteristics from the ground or water it is above, and it also shares those characteristics with the regions that it travels over. Therefore, the temperature and humidity of a particular location depends partly on the characteristics of the air mass that sits over it.

If the air mass is very different from the ground beneath it, storms may form. For example, when a colder air mass moves over warmer ground, the bottom layer of air is heated. That air rises, forming clouds, rain, and sometimes thunderstorms. When a warmer air mass travels over colder ground, the bottom layer of air is cooled. This forms a temperature **inversion**, since the cold air near the ground is trapped. Inversions may form stratus clouds, advection fogs, or they may trap a layer of pollution over a city.

In general, cold air masses tend to flow toward the equator and warm air masses tend to flow toward the poles. This brings heat to cold areas and cools down areas that are warm. It is one of the many processes that act towards balancing out the planet's temperatures.

Fronts

Two air masses meet at a front. Because the two air masses have different temperature and humidity, they have different densities. Air masses with different densities do not easily mix. Ordinarily, when fronts meet, one air mass is lifted above the other. Rising air creates a low pressure zone. If the lifted air is moist enough, there will be condensation and precipitation. Fronts usually also have winds in them. If the temperature difference between the two air masses is high, then the winds will be strong. Fronts are the main cause of stormy weather.

The map symbols for the different types of fronts are shown in (**Figure** 16.15): (**1**) cold front, (**2**) warm front, (**3**) stationary front, (**4**) occluded front, (**5**) surface trough, (**6**) squall line, (**7**) dry line, (**8**) tropical wave.

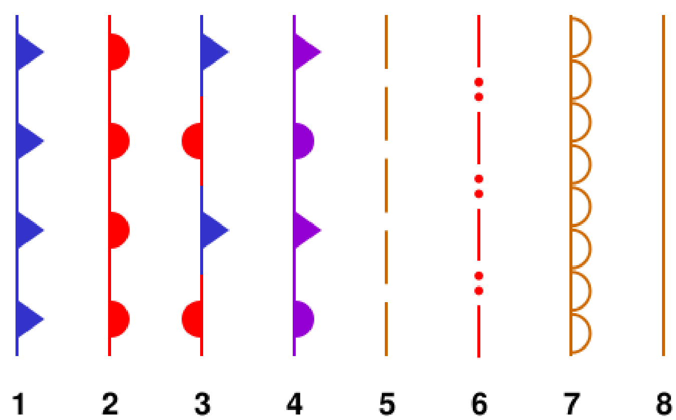

Figure 16.15: The map symbols for different types of fronts. (3)

The direction that fronts move is guided by pressure gradients and the Coriolis Effect. In the Northern Hemisphere, cold fronts and occluded fronts tend to move from northwest to southeast. Warm fronts move southwest to northeast. The direction the different types of fronts move in the Southern Hemisphere is the mirror image of how they move in the Northern Hemisphere. Fronts can be slowed or stopped by a barrier such as a mountain range.

The rest of this section will be devoted to four types of fronts. Three of these fronts move and one is stationary. With cold fronts and warm fronts, the air mass at the leading edge of the front gives the front its name. In other words, a cold front is right at the leading edge of moving cold air and a warm front marks the leading edge of moving warm air.

Stationary Front

Most fronts move across the landscape, but at **stationary fronts** (**3**) the air masses do not move. A front may become stationary if an air mass is stopped by a barrier. For example, cold air masses may be stopped by mountains, because the cold air mass is too dense to rise over them.

A region under a stationary front may experience days of rain, drizzle and fog. This weather may be present over a large area. Winds usually blow parallel to the front, but in opposite directions. This results in shear stress. Shear stresses result when objects are pushed past each other in opposite directions.

After several days, the front will break apart. The **temperature gradient** or temperature difference across the front may decrease, so the air masses start to mix. Shear stresses may force the front to break apart. Conditions may change so that the stationary front is overtaken by a cold front or a warm front. If the temperature gradient between the air masses increases, wind and rainy weather will result.

Cold Fronts

When a cold air mass takes the spot of a warm air mass, there is a **cold front** (**1**) (**Figure** 16.16). Since cold air is denser than the warm air, the cold air mass slides beneath the warm air mass and pushes it up. As the warm air rises, there are often storms.

When cold air moves underneath warm air, the ground temperature drops. The humidity may also decrease since the colder air may also be drier. Winds at a cold front can be strong because of the temperature difference between the two air masses. When a cold front is on its way, there may be a sharp change in dew point, changes in wind direction, changes in air pressure, and certain characteristic cloud and precipitation patterns.

Cold fronts often move rapidly across the landscape. Fast-moving cold fronts create a line of intense storms over a fairly short distance. A **squall line**(**6**) is a line of severe thunderstorms that forms along a cold front (**Figure** 16.17). If the front moves slowly, the storms may form over a larger area.

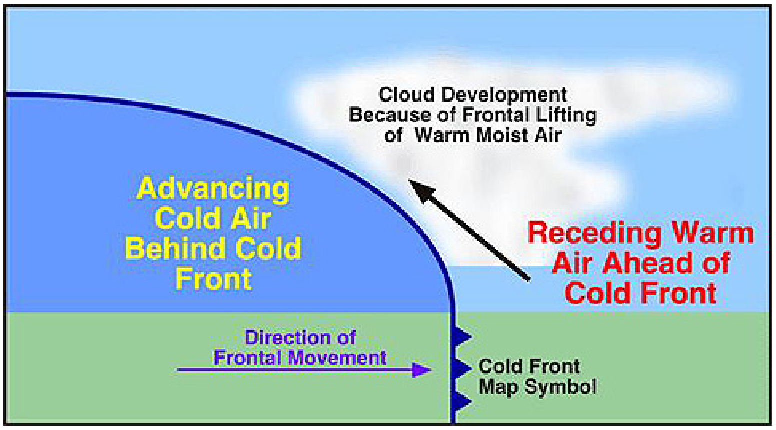

Figure 16.16: A cold front with cold air advancing to displace warm air. The warm air is pushed up over the cold air. (30)

Figure 16.17: A shelf line that commonly precedes a squall. (27)

Imagine that you are standing in one spot as a cold front approaches. Along the cold front, the denser, cold air pushes up the warm air, causing the air pressure to decrease. If the humidity is high enough, some types of cumulus clouds will grow. High in the atmosphere, winds blow ice crystals from the tops of these clouds to create cirrostratus and cirrus clouds. At the front, there will be a line of rain or snow showers or thunderstorms with blustery winds. Behind the front is the cold air mass. This mass is drier and so precipitation stops. The weather may be cold and clear or only partly cloudy. Winds may continue to blow into the low pressure zone at the front.

The weather at a cold front varies with the season. Thunderstorms or tornadoes may form in spring and summer, when the air is unstable. In the spring, the temperature gradient can be very high, causing strong winds to blow at the front. In the summer, thunderstorms may be severe and may also include hailstorms. In the autumn, strong rains fall over a large area. If the front moves slowly, enough rain may fall to cause flooding. Cold fronts in winter may bring frigid temperatures and heavy snows. The cold air mass is likely to have formed in the frigid arctic.

When the temperature gradient across a cold front is low, a cold front has little effect on the weather. This may occur at some locations in the summer. Along the western United States, the Pacific Ocean warms and moistens cold air masses so that the temperature gradient across a cold front is small.

Warm Fronts

A **warm front** (**2**) is found where warm air mass slides over a cold air mass (**Figure** 16.18). Since the warmer, less dense air is moving over the colder, denser air, the atmosphere is relatively stable. Warm fronts travel much more slowly than cold fronts because the leading cold air mass is dense and sluggish.

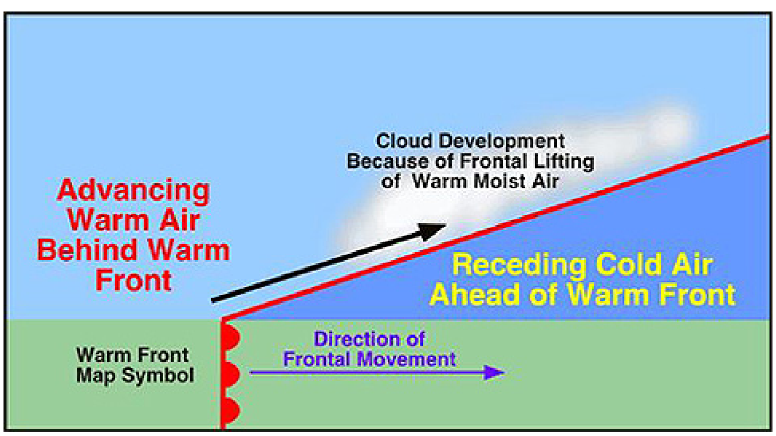

Figure 16.18: A warm front. Warm air moves forward to take over the position of colder air. (9)

Imagine that you are on the ground in the wintertime under a cold winter air mass with a warm front approaching. The transition between the cold air and the warm air takes place over a long distance. This means that the first signs of changing weather appear long before the front is actually over you. In fact, weather changes may appear hundreds of kilometers ahead of the front. Initially, the air is cold: the cold air mass is above you and the warm air mass is above it. High cirrus clouds mark the transition from one air mass to the other.

Over time, cirrus clouds become thicker and cirrostratus clouds form. As the front approaches, altocumulus and altostratus clouds appear and the sky turns gray. Since it is winter, snowflakes fall. Soon the clouds thicken and nimbostratus clouds form. Snowfall increases. Winds grow stronger as the low pressure approaches. As the front gets closer, the cold air mass is just above you but the warm air mass is not too far above that. The weather worsens. As the warm air mass approaches, temperatures rise and snow turns to sleet and freezing rain. Warm and cold air mix at the front, leading to the formation of stratus clouds and fog (**Figure** 16.19).

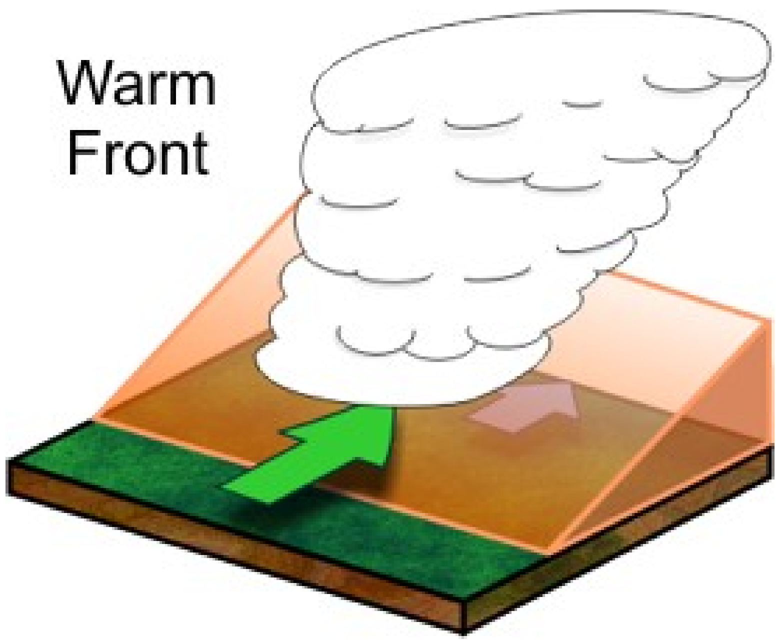

Figure 16.19: Cumulus clouds build at a warm front. (35)

As the front passes over you, the temperature and dew point rise and the rain likely ends. Winds change direction. The transition is not nearly as dramatic as when a cold front passes over, since there is more mixing of the two air masses occurring in a warm front.

The Pacific Ocean also plays a role in modifying the warm fronts that reach the west coast of the United States. These storms are so broad that it is very difficult to spot exactly where the warm front is!

Occluded Front

An **occluded front** or **occlusion** (**4**) usually forms around a low pressure system (**Figure** 16.20). The occlusion starts when a cold front catches up to a warm front. The air masses, in order from front to back, are cold, warm, and then cold again. The boundary line, where the two fronts meet, curves towards the pole because of the Coriolis effect. If the air mass that arrives third is colder than either of the first two air masses, that air mass will slip beneath the other two air masses. This is called a cold occlusion. If the air mass that arrives third is warm, that air mass will ride over the other air mass. This is called a warm occlusion.

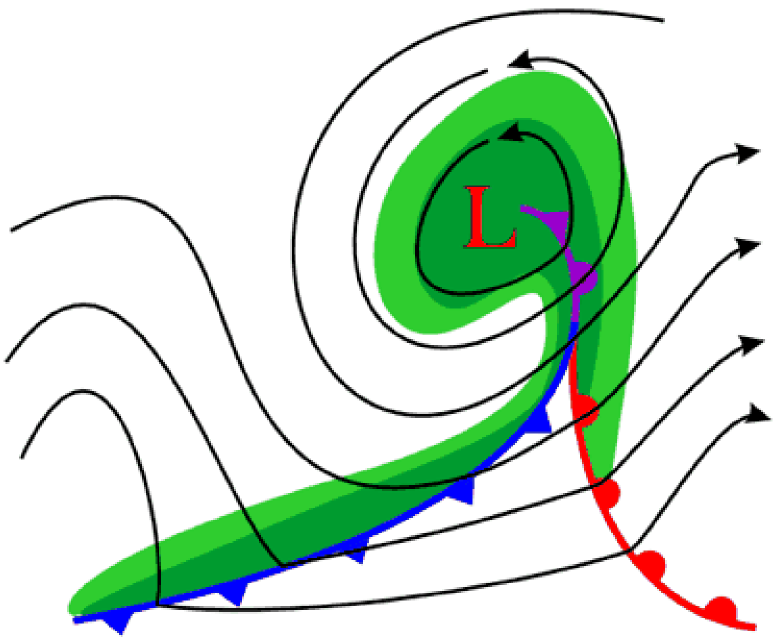

Figure 16.20: An occluded front with a warm front being advanced on by a cold front. The order of air masses from front to rear is cold, warm, and then cold. (33)

Occluded fronts can cause drying or storms. Precipitation and shifting winds are typical. The weather is especially fierce right at the occlusion. The Pacific coast has frequent occluded fronts. All of these fronts are part of the mid-latitude cyclone. These weather systems will be discussed in the next lesson.

Lesson Summary

- An air mass takes on the temperature and humidity characteristics of the location where it originates. Air masses meet at a front.
- Stationary fronts become trapped in place and the weather they bring may last for many days.

- At a cold front, a cold air mass takes the place of a warm air mass and forces the warm air upwards.
- The opposite occurs at a warm front, except that the warm air slips above the cold air mass.
- In an occluded front, a warm front is overtaken by a cold front, which creates variable weather.

Review Questions

1. What type of air mass will be created if a batch of air sits over the equatorial Pacific Ocean for a few days? What is the symbol for this type of air mass?
2. What conditions must be present for air to sit over a location long enough to acquire the characteristics of the land or water beneath it?
3. Discuss how latitude affects the creation of air masses in the tropical, temperate and polar zones.
4. Phoenix, Arizona is a city in the Southwestern desert. Summers are extremely hot. Winter days are often fairly warm but winter nights can be quite chilly. In December, inversions are quite common. How does an inversion form under these conditions and what are the consequences of an inversion to this sprawling, car-dependent city?
5. Why are the directions fronts move in the Southern Hemisphere a mirror image of the directions they move in the Northern Hemisphere?
6. How is a stationary front different from a cold or warm front?
7. What sorts of weather will you experience as a cold front passes over you?
8. What sorts of weather will you experience as a warm front passes over you?
9. How does an occlusion form?
10. What situation creates a cold occlusion and what creates a warm occlusion?

Further Reading / Supplemental Links

- Cold Front animation, Goddard Space Flight Center http://svs.gsfc.nasa.gov/vis/a000000/a002200/a002203/index.html

Vocabulary

air mass A large mass of air with the same temperature and humidity characteristics, although these characteristics may change with altitude.

cold front A front in which a cold air mass is replacing a warm air mass; the cold air mass pushes the warm air mass upward.

front The meeting place of two air masses with different characteristics.

occluded front A front in which a cold front overtakes a warm front.

squall line A line of thunderstorms that forms at the edge of a cold front.

stationary front A stalled front in which the air does not move.

temperature gradient A change in temperature over distance.

warm front A front in which a warm air mass is replacing a cold air mass.

Points to Consider

- How do the various types of fronts lead to different types of weather?
- Why are some regions prone to certain types of weather fronts and other regions prone to other types of weather fronts?
- Why does the weather sometimes change so rapidly and sometimes remain very similar for many days?

16.3 Storms

Lesson Objectives

- Describe how atmospheric circulation patterns cause storms to form and travel.
- Understand the weather patterns that lead to tornadoes, and identify the different types of cyclones.
- Know what causes a hurricane to form, what causes it to disappear, and what sorts of damage it can do.
- Know the damage that heat waves and droughts can cause.

Introduction

Weather happens every day, but only some days have storms. Storms vary immensely depending on whether they're warm or cold, coming off the ocean or off a continent, occurring in summer or winter, and many other factors. The effects of storms also vary depending on whether they strike a populated area or a natural landscape. Hurricane Katrina is a good example, since the flooding after the storm severely damaged New Orleans, while a similar storm in an unpopulated area would have done little damage.

Thunderstorms

Thunderstorms are extremely common. Across the globe, there are about 14 million per year; that's 40,000 per day! Most come and go quickly, dropping a lot of rain on a small area, but some are severe and highly damaging. Thunderstorms are most common when ground temperatures are high. This tends to be in the late afternoon or early evening in spring and summer. As temperatures increase, warm, moist air rises. These updrafts form first cumulus and then cumulonimbus clouds (**Figure** 16.21).

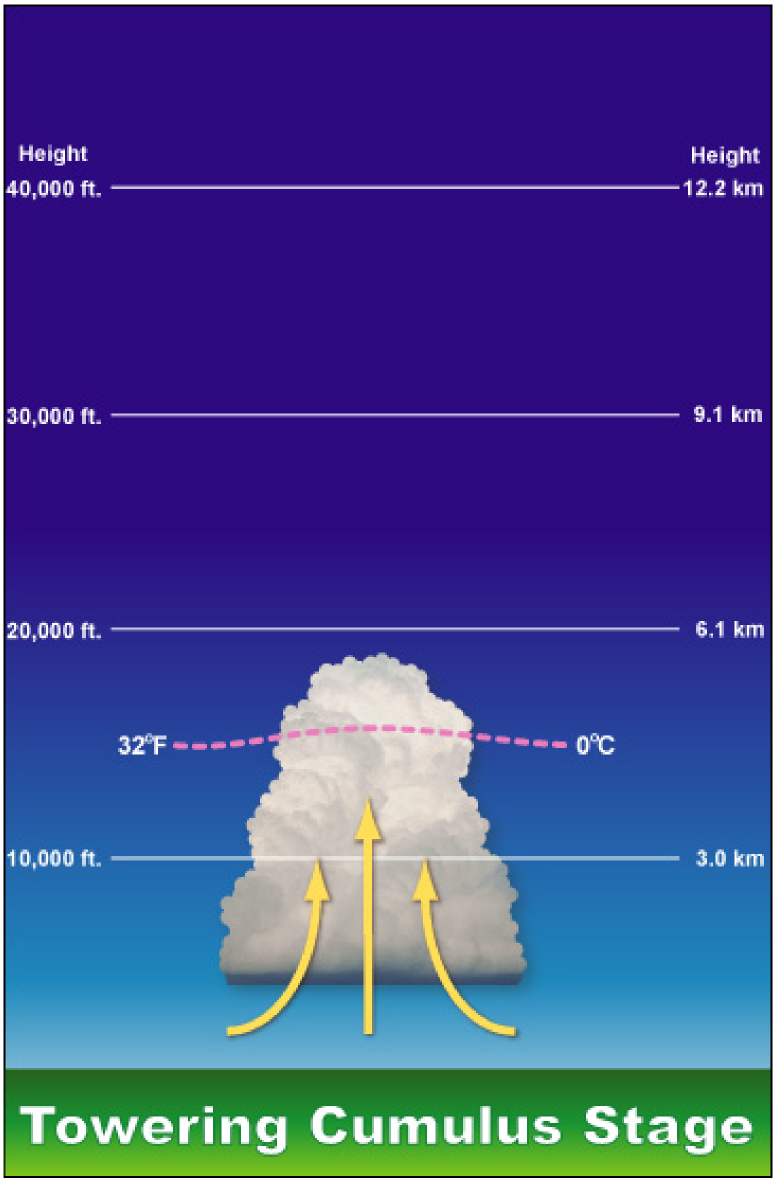

Figure 16.21: On a warm spring or summer day, air warmed near the ground rises and forms cumulus clouds. If warm air continues to rise, cumulonimbus clouds form. (19)

At the top of the stratosphere, upper level winds blow the cloud top sideways to make the anvil shape that characterizes a cloud as a thunderhead (**Figure** 16.22).

Figure 16.22: Winds at the top of the stratosphere blow the top of a cumulonimbus cloud sideways to create the classic anvil-shape of a thunderhead. (1)

Clouds form when water vapor condenses. Remember that when water changes state from a gas to a liquid, it releases latent heat. Latent heat makes the air in the cloud warmer than the air outside the cloud and supplies the cloud with a lot of energy. Water droplets and ice travel through the cloud in updrafts. When these droplets get heavy enough, they fall. This starts a downdraft, and soon there is a convection cell within the cloud. The cloud grows into a cumulonimbus giant. Droplets traveling through the convection cell grow. Eventually, they become large enough to fall to the ground. At this time, the thunderstorm is mature, it produces gusty winds, lightning, heavy precipitation and hail (**Figure** 16.23).

Once downdrafts have begun, the thunderstorm can no longer continue growing. The downdrafts cool the air at the base of the cloud, so the air is no longer warm enough to rise. As a result, convection shuts down. Without convection, water vapor does not condense, no latent heat is released, and the thunderhead runs out of energy. A thunderstorm usually ends only 15 to 30 minutes after it began, but other thunderstorms may start in the same area.

Severe thunderstorms grow larger because the downdrafts are so intense, they flow to the ground. This sends warm air from the ground upward into the storm. The warm air feeds the convection cells in the cloud and gives them more energy. Rain and hail grow huge before gravity pulls them to Earth. Hail that is 1.9 cm (0.75 inch) in diameter is not uncommon. Severe thunderstorms can last for hours and can cause a lot of damage due to high winds, flooding, intense hail, and tornadoes.

Thunderstorms can form individually or in squall lines, which can run along a cold front for hundreds of kilometers. Individual storms within the line may reach an altitude of more

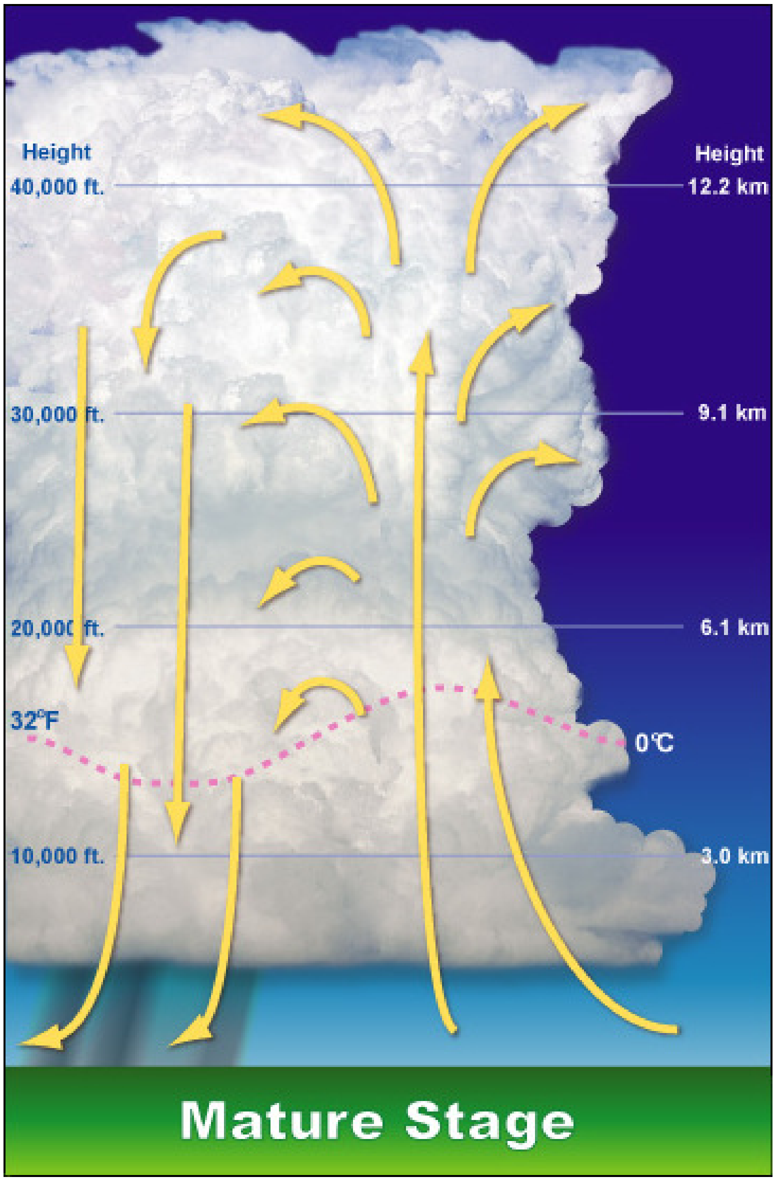

Figure 16.23: A mature thunderstorm showing updrafts and downdrafts that reach the ground. This thunderstorm will no longer grow, since the base of the cloud is being cooled too much for convection to continue. (18)

than 15 kilometers (50,000 feet). In the United States, squall lines form in spring and early summer where the maritime tropical (mT) air mass from the Gulf of Mexico meets the continental polar (cP) air mass from Canada. In the United States, severe thunderstorms are most common in the Midwest.

Lightning is a huge release of electricity that forms in cumulonimbus clouds (**Figure** 16.24). As water droplets in the cloud freeze, positive ions line the colder outside of the drop. Negative ions collect in the warmer inside. If the outside of the drop freezes, the water inside often shatters the outside ice shell. The small, positively-charged ice fragment rises in the updraft. The heavier, negatively-charged water droplet falls in the downdraft. Soon the base of the cloud is mostly negatively-charged and the top is mostly positively-charged. The negative ions at the base of the cloud drive away negative ions on the ground beneath it, so the ground builds up a positive charge. Eventually the opposite charges will attempt to equalize, creating ground to cloud lightning. Only about 20% of lightning bolts strike the ground. Lightning can also discharge into another part of the same cloud or another cloud.

Figure 16.24: Lightning over Pentagon City in Arlington, Virginia. (34)

Lightning heats the air so that it expands explosively. The loud clap is **thunder.** Light waves travel so rapidly that lightning is seen instantly. Sound waves travel much more slowly, about 330 m (1,000 feet) per second. If you were watching a lightning storm, the difference in the amount of time between seeing a lighting bolt and hearing its thunder clap in seconds times 1,000 gives the approximate distance in feet of the lightning strike. For example, if 5 seconds elapse between the lightning and the thunder, the lightning hit about

5,000 feet or about 1 mile (1,650 m) away.

Thunderstorms kill approximately 200 people in the United States and injure about 550 Americans per year, mostly from lightning strikes. Have you heard the common misconception that lightning doesn't strike the same place twice? In fact, lightning strikes the New York City's Empire State Building about 100 times per year (**Figure** 16.25).

Figure 16.25: Lightning strikes some places many times a year. Here, lightning is striking the Eiffel Tower in Paris. (14)

Tornadoes

Tornadoes, also called twisters, are the most fearsome products of severe thunderstorms (**Figure** 16.26). Tornadoes are created as air in a thunderstorm rises, and the surrounding air races in to fill the gap, forming a funnel. A tornado is a funnel shaped, whirling column of air extending downward from a cumulonimbus cloud.

A tornado can last anywhere from a few seconds to several hours. The most important measure of the strength of a tornado is its wind speed. The average is about 177 kph (110 mph), but some can be much higher. The average tornado is 150 to 600 m across (500 to 2,000 feet) across and 300 m (1,000 feet) from cloud to ground. A tornado travels over the ground at about 45 km per hour (28 miles per hour) and travels about 25 km (16 miles) before losing energy and disappearing.

Figure 16.26: The formation of this tornado outside Dimmit, Texas in 1995 was well studied. (10)

Tornadoes strike a small area compared to other violent storms, but they can destroy everything in their path. Tornadoes uproot trees, rip boards from buildings, and fling cars up into the sky. The most violent two percent of tornadoes last more than three hours. These monster storms have winds up to 480 kph (300 mph). They cut paths more than 150 km (95 miles) long and 1 km (one-half mile) wide (**Figure** 16.27).

Figure 16.27: This tornado struck Seymour, Texas in 1979. (31)

Most injuries and deaths from tornadoes are caused by flying debris. In the United States, an average of 90 people are killed by tornadoes each year, according to data from the National Weather Service. The most violent two percent of tornadoes account for 70% of the deaths by tornadoes (**Figure** 16.28).

Figure 16.28: Tornado damage at Stoughton, Wisconsin in 2005. (41)

Tornadoes form at the front of severe thunderstorms, so these two dangerous weather events commonly occur together. In the United States, tornadoes form along the front where the maritime tropical (mT) and continental polar (cP) air masses meet. In a typical year, the location of tornadoes moves along with the front, from the central Gulf States in February, to the southeastern Atlantic states in March and April, and on to the northern Plains and Great Lakes in May and June. Although there is an average of 770 tornadoes annually, the number of tornadoes each year varies greatly (**Figure** 16.29).

Meteorologists can only predict tornado danger over a very wide region, a few hours in advance of the possible storm. Once a tornado is sighted on radar, its path is predicted

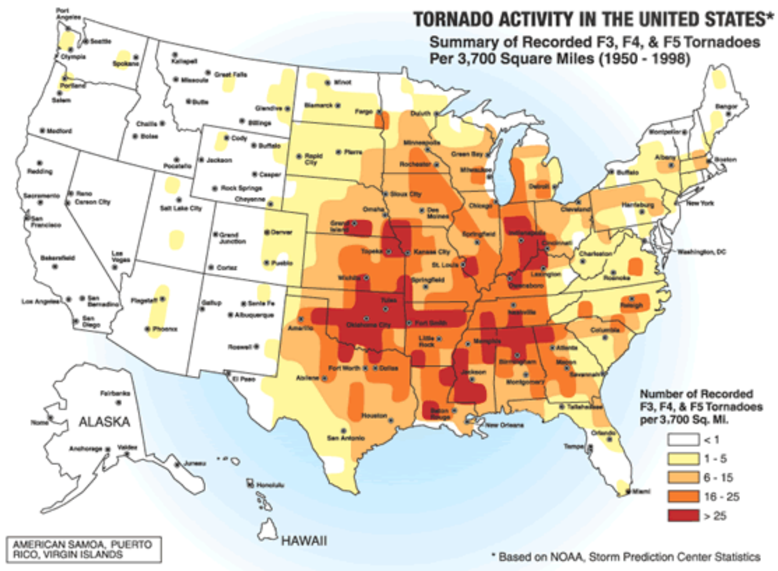

Figure 16.29: The frequency of F3, F4 and F5 tornadoes in the United States. The red region that starts in Texas and covers Oklahoma, Nebraska and South Dakota is called Tornado Alley because it is where most of the violent tornadoes occur. (44)

and a warning is issued to people in that area. The exact path is unknown because tornado movement is not very predictable. The intensity of tornadoes is measured on the Fujita Scale (see **Table** 16.3), which assigns a value based on wind speed and damage.

Table 16.3: **The Fujita Scale (F Scale) of Tornado Intensity**

F Scale	(km/hr)	(mph)	Damage
F0	64-116	40-72	Light - tree branches fall and chimneys may collapse
F1	117-180	73-112	Moderate - mobile homes, autos pushed aside
F2	181-253	113-157	Considerable - roofs torn off houses, large trees uprooted
F3	254-332	158-206	Severe - houses torn apart, trees uprooted, cars lifted

Table 16.3: (continued)

F Scale	(km/hr)	(mph)	Damage
F4	333-419	207-260	Devastating - houses leveled, cars thrown
F5	420-512	261-318	Incredible - structures fly, cars become missiles
F6	>512	>318	Maximum tornado wind speed

Cyclones

A **cyclone** is a system of winds rotating counterclockwise in the Northern Hemisphere around a low pressure center. On the east side, winds come from the south and so are warmer than those on the west side. The swirling air rises and cools, creating clouds and precipitation. Cyclones can be the most intense storms on Earth. There are two types of cyclones: middle latitude cyclones and tropical cyclones. Mid-latitude cyclones are the main cause of winter storms in the middle latitudes. Tropical cyclones are also known as hurricanes.

An **anticyclone**, as you might expect, is the opposite of a cyclone. An anticyclone's winds rotate around a center of high pressure. Air from above sinks to the ground to fill the space left when the air moved away. High pressure centers generally have fair weather. Anticyclone winds move clockwise in the Northern Hemisphere, exactly the opposite of a cyclone. Since winds on the east side of the anticyclone come from the north and those on the west side come from the south, the east side tends to be colder than the west side of the high.

Middle Latitude Cyclones

Middle latitude cyclones, sometimes called extratropical cyclones, form at the polar front when the temperature difference between two air masses is large. These air masses blow past each other in opposite directions. Winds are deflected by Coriolis Effect—to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This causes the winds to strike the polar front at an angle. Warm and cold fronts form next to each other. Most winter storms in the middle latitudes, including most of the United States and Europe, are caused by middle latitude cyclones (**Figure** 16.30).

The warm air at the cold front rises and creates a low pressure cell. Winds rush into the low pressure and create a rising column of air. The air twists, rotating counterclockwise in

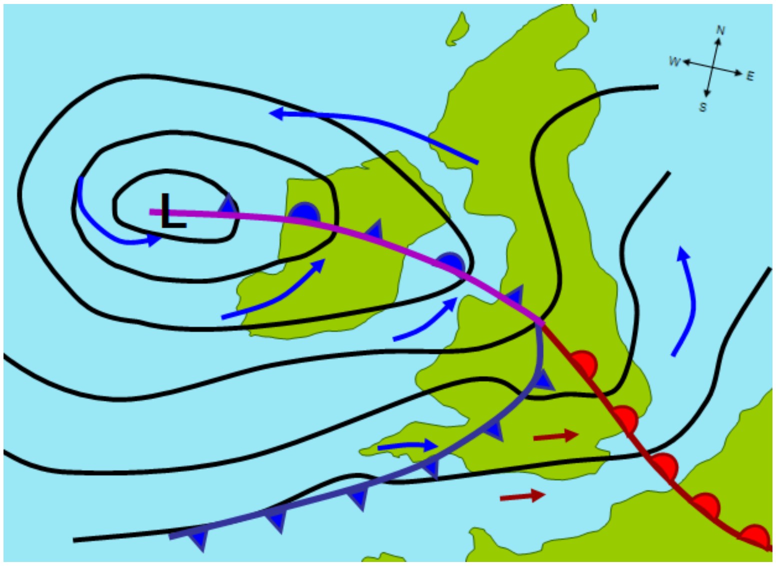

Figure 16.30: A hypothetical mid-latitude cyclone affecting the United Kingdom. The arrows indicate the wind direction and its relative temperature; **L** symbolizes the low pressure area. Notice the warm, cold, and occluded fronts. (21)

the Northern Hemisphere and clockwise in the Southern Hemisphere. Since the rising air is moist, rain or snow falls.

Mid-latitude cyclones form in winter in the mid-latitudes and move eastward with the westerly winds. These two to five day storms can reach 1,000 to 2500 km (625 to 1,600 miles) in diameter and produce winds up to 125 km (75 miles) per hour. Like tropical cyclones, they can cause extensive beach erosion and flooding.

Mid-latitude cyclones are especially fierce in the mid-Atlantic and New England states where they are called **nor'easters**, because they come from the northeast. About 30 nor'easters strike the region each year. Most do little harm, but some are deadly. The typical weather pattern of a nor'easter is familiar to anyone who has lived in this region. First, heavy snow and ice cover the ground. Then, air temperature warms and rain falls. The rain hits the frozen ground and freezes, cloaking everything in ice (**Figure** 16.31).

Hurricanes

Tropical cyclones have many names. They are called **hurricanes** in the North Atlantic and eastern Pacific oceans, *typhoons* in the western Pacific Ocean, *tropical cyclones* in the Indian Ocean, and *willi-willi's* in the waters near Australia (**Figure** 16.32). By any name, they are the most damaging storms on Earth.

For a hurricane to form, sea surface temperature must be 28°C (82°F) or higher. Hurricanes

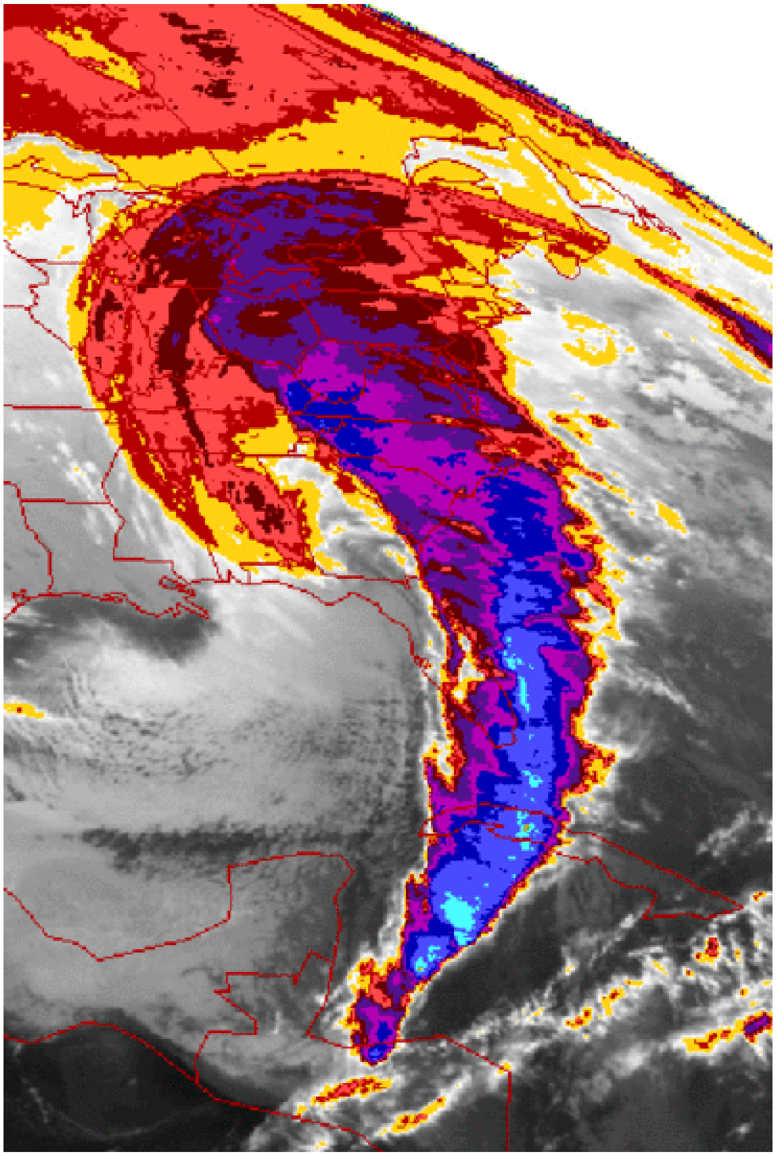

Figure 16.31: The 1993 "Storm of the Century" was a nor'easter that covered the entire eastern seaboard of the United States. (28)

arise in the tropical latitudes (between 10º and 25ºN) in summer and autumn. The warm seas create a large humid air mass. The warm air rises and forms a low pressure cell, known as a **tropical depression**. Thunderstorms materialize around the tropical depression.

If the temperature within the cell reaches or exceeds 28ºC (82ºF) the air begins to rotate around the low pressure. The rotation is counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. As the air rises, water vapor condenses, releasing energy from latent heat. If winds frequently shift directions in the upper atmosphere, the storm cannot grow upward. If wind shear is low, the storm builds into a hurricane within two to three days.

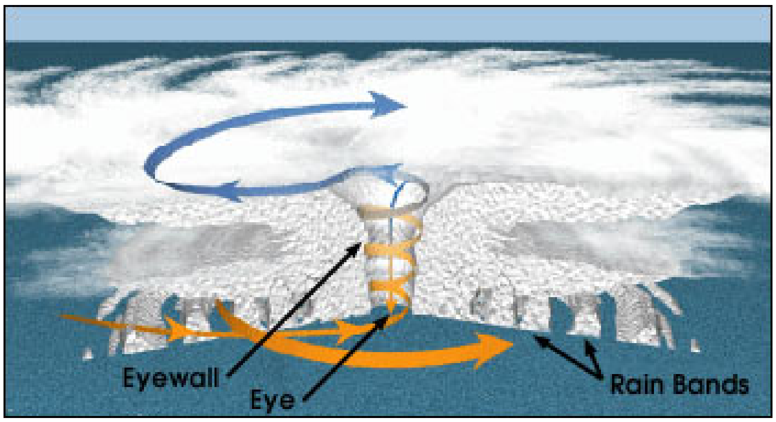

Figure 16.32: A cross-sectional view of a hurricane. (6)

Hurricanes are roughly 600 km (350 miles) across and 15 km (50,000 feet) high. Winds reach at least 118 km (74 miles) per hour. The exception is the relatively calm eye of the storm, which is about 13 to 16 km (8 to 10 miles) in diameter. The eye is calm because it is where air is rising upward.

Rainfall can be as high as 2.5 cm (1") per hour, resulting in about 20 billion metric tons of water released daily in a hurricane. The release of latent heat generates enormous amounts of energy, about 2,000 billion kilowatt hours per day. This amount of energy is nearly the total annual electrical power consumption of the United States. Hurricanes can also generate tornadoes.

Hurricanes are assigned to categories based on their wind speed. An estimate can be made as to the damage that will be caused based on the category of storm. The categories are listed on the Saffir-Simpson hurricane scale (**Table** 16.4).

Table 16.4: **Saffir - Simpson Hurricane Scale**

Category	Kph	Mph	Damage
1 (weak)	119-153	74-95	Above normal; no real damage to structures
2 (moderate)	154-177	96-110	Some roofing, door, and window damage, considerable damage to vegetation, mobile homes, and piers
3 (strong)	178-209	111-130	Some buildings damaged; mobile homes destroyed
4 (very strong)	210-251	131-156	Complete roof failure on small residences; major erosion of beach areas; major damage to lower floors of structures near shore
5 (devastating)	>251	>156	Complete roof failure on many residences and industrial buildings; some complete building failures

Hurricanes move with the prevailing winds. In the Northern Hemisphere, they originate in the trade winds and move to the west. When they reach the latitude of the westerlies, they switch direction and travel toward the north or northeast. Hurricanes typically travel from 5 to 40 kph (3 to 25 mph) and can cover 800 km (500 miles) in one day. Their speed and direction depend on the conditions that surround them. This uncertainty makes it hard for meteorologists to accurately predict where a hurricane will go and how strong it will be when it reaches land.

Damage from hurricanes tends to come from the high winds and rainfall, which can cause flooding. Near the coast, flooding is also caused by **storm surge** (**Figure** 16.33). Storm surge occurs as the storm's low pressure center comes onto land, causing the sea level to rise unusually high. A storm surge is often made worse by the hurricane's high winds blowing seawater across the ocean onto the shoreline. Storm surge may rise as high as 7.0 to 7.5 m

(20 to 25 feet) for up to 160 km (100 miles) along a coastline. If a storm surge is channeled into a narrow bay, it will greatly increase in height.

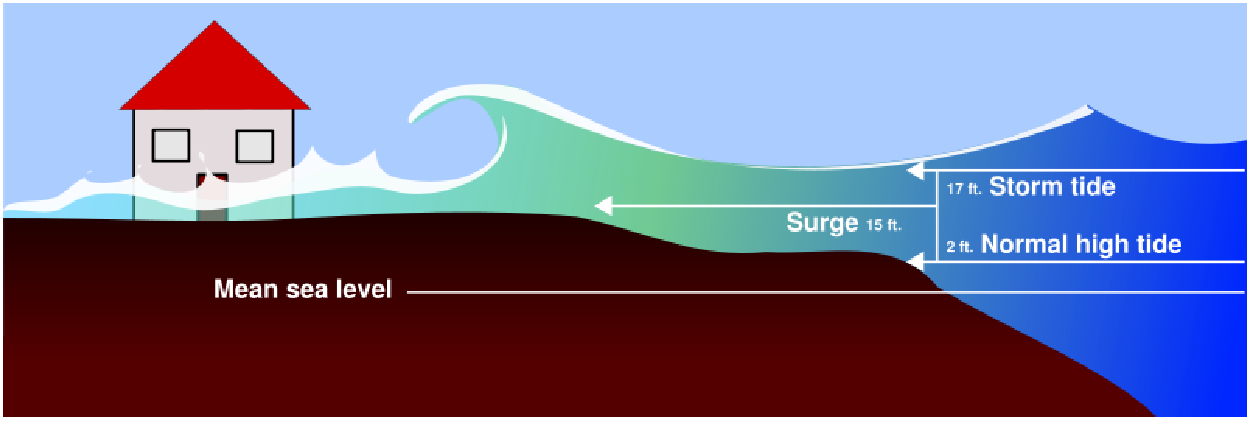

Figure 16.33: Storm surge effects on sea level. (17)

Waves created by a hurricane's high winds and high tide further increase water levels during a storm surge. Flooding can be devastating, especially along low-lying coastlines like the Atlantic and Gulf Coasts. Hurricane Camille in 1969 had a 7.3 m (24 foot) storm surge that traveled 125 miles (200 km) inland.

Hurricanes can last from three hours to three weeks, but 5 to 10 days is typical. Once a hurricane travels over cooler water or onto land, its latent heat source is shut down and it will soon weaken. However, an intense, fast-moving storm can travel quite far inland before its demise. In September, 1938 a hurricane made it all the way to Montreal, Canada before breaking up. When a hurricane disintegrates, it is replaced with intense rains and tornadoes.

There are about 100 hurricanes around the world each year, plus many smaller tropical storms and tropical depressions. As people develop coastal regions, property damage from storms continues to rise. However, scientists are becoming better at predicting the paths of these storms and fatalities are decreasing. There is, however, one major exception to the previous statement: Hurricane Katrina.

The 2005 Atlantic hurricane season was the longest, costliest, and deadliest hurricane season so far. Although the hurricane season officially runs from June 1 to November 30, the 2005 hurricane season was active into January 2006. Total damage from all the storms together was estimated at more than $128 billion, with more than 2,280 deaths. Of the 28 named storms, 15 were hurricanes, including five Category 4 storms and four Category 5 storms on the Saffir-Simpson Scale.

Hurricane Katrina was both the most destructive hurricane and the most costly (**Figure 16.34**). The storm was a Category 1 hurricane as it passed across the southern tip of Florida. It was pushed westward by the trade winds, blowing over the Gulf of Mexico where temperatures were as high as 32°C (89°F). The warm Gulf waters and latent heat fueled the storm until it grew into a Category 5. As it moved through the Gulf, the mayor of the historic city of New Orleans ordered a mandatory evacuation of the city. Not everyone was willing or able to comply.

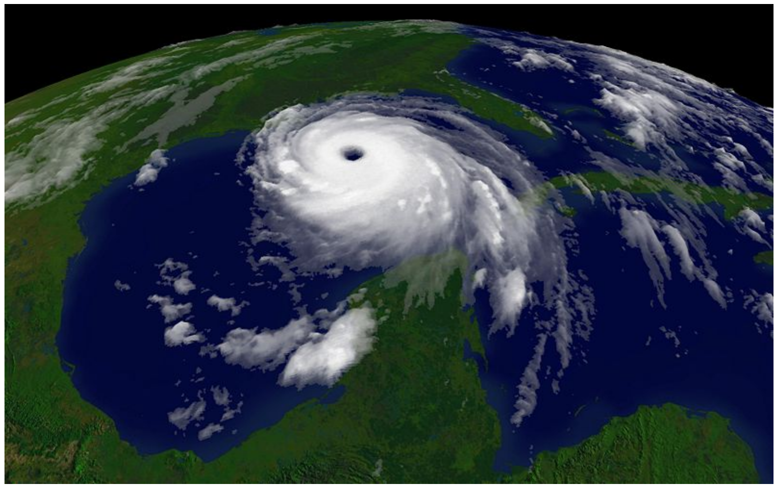

Figure 16.34: Hurricane Katrina nears its peak strength as it travels across the Gulf of Mexico. (24)

When Hurricane Katrina reached the Gulf Coast, it had weakened to a Category 4 storm. Even so, it was the third strongest hurricane to ever hit the United States. The eye of the storm struck a bit east of New Orleans, buffeting the area around Biloxi, Mississippi with the worst direct damage. The initial reports were that New Orleans had been spared. But as water began to rise in the lowest lying portions of the city, officials realized that the storm surge had caused the levee system to breach. Eventually 80% of the city was underwater (**Figure** 16.35). By the end of that horrible period, around 2,500 people were dead or missing from the Gulf Coast, most of them from New Orleans. Over two hundred thousand of people left New Orleans as a result of the hurricane, and many have not returned due to loss of their homes and livelihood.

Blizzards and Lake Effect Snow

A blizzard is distinguished by certain conditions (**Figure** 16.36):

- Temperatures below –7°C (20°F); –12°C (10°F) for a severe blizzard.
- Winds greater than 56 kmh (35 mph); 72 kmh (45 mph) for a severe blizzard.
- Snow so heavy that visibility is 2/5 km (1/4 mile) or less for at least three hours; near zero visibility for a severe blizzard.

Blizzards happen across the middle latitudes and toward the poles. They usually develop on the northwest side of a mid-latitude cyclone. Blizzards are most common in winter, when

Figure 16.35: Flooding in New Orleans after Hurricane Katrina caused the levees to break and water to pour through. (40)

Figure 16.36: A near white out in a blizzard in Minnesota. (22)

the jet stream has traveled south and a cold, northern air mass comes into contact with a warmer, semitropical air mass. The very strong winds develop because of the pressure gradient between the low pressure storm and the higher pressure west of the storm. Snow produced by the storm gets caught in the winds and blows nearly horizontally. Blizzards can also produce sleet or freezing rain.

The snowiest, metropolitan areas in the United States are Buffalo and Rochester, New York. These cities are prone to getting **lake-effect snow**. While other locations can have lake effect snow, the greatest amount is on the leeward side of the Great Lakes. In winter, a continental polar air mass travels down from Canada. As the frigid air travels across one of the Great Lakes, it warms and absorbs moisture. When the air mass reaches the leeward side of the lake, it is very unstable and it drops tremendous amounts of snow. Buffalo is on the leeward side of Lake Erie and Rochester is on the leeward side of Lake Ontario.

While lake effect snow is not a blizzard, the two can work together to create even greater snows. The Great Lakes Blizzard of 1977 was created mostly by the passage of a cold front over the area. The snowfall was aided by lake effect snow coming off of Lake Ontario, which had not yet frozen that winter.

Extreme Heat and Drought

Although not technically storms, extreme heat and drought are important weather phenomena. A heat wave is defined as extreme heat that lasts longer than normal for an area. During a heat wave, a high pressure zone sits over an area and hot air at the ground is trapped. A heat wave can occur because the position of the jet stream makes the area hotter than it is normally. For example, if the jet stream is further north than usual, hot weather can also be found north of where it is usual. Winds coming from a different direction can also make a region hotter than normal. Temperatures that would not ordinarily be too hot may create a heat wave if the humidity rises too high.

More people die from extreme heat on average each year than in any type of storm. The Chicago Heat Wave of 1995 killed about 600 people who did not have access to air conditioning. The world was shocked in July and August 2003, when between 20,000 and 35,000 died in a European heat wave, mostly in France (**Figure** 16.37).

Figure 16.37: Temperature anomalies (outside of the normal, expected range) across Europe in the summer of 2003. France was the hardest hit nation. (26)

Drought strikes a region if it has less rainfall than normal for days, weeks, or years, depending on its location. A normally wet city enters drought at a much greater rainfall level than a city located in the desert. A location may also be experiencing drought, even if it receives rain, if the rain falls so that it is useless to humans. For example, a heavy rain may run off a dried out landscape rather than sinking into the soil and nourishing the plants.

Lesson Summary

- Thunderstorms arise in warm weather when updrafts form cumulonimbus clouds that rain and hail.
- Lightning and thunder result when positive and negative electrical charges in different parts of the cloud and on the ground attempt to equalize.
- Tornadoes form most commonly from thunderstorms. Although they are shorter in duration and affect a smaller area than other severe storms, they do an enormous amount of damage where they strike.
- Cyclones of all sorts are large and damaging; they include nor'easters and hurricanes.
- Heat waves kill more people each year than any type of storm and mostly form in regions beneath an unusually high pressure zone.

Review Questions

1. Describe in detail how a thunderstorm forms and where the energy to fuel it comes from. Start with a warm day and no clouds.
2. How does a thunderstorm break apart and disappear?
3. When and why does a severe thunderstorm get more severe rather than losing energy and disappearing?
4. How do lightning and thunder form?
5. Discuss the pros and cons of living in an area that is prone to tornadoes versus one that is prone to hurricanes.

6. Where are tornadoes most common in the United States?
7. What is a cyclone? What are the two types of cyclone and how do they differ?
8. Describe in detail how a hurricane forms.
9. What level is the most damaging hurricane on the Saffir-Simpson scale? What sorts of damage do you expect from such a strong hurricane?
10. What causes damage from hurricanes?
11. What could have been done in New Orleans to lessen the damage and deaths from Hurricane Katrina?
12. Do you think New Orleans should be rebuilt in its current location?
13. Where do blizzards develop?

Vocabulary

cyclone Winds rotating around a low pressure center.

drought A situation in which there is less precipitation than normal for a matter of days, weeks, or years.

lake-effect snow Extreme snowfall caused by the evaporation of relatively warm, moist air into a cold front that then drops its snow on the leeward side of the lake.

lightning A huge discharge of electricity typical of thunderstorms.

hurricane Cyclones that form in the tropics and spin around a low-pressure center; they can be the world's most damaging storms.

mid-latitude cyclone A cyclone that forms in the middle latitudes at the polar front.

Nor'easter Mid-latitude cyclones that strike the northeastern United States.

storm surge A buildup of sea level due to wind blowing water up against the land and water being sucked upward by low pressure.

thunder The loud clap produced by lightning.

thunderstorm Storms caused by upwelling air and characterized by cumulonimbus clouds, thunder, and lightning.

tornado Violently rotating funnel shaped clouds that grow downward from a cumulonimbus cloud.

tropical depression A low pressure cell that rises in the tropics; thunderstorms materialize around the tropical depression

Points to Consider

- Why is predicting where tornadoes will go and how strong they will be so difficult?
- How would the damage done by Hurricane Katrina have been different if the storm had taken place 100 years ago?
- What knowledge do meteorologists need to better understand storms?

16.4 Weather Forecasting

Lesson Objectives

- List some of the instruments that meteorologists use to collect weather data.
- Describe how these instruments are used to collect weather data from many geographic locations and many altitudes.
- Discuss the role of satellites and computers in modern weather forecasting.
- Describe how meteorologists develop accurate weather forecasts.

Introduction

Weather forecasts are better than they ever have been. According to the World Meteorological Organization (WMO), a 5-day weather forecast today is as reliable as a 2-day forecast was 20 years ago! This is because forecasters now use advanced technologies to gather weather data, along with the world's most powerful computers. Together, the data and computers produce complex models that more accurately represent the conditions of the atmosphere. These models can be programmed to predict how the atmosphere and the weather will change. Despite these advances, weather forecasts are still often incorrect. Weather is extremely difficult to predict, because it is a very complex and chaotic system.

Collecting Weather Data

To make a weather forecast, the conditions of the atmosphere must be known for that location and for the surrounding area. Temperature, air pressure, and other characteristics of the atmosphere must be measured and the data collected. Thermometers measure temperature. One way to do this is to use a temperature-sensitive material, like mercury, placed in a long, very narrow tube with a bulb. When the temperature is warm, the mercury expands, causing it to rise up the tube. Cool temperatures cause the mercury to contract, bringing the level of the mercury lower in the tube. A scale on the outside of the thermometer matches up with the air temperature.

Because mercury is toxic, most meteorological thermometers no longer use mercury in a bulb. There are many ways to measure temperature. Some digital thermometers use a coiled strip composed of two kinds of metal, each of which conducts heat differently. As the temperature rises and falls, the coil unfolds or curls up tighter. Other modern thermometers measure infrared radiation or electrical resistance. Modern thermometers usually produce digital data that can be fed directly into a computer.

Meteorologists use **barometers** to measure air pressure (**Figure** 16.38). A barometer may contain water, air or mercury. Like thermometers, barometers are now mostly digital. Air pressure measurements are corrected so that the numbers are given as though the barometer were at sea level. This means that only the air pressure is measured instead of also measuring the effect of altitude on air pressure.

Figure 16.38: Barometers are Mercury columns used to measure air pressure. (13)

A change in barometric pressure indicates that a change in weather is coming. If air pressure rises, a high pressure cell is on the way and clear skies can be expected. If pressure falls, a low pressure is coming and will likely bring storm clouds. Barometric pressure data over a larger area can be used to identify pressure systems, fronts and other weather systems.

Other instruments measure different characteristics of the atmosphere. Below is a list of a few of these instruments, along with what they measures:

1. anemometers: wind speed
2. hygrometers: humidity
3. wind vane: wind direction
4. rain gauge: the amount of liquid precipitation over a period of time
5. snow gauge: the amount of solid precipitation over a period of time

These instruments are placed in various locations so that they can check the atmospheric characteristics of that location. Weather stations are located on land, the surface of the sea, and in orbit all around the world (**Figure** 16.39). According to the WMO, weather information is collected from 15 satellites, 100 stationary buoys, 600 drifting buoys, 3,000 aircraft, 7,300 ships and some 10,000 land-based stations.

Instruments are also sent into the atmosphere in weather balloons filled with helium or hydrogen. As the balloon ascends into the upper atmosphere, the gas in the balloon expands until the balloon bursts. The specific altitude at which the balloon bursts depends on its diameter and thickness, but is ordinarily about 40 km (25 miles) in altitude. The length of the flight is ordinarily about 90 minutes. Weather balloons are intended to be used only once, and the equipment they carry is usually not recovered.

Weather balloons contain **radiosondes** that measure atmospheric characteristics, such as temperature, pressure and humidity (**Figure** 16.40). Radiosondes in flight can be tracked to obtain wind speed and direction. Radiosondes use a radio to communicate the data they collect to a computer.

Radiosondes are launched from around 800 sites around the globe twice daily (at 0000 and 1200 UTC; UTC is Coordinated Universal Time; it is the same as Greenwich Mean Time — the time in the city of Greenwich, England) at the same time to provide a profile through the atmosphere. Special launches are done when needed for special projects. Radiosondes can be dropped from a balloon or airplane to make measurements as they fall. This is done to monitor storms, for example, since they are dangerous places for airplanes to fly.

Weather information can also come from remote sensing, particularly radar and satellites (**Figure** 16.41). **Radar** stands for *Ra*dio *D*etection *a*nd *R*anging. In radar, a transmitter sends out radio waves. The radio waves bounce off the nearest object and then return to a receiver. Weather radar can sense many characteristics of precipitation: its location, motion, intensity, and the likelihood of future precipitation. Most weather radar is Doppler radar,

Figure 16.39: A land-based weather station. Since some of the instruments must be protected from precipitation and direct heat, they are held behind a screen. (38)

Figure 16.40: A weather balloon with a radiosonde beneath it. The radiosonde is the bottom piece and the parachute that will bring it to the ground, is above it. (39)

which can also track how fast the precipitation falls. Radar can outline the structure of a storm and in doing so estimate the possibility that it will produce severe weather.

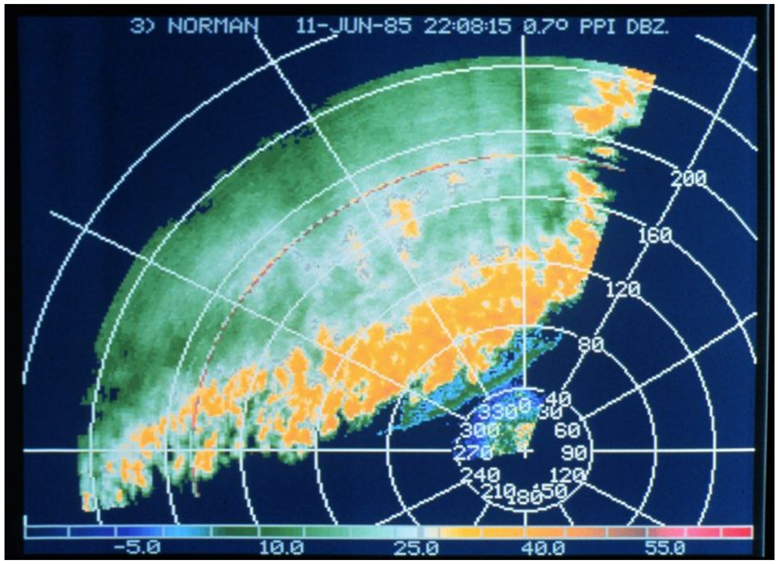

Figure 16.41: Radar view of a line of thunderstorms. (8)

Weather satellites have been increasingly important sources of weather data since the first one was launched in 1952. Weather satellites are the best way to monitor large scale systems, like storms. Satellites can also monitor the spread of ash from a volcanic eruption, smoke from fires, and pollution. They are able to record long-term changes, such as the amount of ice cover over the Arctic Ocean in September each year.

Weather satellites may observe all energy from all wavelengths in the electromagnetic spectrum. Most important are the visible light and infrared (heat) frequencies. Visible light images record images the way we would see them, including storms, clouds, fires, and smog. Infrared images measure heat. These images can record clouds, water and land temperatures, and features of the ocean, such as ocean currents. Weather patterns like the El Niño are monitored in infrared images of the equatorial Pacific Ocean.

Two types of weather satellites are geostationary and polar orbiting (**Figure** 16.42). Geostationary satellites orbit the Earth at the same rate that the Earth rotates; therefore, they remain fixed in a single location above the equator at an altitude of about 36,000 km (22,000 miles). This allows them to constantly monitor the hemisphere where they are located. A geostationary satellite positioned to monitor the United States will have a constant view of the mainland, plus the Pacific and Atlantic Oceans, as it looks for hurricanes and other potential hazards.

Polar orbiting satellites orbit much lower in the atmosphere, at about 850 km (530 miles) in altitude. They are not stationary but continuously orbit making loops around the poles, passing over the same point at around the same time twice each day. Since these satellites

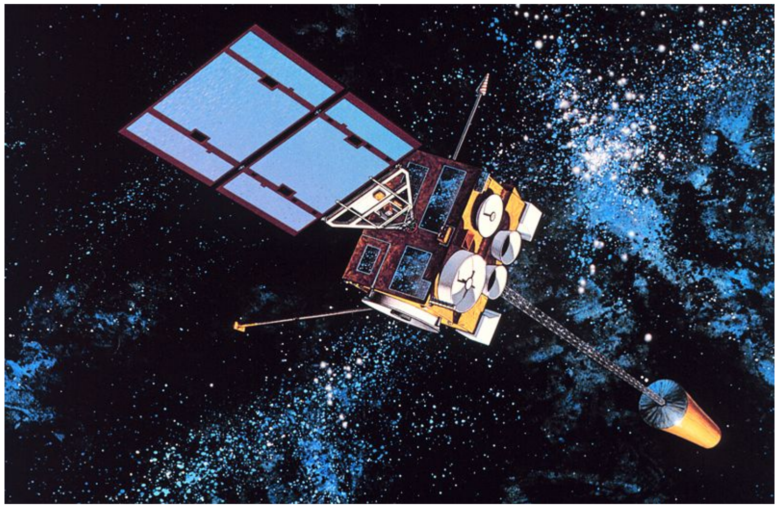

Figure 16.42: One of the geostationary satellites that monitors conditions over the United States. (2)

are lower, they get a more detailed view of the planet.

Forecasting Methods

There are many ways to create a forecast, some simple and some complex. Some use only current, local observations, while others deal with enormous amounts of data from many locations at different times. Some forecasting methods are discussed below.

Perhaps the easiest way to forecast weather is with the 'persistence' method. In this method, we assume that the weather tomorrow will be like the weather today. The persistence method works well if a region is under a stationary air mass or if the weather is consistent from day to day. For example, Southern California is nearly always warm and sunny on summer days, and so that is a fairly safe prediction to make. The persistence method can also be used for long-term forecasts in locations where a warm, dry month is likely to lead to another warm dry month, as in a Southern California summer.

The 'climatology 'method assumes that the weather will be the same on a given date as it was on that date in past years. This is often not very accurate. It may be snowing in Yosemite one New Year's Day and sunny and relatively warm on the next. Using the 'trend' method, forecasters look at the weather upwind of their location. If a cold front is moving in their direction at a regular speed, they calculate when the cold front will arrive. Of course, the front could slow down, speed up, or shift directions, so that it arrives late, early, in a strengthened or weakened state, or never arrives at all. Forecasters use the 'analog' method when they identify a pattern. Just like an analogy compares two similar things, if last week a certain pattern of atmospheric circulation led to a certain type of weather, the forecaster assumes that the same pattern this week will lead to the same weather. There are lots of possible variations in patterns and changes often occur, so this method is also not entirely accurate.

Numerical Weather Prediction

The most accurate weather forecasts are made by advanced computers, with analysis and interpretation added by experienced meteorologists. These computers have up-to-date mathematical models that can use much more data and make many more calculations than would ever be possible by scientists working with just maps and calculators. Meteorologists can use these results to give much more accurate weather forecasts and climate predictions.

In Numerical Weather Prediction (NWP), atmospheric data from many sources are plugged into supercomputers running complex mathematical models. The models then calculate what will happen over time at various altitudes for a grid of evenly spaced locations. The grid points are usually between 10 and 200 kilometers apart. Using the results calculated by the model, the program projects that weather further into the future. It then uses these results to project the weather still further into the future and so on, as far as the meteorologists want to go. The final forecast is called a **prognostic chart** or **prog**.

Certain types of progs are better at particular types of forecasts and experienced meteorologists know which to use to predict different types of weather. In addition to the prog, scientists use the other forecasting methods mentioned above. With so much data available, meteorologists use a computerized system for processing, storage, display and telecommunications. Once a forecast is made, it is broadcast by satellites to more than 1,000 sites around the world.

NWP produces the most accurate weather forecasts, but as anyone knows, even the best forecasts are not always right. Some of the reasons for this are listed below:

- Not enough data was initially entered into the program. This is most likely to happen for a region near an ocean or a remote area.
- The computer program makes certain assumptions about how the atmosphere operates, which may not always be correct.
- The programs only deal with weather locally, which means errors are likely at the edges of the area studied. A global model would be more accurate, but producing one would require an incredible number of calculations.
- The weather system may be too small to show up on the grid. If a system is small, like a thunderstorm, it will not be modeled. If distances between grid points are reduced, many more calculations and therefore more powerful computers are needed.
- There is always the possibility that conditions change unpredictably. Weather is a chaotic system and small, unpredictable things always happen. The farther into the future a model tries to forecast, the more unpredictable things arise to change the forecast.

Weather Maps

Weather maps simply and graphically depict meteorological conditions in the atmosphere. Weather maps may display only one feature of the atmosphere or multiple features. They can depict information from computer models or from human observations. Weather maps are found in newspapers, on television, and on the Internet.

On a weather map, each weather station will have important meteorological conditions plotted. These conditions may include temperature, current weather, dew point, the amount of cloud cover, sea level air pressure, and the wind speed and direction. On a weather map, meteorologists use many different symbols. These symbols give them a quick and easy way to put information onto the map. **Figure** 16.43 shows some of these symbols and explains what they mean (**Figure** 16.44).

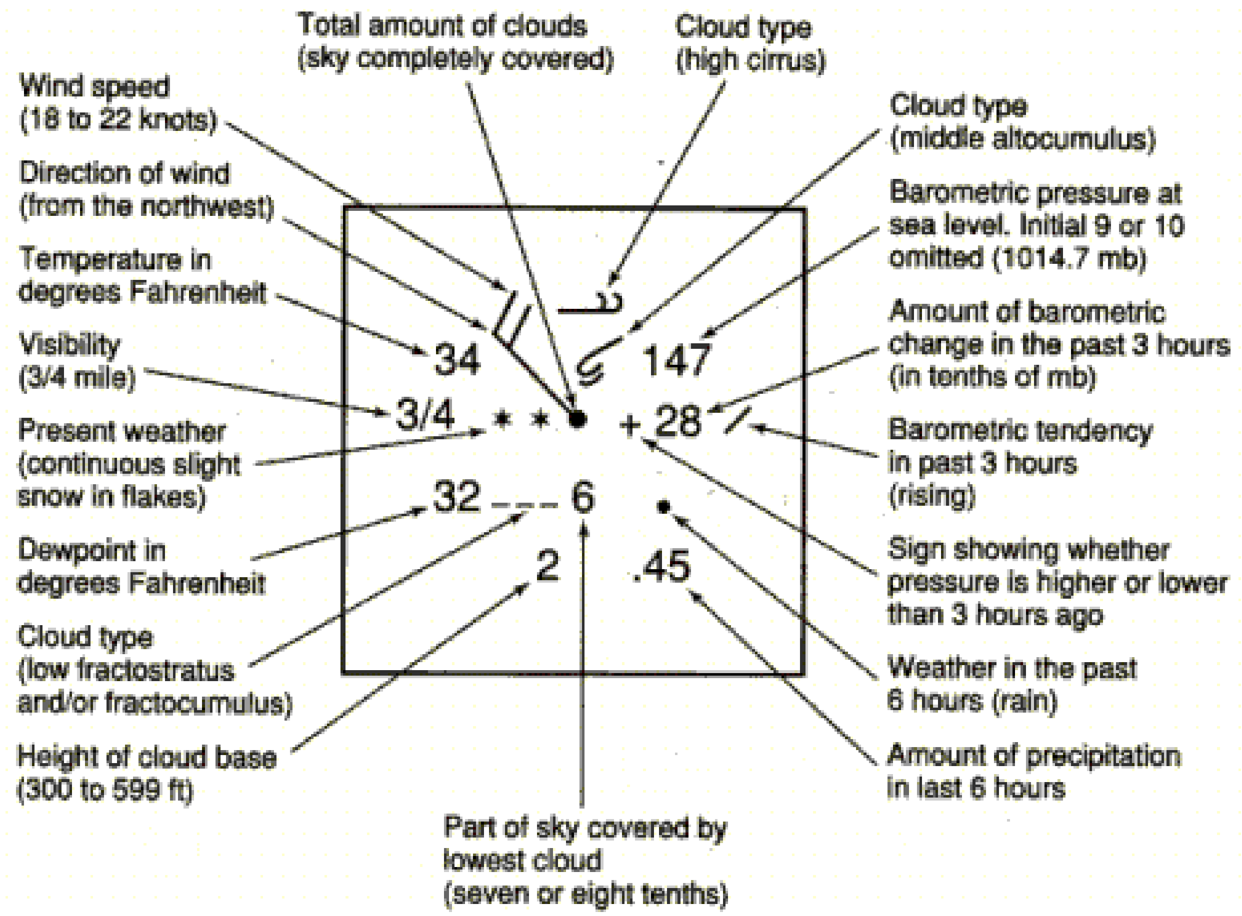

Figure 16.43: Explanation of some symbols that may appear on a weather map. (4)

Once conditions have been plotted, points of equal value can be connected. This is like the contour line on a topographic map, in which all points at a certain elevation are joined.

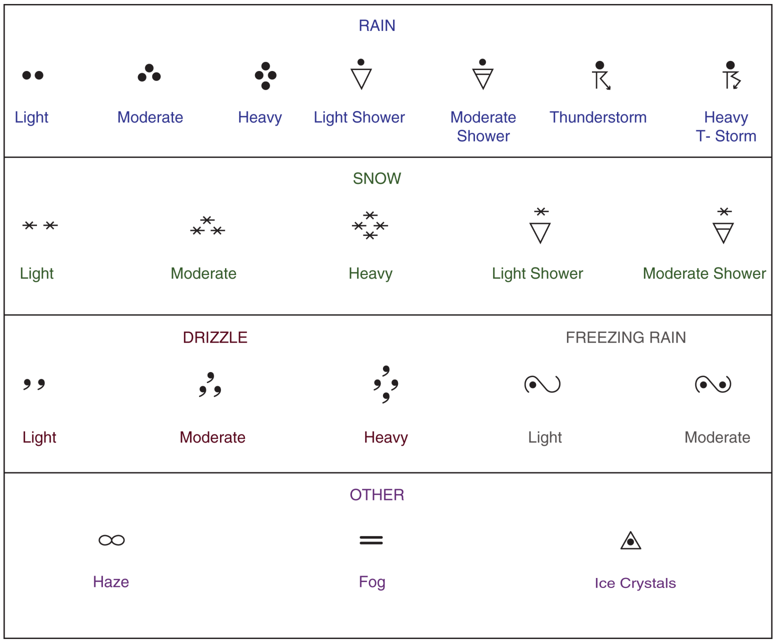

Figure 16.44: Different types of weather that can be shown using a weather symbol. (23)

Weather maps can have many types of connecting lines. For example:

- Lines of equal temperature are called **isotherms**. Isotherms show temperature gradients and can indicate the location of a front. The 0°C (32°F) isotherm will show where rain is likely to give way to snow.
- **Isobars** are lines of equal average air pressure at sea level (**Figure** 16.45). Closed isobars represent the locations of high and low pressure cells. High pressure cells are shown as **H**'s and low pressure cells as **L**'s. A thick, brown dashed line is often placed inside a long low pressure trough.

- **Isotachs** are lines of constant wind speed. Where the minimum values occur high in the atmosphere, tropical cyclones may develop. The highest wind speeds can be used to locate the jet stream.

Surface weather analysis maps are weather maps that only show conditions on the ground (**Figure** 16.46). These maps show sea level mean pressure, temperature and amount of cloud cover. This information will reveal features such as high and low pressure cells.

Weather maps can also depict conditions at higher altitudes. Aviation maps show conditions in the upper atmosphere, particularly those that are of interest to pilots. These include current weather, cloud cover, and regions where ice is likely to form.

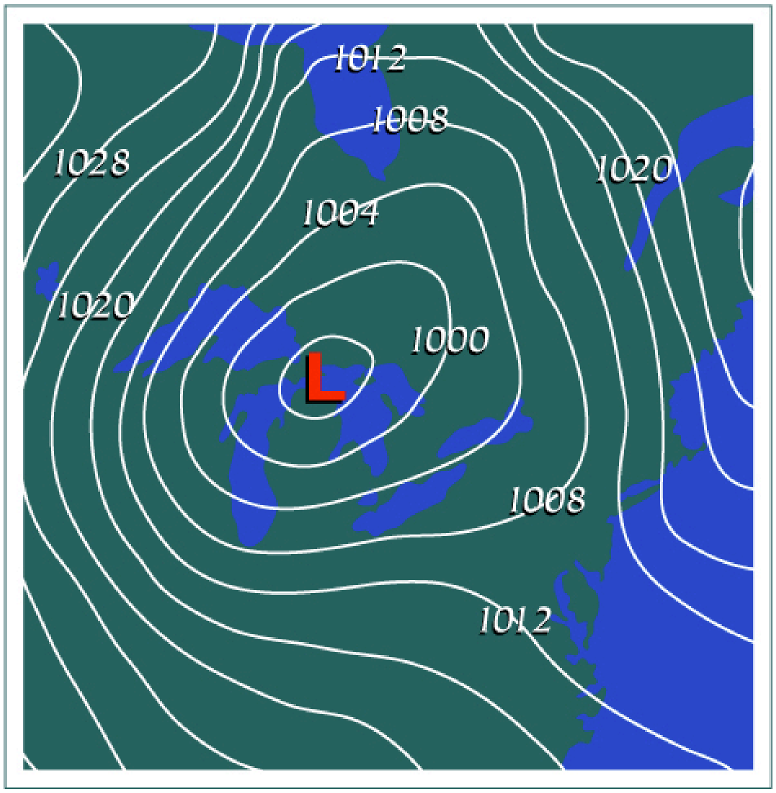

Figure 16.45: Lines of equal pressure drawn on a weather map are isobars. Isobars can be used to help visualize high and low pressure cells. (29)

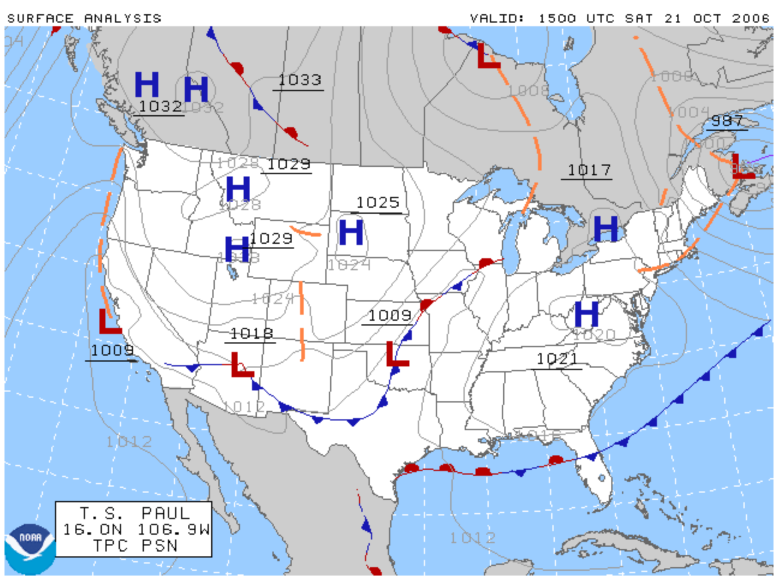

Figure 16.46: Surface analysis map of the contiguous United States and southern Canada. (5)

Lesson Summary

- Weather forecasts are more accurate than ever before. Older instruments and data collection methods such as radiosondes and weather balloons are still used.
- These techniques have now been joined by satellites and computers to create much more detailed and accurate forecasts.
- Still, forecasts are often wrong, particularly those that predict the weather for several days.
- Meteorologists are working hard to improve weather forecasts one to two weeks in advance of potentially hazardous weather.

Review Questions

1. What types of instruments would you expect to find at a weather station and what do these instruments measure?
2. How does a thermometer work?
3. How could a barometer at a single weather station be used to predict an approaching storm?
4. Why are weather balloons important for weather prediction? What information do they give that isn't obtainable in other ways?
5. How does radar work, and what is its value in weather prediction?
6. What type of weather satellite is best to use for monitoring hurricanes that may cause problems in the United States and why?
7. Imagine that your teacher asks you to predict what the weather will be like tomorrow. You can go outside, but can't use a TV or computer. What method will you use?
8. Imagine that you need to predict tomorrow's weather and you are allowed to use a telephone, but no other electronics. Who will you call and what method will you use?
9. Okay, now you need to predict tomorrow's weather and you have access to electronics, but not to weather forecasts. That is, you can look at information such as weather maps and radar images but you cannot look at the interpretations made by a meteorologist. Now what method are you using?
10. No rain is in the forecast, but it's pouring outside. How could the NWP weather forecast have missed this weather event?
11. What does it mean to say that weather is a chaotic system? How does this affect the ability to predict the weather?

Further Reading / Supplemental Links

- National Doppler Radar Sites http://radar.weather.gov/
- Google Earth Visualizations, Barnabu http://www.barnabu.co.uk/global-cloud-animations-up

Vocabulary

barometer An instrument for measuring atmospheric pressure.

isobars Lines connecting locations that have equal air pressure.

isotachs Lines connecting locations that have equal wind speed.

isotherms Lines connecting locations that have equal temperatures.

prognostic chart (prog) A chart showing the state of the atmosphere at a given time in the future.

radar Radio detection and ranging device that emits radio waves and receives them after they bounce on the nearest surface. This creates an image of storms and other nearby objects.

radiosonde A group of instruments that measure the characteristics of the atmosphere—temperature, pressure, humidity, etc. — as they move through the air.

weather map A map showing weather conditions over a wide area at a given time, it collects data from many locations.

weather satellite A human made object that orbits the Earth and senses electromagnetic waves, mostly in the visible light and infrared spectra.

Points to Consider

- With so much advanced technology available, what is the role of meteorologists in creating accurate weather forecasts?
- With so much advanced technology available, why are weather forecasts so often wrong?
- What advances do you think will be necessary for meteorologists to create accurate weather forecasts one- to two-weeks in advance of a major weather event?

Image Sources

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(35) *Cumulus clouds build at a warm front.*. GNU-FDL.

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(46) *Snow storm in Cleveland, Ohio.*. GNU-FDL.

Chapter 17

Climate

17.1 Climate and Its Causes

Lesson Objectives

- Describe the effect of latitude on the solar radiation a location receives and how this influences climate.
- Diagram the Hadley, Ferrell and Polar atmospheric circulation cells and show how they influence the climate of various locations.
- Discuss the other important location factors that influence a location's climate: position in the global wind belts, proximity to a large water body, position relative to a mountain range and others.

Introduction

While almost anything can happen with the weather, climate is more predictable. The weather on a particular winter day in San Diego may be colder than on the same day in Lake Tahoe, but, on average, Tahoe's winter climate is significantly colder than San Diego's. Climate then is the long-term average of weather. Good climate is why we choose to vacation in Hawaii in February, even though the weather is not guaranteed to be good!

What is Climate?

Weather is what is happening in the atmosphere at a particular location at the moment. Climate is the average of weather in that location over a long period of time, usually for at least 30 years. A location's climate can be described by its air temperature, humidity, wind speed and direction, and the type, quantity, and frequency of precipitation. The climate of a location depends on it position relative to many things. Most important is latitude, but other factors include global and local winds, closeness to an ocean or other large bodies of water, nearness to mountains, and altitude. Climate can change, but only over long periods of time.

The term climate also refers to Earth's entire climate system. The climate system is influenced by the movement of heat around the globe. Heat is carried by currents within the atmosphere and oceans. The type and amount of vegetation also affects climate. Plants absorb heat and retain water, which may increase or decrease rainfall. The composition of the atmosphere also controls climate. If the concentration of greenhouse gases increase or decrease, the heat-trapping abilities of the atmosphere rise or fall.

Latitude

The amount of solar energy a particular location receives is the most important factor in determining that location's temperature. The amount of sunlight that strikes the ground is different at each latitude. The lower the latitude, the more sunlight an area will receive. At the equator, days are equally long year-round and the sun is just about directly overhead at midday. At the poles, during the winter, nights are long and the sun never rises very high in the sky. Sunlight filters through a thick wedge of atmosphere, making the sunlight much less intense. Ice and snow at high latitudes also reflect a good portion of the sun's light, giving these regions much greater albedo.

This animation shows the average surface temperature across the planet as it changes through the year

Monthly Mean Temperatures (`http://upload.wikimedia.org/wikipedia/commons/b/b3/MonthlyMeanT.gif`)

From all this information you can understand why the tropics are warmer than the polar areas. The temperate regions are in between, both in latitude and average air temperature. The air in Earth's atmosphere moves as the Sun warms some areas more than others. The main reason we have different climates at various latitudes is also determined by the amount of sunlight that hits each place (**Figure** 17.1).

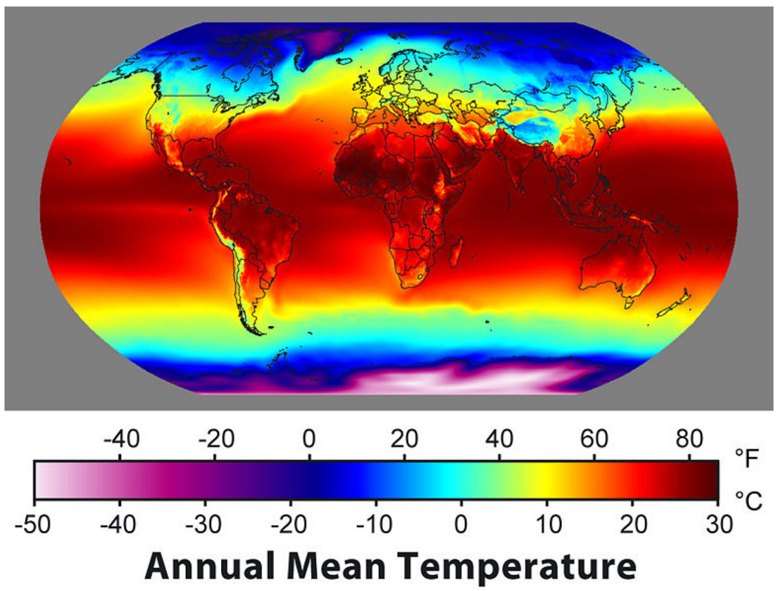

Figure 17.1: This map of annual average temperatures shows how dramatically temperature decreases from the low latitudes to the high latitudes. (21)

Prevailing Winds

There are winds that usually blow in one particular direction, called the global wind belts. These winds are called the trade winds, the westerlies and the polar easterlies. The direction these winds blow is different at various latitudes. In the Earth's Atmosphere chapter, you learned that air rises at low pressure areas, which form at 0° and again at 50° to 60° north and south of the equator. Air sinks at high pressure areas, which form at around 30° N and S and at the poles. These low and high pressure zones represent the upward and downward flowing regions of the Hadley, Ferrell and Polar atmospheric circulation cells (**Figure** 17.2). Low pressure areas form where air is moving upwards or rising. High pressure areas form where cooler, drier air sinks. Areas of high pressure often have climates that are cooler and drier. Low pressure zones often have climates that are warm and rainy.

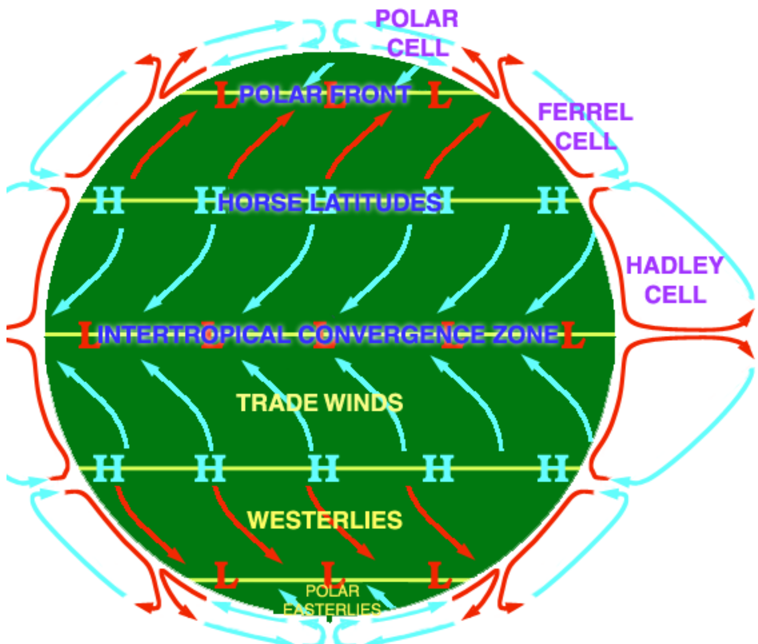

Figure 17.2: The atmospheric circulation cells and their relationships to air movement on the ground. (34)

The low pressure area near the equator is located at the boundary between the two Hadley Cells. In both these cells, air rises up at the equator and then travels away from the equator. This band of rising air is called the **Intertropical Convergence Zone (ITCZ)** (**Figure** 17.3). As the air rises, it cools and condenses to create clouds and rain. Climate along the ITCZ is therefore warm and wet. In an area where the air is mostly rising, there is not much wind. Early mariners called this region the doldrums because their ships were often unable to sail without steady winds.

The ITCZ migrates slightly with the season. Land areas heat more quickly than the oceans. Since there are more land areas in the Northern Hemisphere, the ITCZ is influenced by the heating effect of the land. In Northern Hemisphere summer, it is approximately 5 ^{o} north of the equator while in the winter, it shifts back and is approximately at the equator. As the ITCZ shifts, the major wind belts also shift slightly north in summer and south in winter, which causes the wet and dry seasons in this area (**Figure** 17.4).

At the high pressure zone where the Hadley cell and Ferrell cells meet, at about 30^{o}N and 30^{o}S, the air is fairly warm since much of it came from the equator. It is also very dry for two reasons: (1) The air lost much of its moisture at the ITCZ, and (2) Sinking air is more likely to cause evaporation than precipitation. Mariners had a very grim reason for naming this region the horse latitudes. Often the lack of wind would cause their ships to be delayed

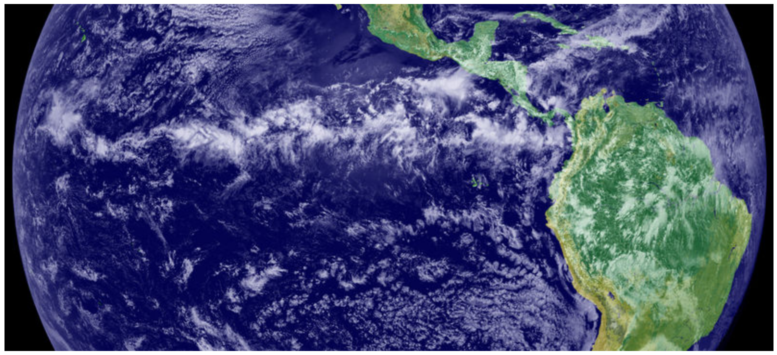

Figure 17.3: The ITCZ can be easily seen where thunderstorms are lined up north of the equator. (8)

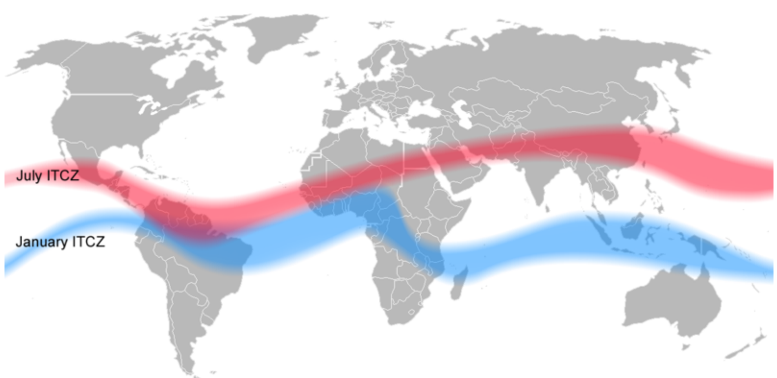

Figure 17.4: Seasonal differences in the location of the ITCZ are shown on this map. (7)

for so long that they would run out of water and food for their livestock. Sailors would toss horses and other animals over the side of the ship after they died. Sailors sometimes didn't make it either. On land, these high pressure regions mark the locations of many of the world's great deserts, including the Sahara in Africa and the Sonora in North America.

The other low pressure zone is between the Ferrell and Polar Cells at around 50-60º. This is the usual location of the polar jet stream, where cold air from the poles meets warmer air from the tropics and storms are common. As the Earth orbits the Sun, the angle of the Sun shifts between 23.5°N and 23.5°S; in turn, this shift causes the polar jet stream to move. Like the ITCZ, the position of the polar jet stream moves seasonally, creating seasonal weather changes in the mid-latitudes.

The direction of the prevailing winds greatly influences the climate of a region. These winds form the bases of the Hadley, Ferrell and Polar Cells. Winds often bring the weather from the locations they come from. For example, in California, the predominant winds are the westerlies. These winds blow in from the Pacific Ocean. The stability of the ocean's temperatures moderates California temperatures, so that summers are cooler and winters are warmer. In the middle of the continent, the winds bring more variable conditions. Local winds also influence local climate. For example, land breezes and sea breezes moderate coastal temperatures.

Continental Position

When a particular location is near an ocean or large lake, the body of water plays an extremely important role in affecting the region's climate. When a location has a **maritime climate** its climate is strongly influenced by the nearby sea: summers are not too hot and winters are not too cold. Temperatures also do not vary much between day and night. For a location to have a true maritime climate, the winds must most frequently come off the sea. A **continental climate** is more extreme, with greater temperature differences between day and night and between summer and winter.

The ocean's influence in moderating climate can be seen in the following temperature comparisons. Each of these cities is located at 37°N latitude, within the westerly winds. San Francisco is on the Pacific coast; Wichita, Kansas is in the middle of the North American continent; and Virginia Beach, Virginia is on the Atlantic coast. San Francisco is cooler in July and warmer in January than either of the other two cities. This is typical of a maritime climate; not too hot, not too cold. Wichita has the greatest range of temperatures; the hottest temperatures in July and coldest in January, which is typical for a continental climate. Although Virginia Beach is located on the Atlantic Ocean, it has a mostly continental climate since the westerly winds come off the continent (**Table** 17.1).

Table 17.1: **Average Temperature**

Location	City	July: high (°C/°F)	January: low (°C/°F)
West Coast	San Francisco, CA	19/66	8/46
Central United States	Wichita, KS	33/92	−7/20
East Coast	Virginia Beach, VA	32/89	1/31

(Source: wikipedia.org)

Ocean Currents

The temperature of the water offshore will influence the temperature of a coastal location, particularly if the winds come off the sea. The California Current runs from north to south along the length of the western coast of North America. The cool waters of the California Current bring cooler temperatures to the California coastal region. Coastal upwelling also brings cold, deep water up to the ocean surface off of California, which contributes to the cool, coastal temperatures. Further north, in southern Alaska, the upwelling actually raises the temperature of the surrounding land because the ocean water is much warmer than the land.

The California Current is part of the global system of surface ocean currents that spread the Sun's heat around the world. These currents bring cool water from high latitudes to the low latitudes and warm water from low latitudes to the high latitudes. Just as the California current brings cooler temperatures into the temperate regions, the Gulf Stream raises air temperatures along the southeastern United States as it brings warm equatorial water north along the Western Atlantic ocean (**Figure** 17.5).

The Gulf Stream even has a large effect on the climate of Northern Europe. After it travels past Canada, the current moves eastward across the Atlantic and then splits. One portion flows northward between Great Britain and Northern Europe, the other moves south along Europe and northern Africa. These warm waters raise temperatures in the North Sea, which raises air temperatures over land between 3 to 6°C (5 to 11°F). London, U.K. for example, is at the same latitude as Quebec, Canada. However, London's average January temperature is 3.8°C (38°F), while Quebec's is only -12°C (10°F). Because air traveling over the warm water in the Gulf Stream picks up a lot of water, London gets a lot of rain. In contrast, Quebec is much drier and receives its precipitation as snow.

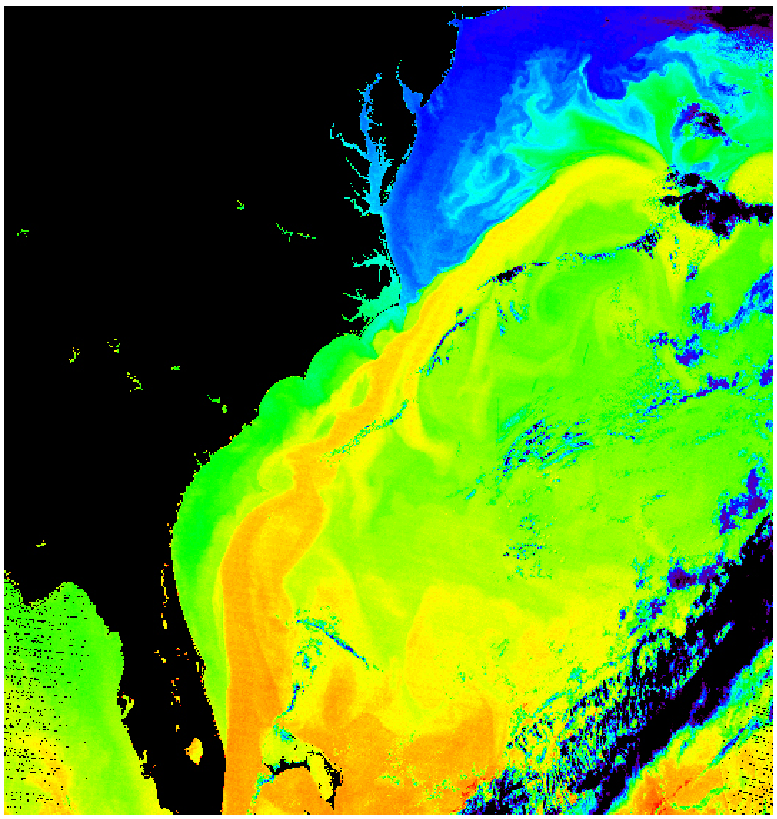

Figure 17.5: The Gulf Stream can be identified in this image of the Atlantic Ocean off of the eastern United States and Canada. The warm current appears in orange and yellow. (29)

Altitude and Mountain Ranges

All else being equal, air temperature decreases at higher altitudes. A town at 3000 meters in the mountains will be much cooler, on average, than a town at the base of the same mountains. Gravity pulls air molecules closer together at sea level than at higher altitudes. The closer molecules are packed together, the more likely they are to collide. Collisions between molecules give off heat, which warms the air. At higher altitudes, the air is less dense and air molecules are more spread out and less likely to collide.

Mountain ranges have two effects on the climate of the surrounding region. One is the rainshadow effect. As moist air rises over a mountain, it cools and drops precipitation. The air then descends down the leeward side of the range. This process creates a high pressure region on the back side of the mountain where evaporation exceeds precipitation. The result is that the windward side of the mountain range is wet but the leeward side is dry. The other effect occurs when the mountain range separates the coastal region from the rest of the continent. In this case, the ocean can only influence the coastal area before the mountain range. The coastal area near the ocean will have a maritime climate but just over the mountain, the inland area will have a continental climate.

California has two mountain ranges that exhibit both effects on climate: the Coast Range right along the coast and the Sierra Nevada, further east. The predominant winds here are the westerlies, winds that blow from the west over the ocean onto the continent. Both ranges trap cool air from the Pacific so that it has a difficult time moving eastward. As this moist ocean air rises over the Coast Range, it drops a lot of rain on the windward side. A rainshadow is created as the air then descends into the Central Valley, some of which receives so little rainfall it is classified as a desert. As the air continues eastward, it rises over the Sierra Nevada Mountains and drops more rain and snow on the west side of these mountains. On the leeward side, the air then descends into Nevada. The Sierra Nevada rain shadow creates the Great Basin desert, covering Nevada, western Utah and a small part of southeastern Oregon (**Figure** 17.6).

Lesson Summary

- Many factors influence the climate of a region, all of them somehow related to the region's position.
- Latitude determines how much solar energy a particular place receives during a day or a year.
- Latitude is directly related to location within one of the global wind belts, therefore latitude determines if a location is beneath a high or low pressure cell, where winds are low.
- If a region is near a large water body, its climate will be influenced by that water body.
- Mountain ranges can separate land areas from the oceans and can create rainshadow effects, which also influence climate.

Figure 17.6: The Bonneville Salt Flats are part of the very dry Great Basin. They receive so little rainfall because they are on the leeward side of the Sierra Nevada, part if its rainshadow. (17)

Review Questions

1. Describe the weather of the location where you are right now. How is the weather today typical or atypical of your usual climate?
2. In what two ways could a desert be found at 30°N?
3. Could a desert form at 45°N latitude?
4. Why is there so little wind in the locations where the atmospheric circulation cells meet?
5. If it is windy at 30°N where there is normally little wind, does that mean the model of the atmospheric circulation cells is wrong?
6. What is the Intertropical Convergence Zone (ITCZ)? What winds do you expect to find here?
7. How does the polar jet stream move from summer to winter? How would this affect the climate of the locations where it moves?
8. How would the climate of a city at 45°N near the Pacific Ocean differ from one at the same latitude near the Atlantic Coast?
9. Why does the ocean water off California cool the western portion of the state, while the water off the southeastern United States warms that region?
10. Think about what you know about surface ocean currents. How would you expect the climate of western South America to be influenced by the Pacific Ocean? Could this same effect happen in the Northern Hemisphere?
11. The Andes Mountains line western South America. How do you think they influence the climate of that region and the lands to the east of them?

Vocabulary

climate Weather averaged over a long period of time, usually about 30 years.

continental climate A location in which the climate is dominated by a vast expanse of land. Continental climates are more variable.

Intertropical Convergence Zone (ITCZ) A low pressure zone where the Hadley Cells in the northern and southern hemispheres meet. The trade winds meet at the ITCZ.

maritime climate A location in which the climate is dominated by a nearby ocean. Maritime climates are less variable than continental climates.

rainshadow Dry conditions that are created on the leeward side of a mountain range.

upwelling Upward flow of deep water to the surface because the deep water is less dense than the surface water.

Points to Consider

- Describe how two cities at the same latitude can have very different climates. For example, Tucson, Arizona has a hot, dry desert climate and New Orleans, Louisiana has a warm, muggy climate even though both cities are at approximately the same latitude.
- How does climate influence the plants and animals that live in a particular place?
- Would you expect climate at similar latitudes to be the same or different on the opposite side of the equator, e.g. how would the climate of a city at 45°N be similar or different to one at 45°S latitude?

17.2 World Climates

Lesson Objectives

- Describe the relationship between the climate zones and the factors that influence climate.
- Discuss the relationship between climate zones and biomes.
- Discuss the different biomes based on a general description.

Introduction

A climate zone results from the climate conditions of an area: its temperature, humidity, amount and type of precipitation, and the season. A climate zone is reflected in a region's natural vegetation. Perceptive travelers can figure out which climate zone they are in by looking at the vegetation, even if the weather is unusual for the climate on that day!

Climate Zones and Biomes

The major factors that influence climate also determine the different climate zones. The same type of climate zone will be found at similar latitudes and in similar positions on nearly all continents, both in the Northern and Southern Hemispheres. The one exception to this pattern is the climate zones called the continental climates, which are not found at higher latitudes in the Southern Hemisphere. This is because the Southern Hemisphere land masses are not wide enough to produce a continental climate.

Climate zones are classified by the Köppen classification system (**Figure** 17.7). This system is based on the temperature, the amount of precipitation and the times of year when precipitation occurs. Since climate determines the type of vegetation that grows in an area, vegetation is used as an indicator of climate type. A climate type and its plants and animals make up a **biome**. The organisms of a particular biome share certain characteristics around the world, because their environment has similar advantages and challenges. The organisms have adapted to that environment in similar ways over time. For example, different species of cactus live on different continents, but they have adapted to the harsh desert in similar ways.

The Köppen classification system recognizes five major climate groups, each with a distinct capital letter A through E. Each lettered group is divided into subcategories. Some of these subcategories are forest (f), monsoon (m), and wet/dry (w) types, based on the amount of precipitation and season when that precipitation occurs.

Tropical Moist Climates (Group A)

Tropical Moist (Group A) climates are found in a band about 15° to 25° N and S of the equator (**Figure** 17.8). Intense sunshine means that the tropics are warm year-round: each month has an average temperature of at least 18°C (64°F). Rainfall is abundant — at least 150 cm (59 inches) per year. The subcategories of this zone are based on when the rain falls.

Tropical Wet (Af)

The wet tropics lie in a band around the equator, covering about 10% of the Earth's land. The wet tropics are consistently warm, with almost no annual temperature variation. Great

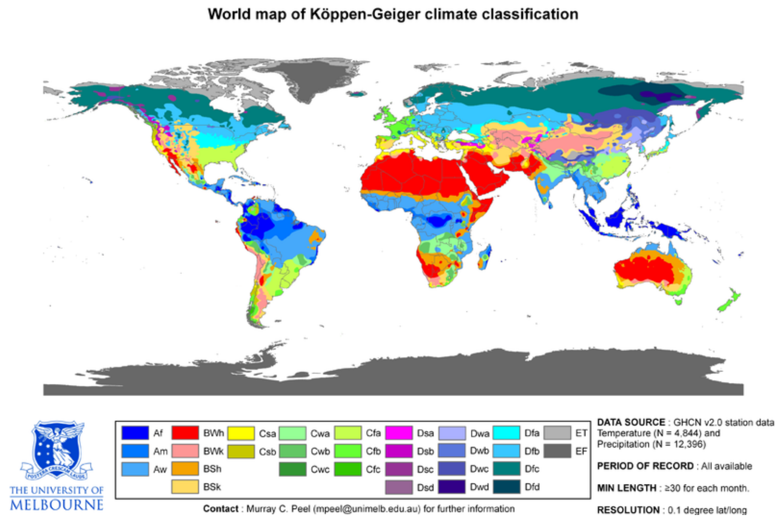

Figure 17.7: This world map of the Köppen classification system gives a good general idea of where the climate zones and major biomes are located. Where the groups are not represented by stripes (like in the western United States) the situation is complicated by geographic features such as mountains. All of the c (12)

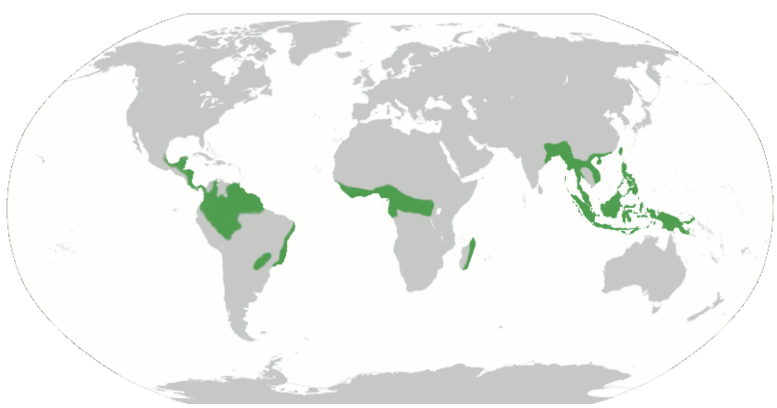

Figure 17.8: Tropical Moist Climates (Group A) are shown in green. The main vegetation for this climate is the tropical rainforest, which are found in the Amazon in South America, the Congo in Africa and the lands and islands of southeast Asia. (5)

amounts of rain fall year-round, between 175 and 250 cm (65 and 100 inches) per year. These conditions support the **tropical rainforest** biome (**Figure** 17.9). The forest is dominated by densely packed, broadleaf evergreen trees. Many habitats are found in rainforests, as a result of the high number of plant types and the different environments within the layers of the forest. Rainforests have the highest number of species or **biodiversity** of any ecosystem.

Figure 17.9: The Amazon river and rainforest in Brazil. (35)

Tropical Monsoon (Am)

The *tropical monsoon* climate resembles the tropical wet biome (Af) but has very low precipitation for one to two months each year. During these months, less than 6 cm (2.4 inches) of rain falls. Rainforests can grow here because the dry period is short, and the trees can be supported by moisture trapped in the soil. This climate is found where the monsoon winds blow, primarily in southern Asia, western Africa, and northeastern South America.

Tropical Wet and Dry (Aw)

The *tropical wet and dry* climate lies north and south of the tropical wet climate, between about 5° and 10° latitude to around 15° to 20° latitude. The average annual temperature is similar to the wet tropics, but the temperature range is greater. This climate zone receives less rain than the wet tropics, about 100 to 150 cm (40 to 60 inches). For more than two months each year, rainfall is less than 6 cm (2.4 inches). Wet and dry seasons are related to the location of the ITCZ. In the summer, when the ITCZ drifts northward, the zone is wet. In the winter, when the ITCZ moves back toward the equator, the region is dry. This climate exists where strong monsoon winds blow from land to sea, such as in India.

Rainforests cannot survive the months of low rainfall, so the typical vegetation is **savanna** (**Figure** 17.10). This biome consists mostly of grasses, with widely scattered deciduous trees and rare areas of denser forests. Central Africa is famous for its savanna and the unique animals that live there.

Figure 17.10: A male lion stalks the African savanna. (19)

Dry Climates (Group B)

The *Dry Climates* (Group B) generally have less precipitation than evaporation and are further from the equator than Tropical (Group A) climates. They have cooler winters and longer, harsher dry seasons. Rainfall is irregular; several years of drought are often followed by a single year of abundant rainfall. Summer temperatures are high, and much of the rain evaporates before it reaches the ground. Dry climate zones cover about 26% of the world's land area. Low latitude **deserts** form as a result of the Ferrell cell high pressure zone. Higher latitude deserts occur within continents or in rain shadows where the air has little humidity.

Arid Desert (Bw)

Low-latitude, arid deserts are found between 15° to 30° N and S latitudes. This is where warm dry air sinks at high pressure zones. True deserts make up around 12% of the world's lands. Deserts are found in southwestern North America, Africa, Australia and central Asia. Humidity is low, and as a result there are few clouds in the sky. The Sahara is the world's largest desert (**Figure** 17.11).

In the Sonora Desert of the southwestern United States and northern Mexico, most weather stations record sunshine 85% of the time, both in summer and winter (**Figure** 17.12). Clear skies allow the ground to heat rapidly during the day and cool rapidly at night. The summer

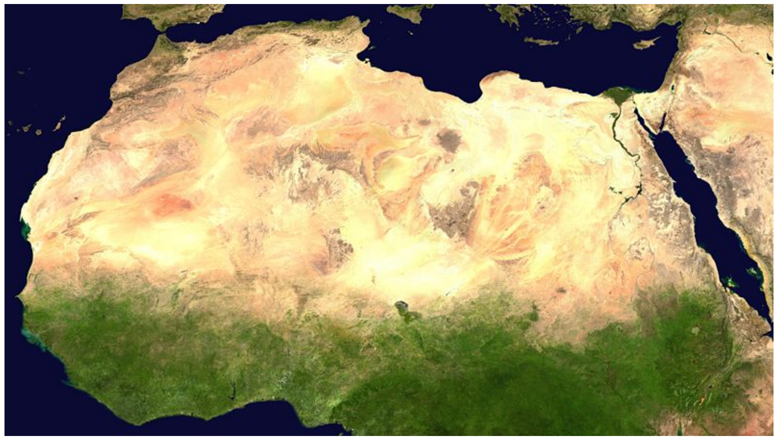

Figure 17.11: The Sahara desert takes up much of northern Africa. The green band below the sandy Sahara is the Congo. (10)

sun can be merciless and daytime temperatures are extremely hot. Temperatures often plunge when the Sun goes down and the daily temperature range may be 15° to 25°C (27° to 45°F). Annual rainfall is mostly less than 25 cm (10 inches). The Sonora desert gets much of its rain in the winter, when storms come in from the Pacific. Summer monsoon rains drop a great deal of rain in some areas. The existence of two wet seasons a year allows a unique group of plants and animals to survive in the southwestern deserts.

Vegetation is limited, since water is scarce. Desert plants are adapted to surviving long periods of drought. Cacti and shrubby plants have wide or deep roots to reach water after a rain. Many desert plants are able to store water. Some plants lie dormant as seeds, and bloom after rain falls.

Semi-arid or Steppe (Bs)

Deserts in continental interiors or in rain shadows are found at higher latitudes. Semi-arid deserts often receive more rain than the arid deserts, between 20 to 40 cm (8 to 16 inches) annually. Because land areas change temperature easily, these areas have lower annual average temperatures plus greater annual temperature ranges. In the winter, these climate zones get very cold under cold high pressure cells. In the summer, they heat up, allowing air to rise and rain to fall.

In the United States, the Great Plains, portions of the southern California coast and the Great Basin are semi-arid deserts. The biome is called **steppe**, which has short bunch grass, and scattered low bushes, or sagebrush (**Figure** 17.13). A steppe has few or no trees because there is not enough rain for trees to grow.

Figure 17.12: The Sonora desert is home to many well-adapted plants including cacti, scrubby bushes, and perennials. (14)

Figure 17.13: This photo of the Great Basin in Utah illustrates the steppe biome. (26)

Moist Subtropical Mid-latitude (Group C)

The *Moist Subtropical Mid-latitude* (Group C) climates are found along the coastal areas in the United States. Seasons are distinct, although winters are mild. The average temperature of the coldest month ranges from just below freezing to almost balmy, between -3°C and 18°C (27° to 64°F). Summers are often mild with average temperatures above 10°C (50°F). There is plentiful annual rainfall.

Dry Summer Subtropical or Mediterranean Climates (Cs)

The *Dry Summer Subtropical* climate is found on the western sides of continents between 30° and 45° latitude. Annual rainfall is 30 to 90 cm (14 to 35 inches), most of which comes in the winter. This climate is also called the *Mediterranean* climate because it is found around the Mediterranean Sea (**Figure** 17.14). The climate is also typical of coastal California, which sits beneath a summertime high pressure for about five months each year. Land and sea breezes make winters moderate and summers cool. The mild winters and foggy summers of San Francisco represent a coastal Mediterranean climate. Further inland in Sacramento, summer temperatures are much higher, representing an interior Mediterranean climate. Vegetation must survive long summer droughts. This vegetation type is called **chaparral**. Scrubby, woody plants and trees are common (**Figure** 17.15).

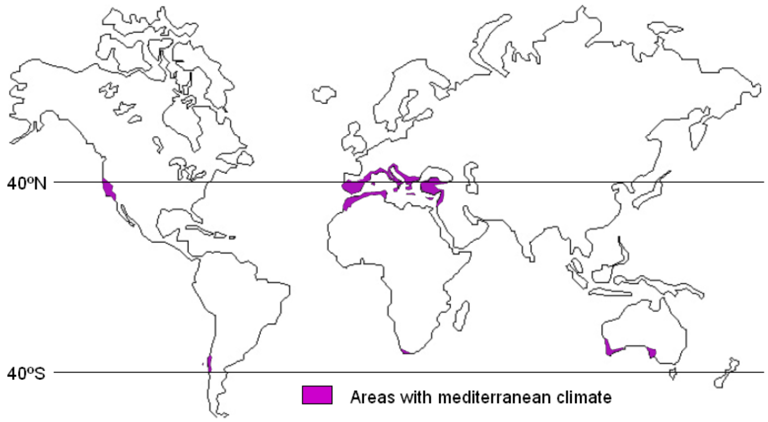

Figure 17.14: A map showing locations which have a Mediterranean climate. The areas around the Mediterranean Sea are the best representatives of this climate type. (25)

Figure 17.15: The scrubby plants that are typical of a Mediterranean climate. This photo is from southern France. (1)

Humid Subtropical (Cfa)

The *Humid Subtropical* climate zone is found mostly on the eastern sides of continents (**Figure** 17.16). Rain falls throughout the year with annual averages between 80 and 165 cm (31 and 65 inches). Summer days are humid and hot, from the lower 30's up to 40°C (mid-80's up to 104°F). Afternoon and evening thunderstorms are common. These conditions are due to warm tropical air passing over the hot continent. Winters are mild, but middle-latitude storms called cyclones may bring snow and rain. The southeastern United States, with its hot humid summers and mild, but frosty winters, is typical of this climate zone.

Figure 17.16: The humid subtropical climate zone is shown in green. (36)

Forests grow thickly in much of this region, due to the mild temperatures and high humidity. Pine forests are common in the lower latitudes, while oak are more common at higher latitudes (**Figure** 17.17).

Marine West Coast Climate (Cfb)

This climate lines western North America between 40° and 65° latitude, an area known as the Pacific Northwest (**Figure** 17.18). Ocean winds bring mild winters and cool summers. The temperature range between seasons and between day and night is fairly small. Rain falls year-round, although summers are drier as the jet stream moves northward. Low clouds, fog, and drizzle are typical. Snowfall is infrequent and short-lived. The mountain ranges that line the western U.S. keep this climate from extending far inland.

Dense forests of **Douglas fir** thrive in the heavy rain and mild temperatures (**Figure** 17.19). In Western Europe the climate covers a larger region since no high mountains are near the coast to block wind blowing off the Atlantic.

Continental Climates (Group D)

Continental (Group D) climates are found in most of the North American interior from about 40°N to 70°N. In this climate, summers are cool-to-warm and winters are very cold

Figure 17.17: Pine forests are common in the humid subtropical climate zone. (32)

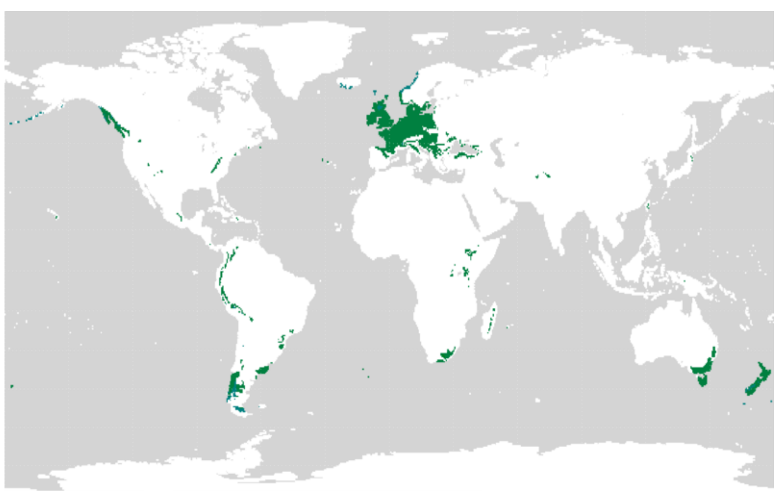

Figure 17.18: The west coast marine climate zone. (16)

Figure 17.19: A Douglas fir forest in the Pacific Northwest. (38)

and stormy. The average temperature of the warmest month is higher than 10°C (50°F) and the coldest month is below -3°C (-27°F). Snowfall is common and the cold temperatures mean that snow stays on the ground for long periods of time. Trees grow in continental climates, even though winters are extremely cold, because the average annual temperature is fairly mild. Continental climates are not found in the Southern Hemisphere due to the absence of a continent large enough to generate this effect.

Humid Continental (Dfa, Dfb)

Humid continental climates are found around the polar front at about 60°N latitude within continental North America and Europe (**Figure** 17.20). In the winter, middle-latitude cyclones bring chilly temperatures and snow. In the summer, westerly winds bring continental weather and warm temperatures. The average July temperature is often above 20°C (70°F). The region is typified by deciduous trees, which protect themselves in winter by losing their leaves.

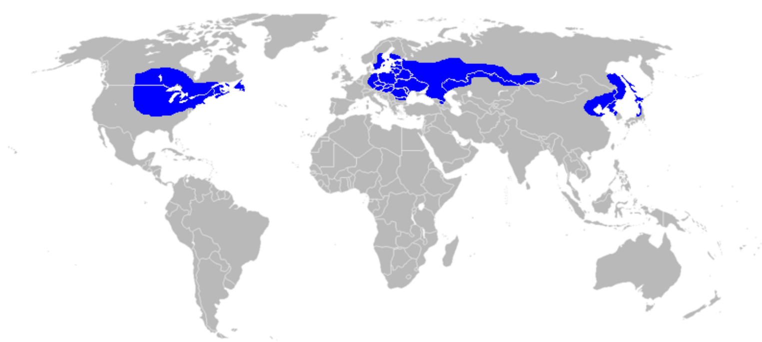

Figure 17.20: The humid continental climate zone covers much of the northeastern United States, southeastern Canada and middle Europe. (18)

The two variations of this climate are based on summer temperatures. In the humid continental climate with *long, hot summers* (Dfa), the long summers and high humidity foster plant growth (**Figure** 17.21). Summer days may be over 38°C (100°F), nights are warm and the temperature range is large, perhaps as great as 31°C (56°F)! In the humid continental climate with *long, cool summers* (Dfb), summertime temperatures and humidity are lower. Winter temperatures are below -18°C (0°F) for long periods. For example, Winnipeg, Canada has a 38°C (68°F) annual temperature range.

Subpolar (Dfc)

The *subpolar* climate is found between the humid continental and the polar tundra climates (**Figure** 17.22). This climate is dominated by long, very cold winters with very little precipitation. Continental polar air masses form when air stagnates in this zone. Snowfall is

Figure 17.21: Parts of South Korea lies in the humid continental climate zone. (28)

light, but temperatures are so cold that snowfall remains on the ground for months. Most of the approximately 50 cm (20 inches) of annual precipitation falls during summer cyclonic storms. The angle of the Sun's rays is low but the Sun is visible in the sky for most or all of the day, so temperatures may get warm, but are rarely hot. These continental regions have very high annual temperature ranges. The climate of Fairbanks, Alaska is a typical subarctic climate.

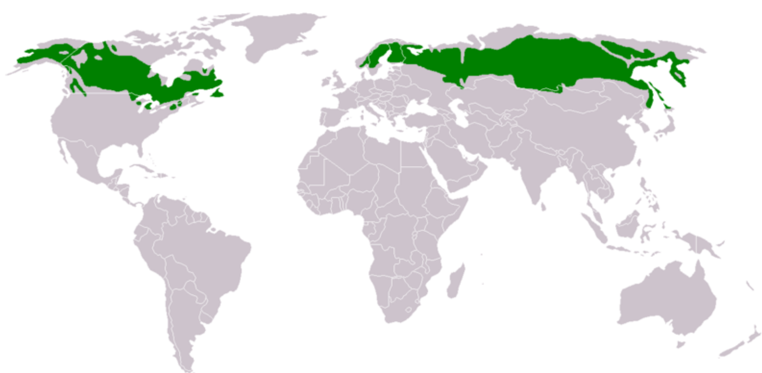

Figure 17.22: The location of the subpolar climate. (40)

The boreal coniferous forests of this climate are called **taiga** (**Figure** 17.23). These vast forests stretch across North America from western Alaska to Newfoundland, and across Eurasia from Norway to the Pacific coast.

Figure 17.23: The vast taiga is known for its small, hardy, and widely-spaced trees. This photo is of the Alaska Range in Alaska. (31)

Polar Climates (Group E)

In the polar regions, winters are entirely dark and bitterly cold. In the summer, days are long, but the sun is low on the horizon. Summers are cool with the average temperature of the warmest month at less than 10°C (50°F). Winters are extremely cold, so the annual temperature range is large. Polar climates receive less than 25 cm (10 inches) precipitation, mostly during the summer. This climate is found across the continents that border the Arctic Ocean, Greenland and Antarctica.

Polar Tundra (ET)

The *polar tundra* climate is continental, with severe winters (**Figure** 17.24). Temperatures are so cold that a layer of permanently frozen ground, called **permafrost** forms below the surface. This frozen layer can extend hundreds of meters deep. The average temperature of the warmest months is above freezing, so summer temperatures defrost the uppermost portion of the permafrost. In winter, the permafrost prevents water from draining downward. In summer, the ground is swampy. Although the precipitation is low enough in many places to qualify as a desert, evaporation rates are also low, so the landscape receives more usable water than a desert.

The only plants that can survive the harsh winters and soggy summers are small ground-hugging plants like mosses, lichens, small shrubs and scattered small trees that make up the **tundra** (**Figure** 17.25). Due to the lack of ice-free land near the South Pole, there is very little tundra in the Southern Hemisphere. The area surrounding the Arctic Ocean is the only part of the globe with much tundra.

Figure 17.24: Tundra loses its green in the fall, as mosses and leaves turn brown. (11)

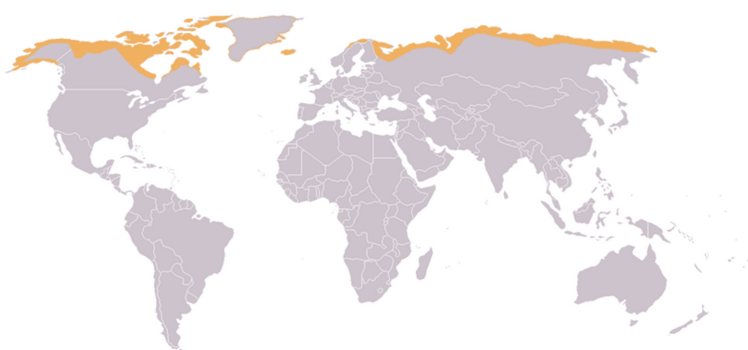

Figure 17.25: The tundra biome is shown in this map. (3)

Ice Cap

Ice caps are found mostly on Greenland and Antarctica, about 9% of the Earth's land area (**Figure** 17.26). Ice caps may be thousands of meters thick. Ice cap areas have extremely low average annual temperatures, e.g. -29°C (-20°F) at Eismitte, Greenland. Precipitation is low, since the air is too cold to hold much moisture. Snow occasionally falls in the summer.

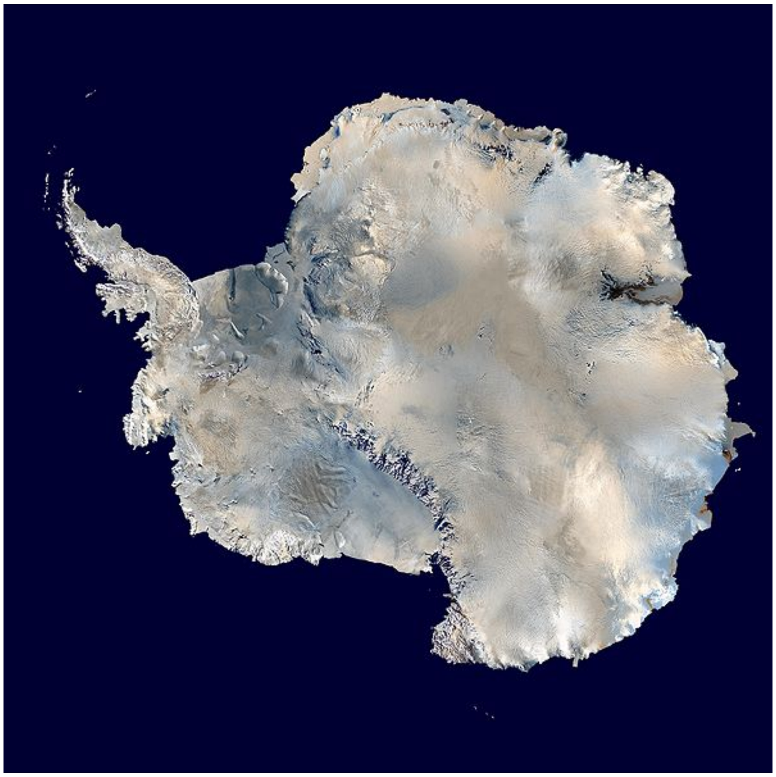

Figure 17.26: A composite satellite image of Antarctica. Almost all the continent is covered with an ice cap. (6)

Microclimates

When climate conditions in a small area are different from those of the surroundings, the climate of the small area is called a **microclimate.** The microclimate of a valley may be cool relative to its surroundings since cold air sinks. The ground surface may be hotter or colder than the air a few feet above it, since rock and soil gain and lose heat readily. Different sides of a mountain will have different microclimates. In the Northern Hemisphere, a south-facing slope receives more solar energy than a north-facing slope, and so each side supports different amounts and types of vegetation.

Altitude mimics latitude in climate zones. Climates and biomes typical of higher latitudes may be found in other areas of the world at high altitudes. Mt. Kilimanjaro in Africa lies near the equator in the tropics, but the top of the mountain is in the tundra biome and there is also a small glacier at the top.

Lesson Summary

- A climate zone depends on a region's latitude, continental position, and relationship to prevailing winds, large water bodies and mountains, among other factors.
- The temperature, rainfall, length of dry season, and other features of the climate zone determine which plants can grow.
- When living organisms develop in similar climates, they must adapt to that same environment. So the organisms in similar climate zones resemble each other, no matter how geographically distant they are. Because the organisms are so similar, a climate zone and its organisms make up a biome.

Review Questions

1. Why are most climate zones found in similar locations on continents within the Northern Hemisphere?
2. What are some reasons that climate zones differ between continents, even though locations are similar?
3. Why do organisms in the same biome often look the same even though they are not the same species? Think about desert plants, for example. Why are the plants that live in low latitude deserts on different continents so similar?
4. Why is the length of the dry season important in distinguishing different types of climate zones? Give an example.
5. Since the equator receives the most solar radiation over the course of a year, why are the hottest temperatures found in the low-latitude deserts? Why are low-latitude deserts often chilly at night, even in the summer?
6. What are the differences between arid and semi-arid deserts?
7. What conditions bring about the hot and humid summer days found in the American South?
8. What is the most important factor in determining the presence of a forest?
9. Look at **Figure 7** and see which major climate types are found in California (ignore the 3rd letter on each symbol). Look at a geographic map at the same time if you need to. Which climate type is the most common and where is it found? Which other two types of climates are found and where? Why does California have so many major climate types?
10. Polar regions receive little precipitation. Why are they not considered deserts?
11. What is permafrost? Does it stay the same year-round?
12. Why are microclimates important to living things?

Vocabulary

biodiversity The number of species of plants, animals and other organisms within a particular habitat.

biome The living organisms that are found within a climate zone that make that zone distinct, such as rainforests, arid deserts, tundra, and ice caps.

chaparral Scrubby woody plants and widely scattered trees typical of the Mediterranean climate.

desert Areas receiving very little precipitation, less than 25 cm (10") per year; found in arid climates; plants are infrequent.

Douglas fir A coniferous, evergreen tree found in enormous forests in western North America.

ice cap Permanent ice that is found mostly around Greenland and Antarctica.

permafrost Permanently frozen ground that is found in the polar regions, where temperatures do not rise above freezing most months.

rainforest The tropical wet biome where temperatures are warm and rain falls nearly every day.

savanna The tropical wet and dry biome, typified by grasses and widely scattered deciduous trees.

steppe The biome found in semi-arid deserts, typified by bunch grasses, scattered low bushes and sagebrush.

taiga Vast, boreal forests of small, more widely spaced trees that are typical of the subpolar climate.

tundra The treeless area of the arctic with very cold, harsh winters. The only polar climate that contains living organisms.

Points to Consider

- Why aren't biomes always determined by latitude? What geographic features or other factors affect the climate?
- Climate zones and biomes depend on many climate features. If climate changes, which of these features changes too?
- If global warming is increasing average global temperatures, how would you expect biomes to be affected?

17.3 Climate Change

Lesson Objectives

- Describe some ways that climate change has been an important part of Earth history.
- Discuss what factors can cause climate to change and which of these can be exacerbated by human activities.
- Discuss the consequences of rising greenhouse gas levels in the atmosphere, the impacts that are already being measured, and the impacts that are likely to occur in the future.

Introduction

For the past two centuries, climate has been relatively stable. People placed their farms and cities in locations that were in a favorable climate without thinking that the climate could change. But climate has changed throughout Earth history, and a stable climate is not the norm. In recent years, Earth's climate has begun to change again. Most of this change is warming due to human activities that release greenhouse gases into the atmosphere. The effects of warming are already being seen and will become more extreme as temperature rise.

Climate Change in Earth History

Climate has changed throughout Earth history. At times, the Earth's climate was hotter and more humid than it is today, but climate has also been colder than it is today, when glaciers covered much more of the planet. The most recent ice ages were in the Pleistocene Epoch, between 1.8 million and 10,000 years ago (**Figure** 17.27). Glaciers advanced and retreated in cycles, known as glacial and interglacial periods. With so much of the world's water bound into the ice, sea level was about 125 meters (395 feet) lower than it is today. We are currently in a warm, interglacial period that has lasted about 10,000 years.

It is likely that the average global temperature during glacial periods was only 5.5°C (10°F) less than Earth's current average temperature. Temperatures during the interglacial peri-

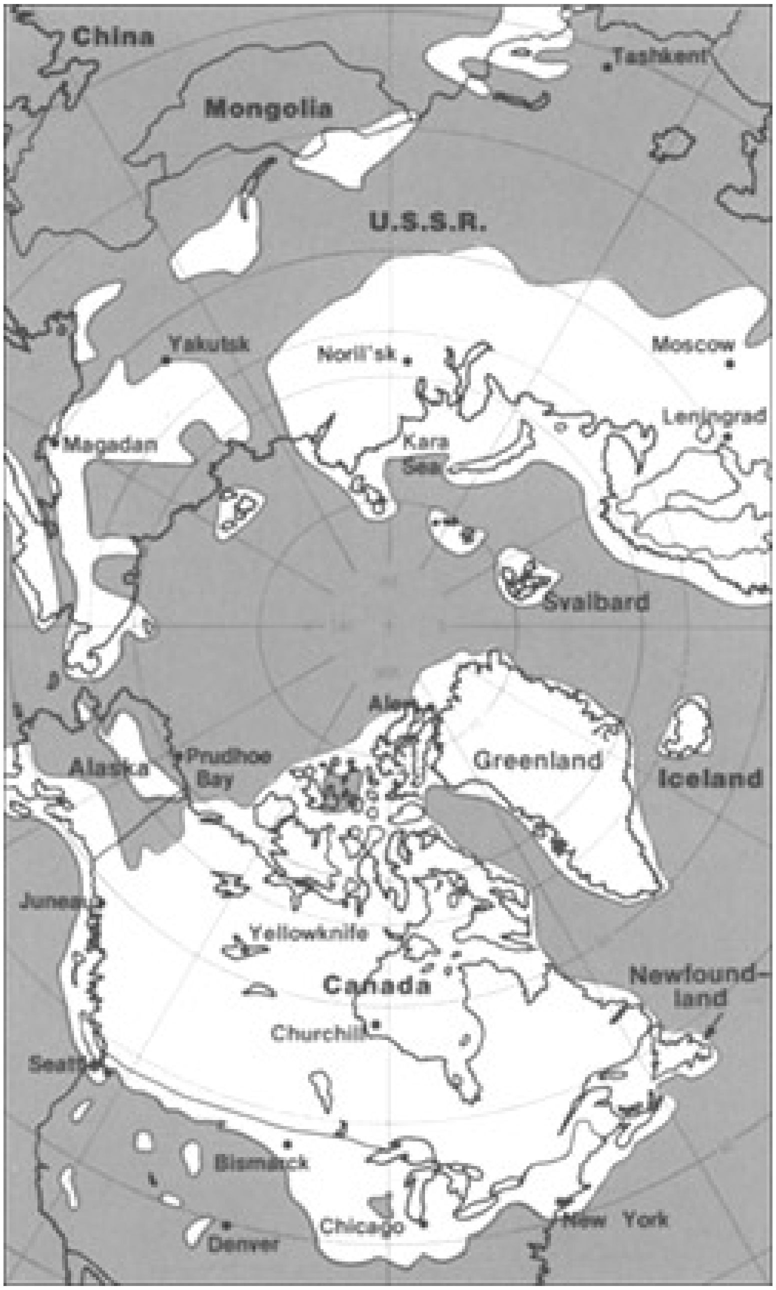

Figure 17.27: The maximum extent of glaciers in the Northern Hemisphere during the Pleistocene epoch. (39)

ods were about 1.1°C (2.0°F) higher than today (**Figure** 17.28). Notice that fairly small temperature changes can have major effects on global climate. Over the last 900,000 years, Earth's average temperature has varied less than 5 º C. Some scientists think that glaciers will advance again, but not for thousands of years.

Since the end of the Pleistocene, the global average temperature has risen about 4°C (7°F). Glaciers are retreating and sea level is rising. The climate has been relatively mild and stable when compared with much of Earth's history. Climate stability has been beneficial for human civilization. Stability has allowed the expansion of agriculture and the development of towns and cities. While climate is getting steadily warmer, there have been a few more extreme warm and cool times in the last 10,000 years. The Medieval Warm Period from 900 to 1300 A.D. allowed Vikings to colonize Greenland and Great Britain to grow wine grapes. When the climate cooled in the The Little Ice Age, from the 14^{th} to 19^{th} centuries, the Vikings were forced out of Greenland and humans had to plant crops further south.

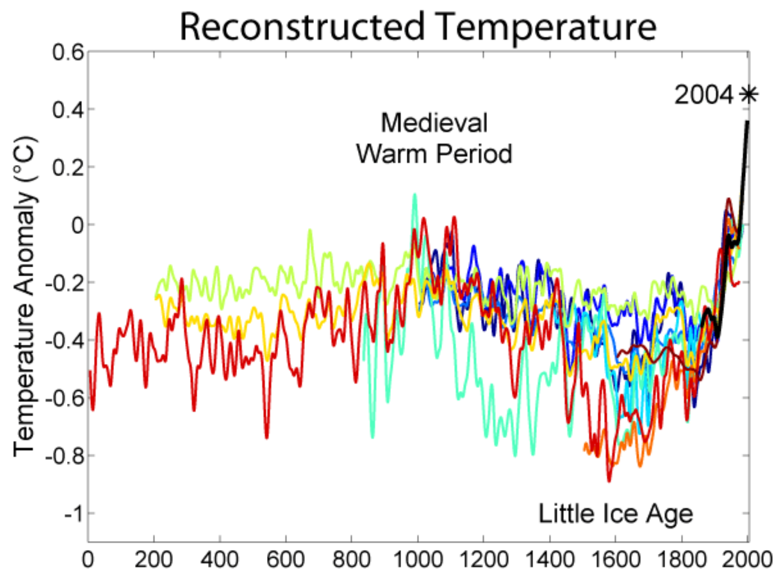

Figure 17.28: The graph is a compilation of 10 reconstructions (the colored lines) of mean temperature changes over the past 2,000 years, and one graph of instrumentally recorded data of mean temperature changes (black). This illustrates the high temperatures of the Medieval Warm Period, the lows of the Little Ice Age, and the very high (and climbing) temperature of this decade. (15)

Short-Term Climate Oscillations

Short-term changes in climate are common as conditions oscillate (or change) from one state to another (**Figure** 17.29). The largest and most important of these is the Southern Oscillation between **El Niño** and **La Niña** conditions. This oscillation drives changes in climate that are felt around the world about every two to seven years.

In a normal year, the trade winds blow across the Pacific Ocean near the equator from east to west (in the direction of Southeast Asia), piling up warm water in the western Pacific Ocean and actually raising sea levels there by half a meter. Meanwhile, along the western coast of South America, the Peru Current carries cold water northward, and cold, nutrient-rich waters upwell from the deep sea. When the Peru Current nears the equator, it flows westward across the Pacific Ocean with the trade winds.

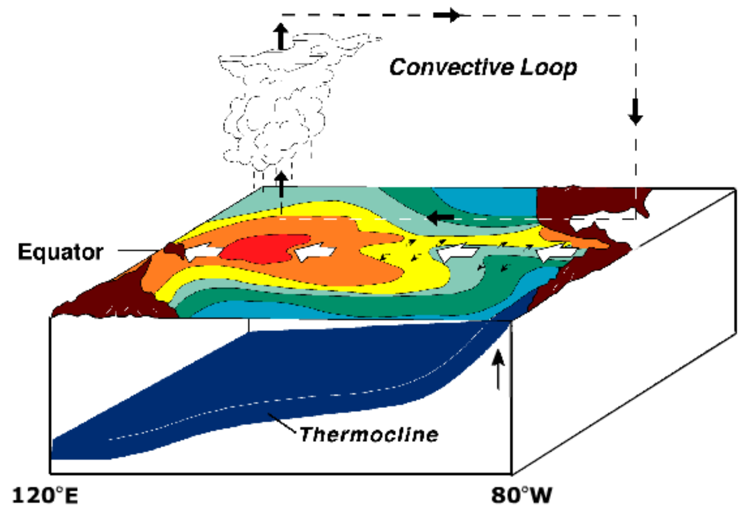

Figure 17.29: Normal conditions in the Southern Oscillation have a low pressure region in the western Pacific Ocean and warm water (shown in red) building up there as well. Notice that continents are shown in brown in the image. North and South America are on the right in this image. (2)

When water temperature reaches around 28°C (82°F), the trade winds weaken or reverse direction and blow east (towards South America). An El Niño cycle has begun (**Figure** 17.30). Warm water is dragged back across the Pacific Ocean, heating the central Pacific Ocean and the surface waters off the west coast of South America. With warm, low density water at the surface, no upwelling occurs along the coast of South America. Without upwelling, nutrients are scarce and plankton populations decline. Since plankton form the base of the food web, fish cannot find food, and fish numbers decrease as well. All the animals that eat fish, including birds and humans are affected by the decline in fish.

El Niño events change global climate when circulation patterns in the atmosphere and oceans change. Some regions receive more than average rainfall, including the west coast of North and South America; the southern United States; and Western Europe. Drought occurs in other parts of South America, the western Pacific, southern and northern Africa, and southern Europe.

An El Nino cycle lasts one to two years and ends when the warm mass of central Pacific water has moved eastward once more. Normal circulation patterns resume, but sometimes

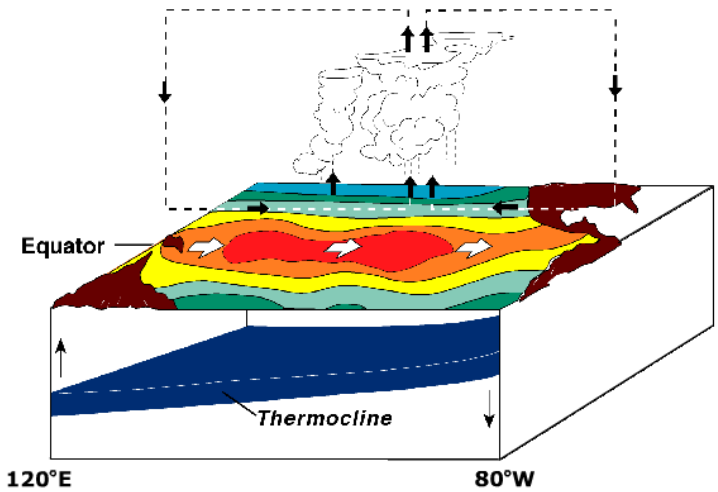

Figure 17.30: In El Niño conditions, the trade winds weaken or reverse directions. Warm water moves eastward across the Pacific Ocean and piles up against South America. (30)

they are quicker and more energetic. This pattern, with unusually cold water in the eastern Pacific Ocean, is called La Niña (**Figure** 17.31). El Niño events take place every three to seven years but vary in their strength.

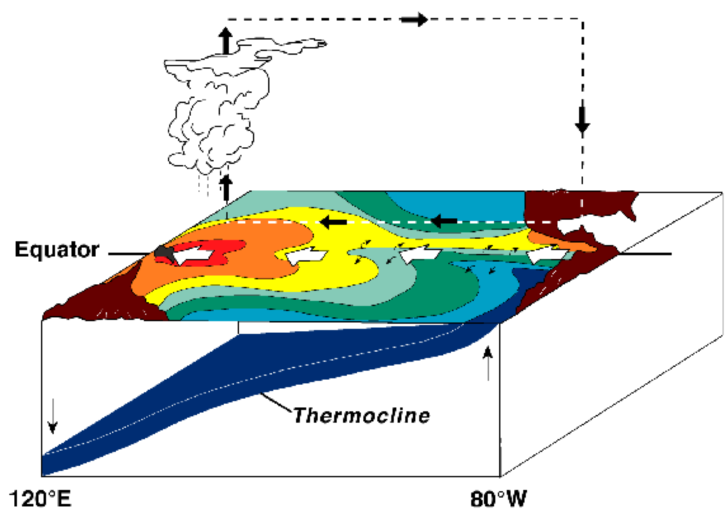

Figure 17.31: During a La Niña, ocean temperatures along the coast of South America are colder than normal (instead of warmer, as in El Niño) and cold water reaches farther into the western Pacific than normal. As in a normal year, trade winds moving from east to west and warm water piles up in the western Pacific Ocean. (20)

Other important oscillations are smaller and have a local, rather than global, effect. The

North Atlantic Oscillation mostly alters climate in Europe. The Mediterranean also goes through cycles, varying between being dry at some times, and warm and wet at others.

Causes of Climate Change

Many natural processes cause climate to change. There can be changes in the amount of energy the Sun produces. As Earth orbits the Sun, there are also changes over thousands of years in the tilt of Earth's axis and orbit. Over millions of years, the positions of our continents change, driven by plate tectonic motions. Random catastrophic events, like a large asteroid impact can cause sudden, dramatic changes in climate. Human activities have greatly increased the amount of greenhouse gases in the atmosphere, which impacts global climate by warming the Earth.

Solar Variation

The amount of energy the Sun radiates is variable. **Sunspots** are magnetic storms on the Sun's surface that increase and decrease over an 11-year cycle (**Figure** 17.32). When the number of sunspots is high, solar radiation is also relatively high. But the entire variation in solar radiation is tiny relative to the total amount of solar radiation that there is and there is no known 11-year cycle in climate variability. The Little Ice Age corresponded to a time when there were no sunspots on the Sun.

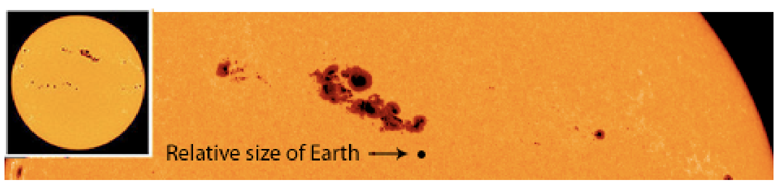

Figure 17.32: Sunspots on the face of the Sun. (33)

Plate Tectonics

Plate tectonic movements can alter climate. Over millions of years as seas open and close, ocean currents may distribute heat differently. For example, when all the continents are joined into one supercontinent (like Pangea), nearly all locations experience a continental climate. When the continents separate, heat is more evenly distributed. Plate tectonic movements may help start an ice age. When continents are located near the poles, ice can accumulate, which may increase albedo and lower global temperature. Low enough temperatures may start a global ice age.

Plate tectonics also triggers volcanic eruptions, which release dust and CO_2 into the atmosphere. Ordinary eruptions, even large ones, have only a short-term effect on weather. Ash from the 1991 eruption of Mount Pinatubo in the Philippines cooled global temperature by around 0.5°C (0.9°F) for a year. Massive eruptions of a fluid type of lava can flood the surface, releasing much more gas and dust, changing climate for many years. This type of eruption is exceedingly rare; none has occurred since humans have lived on Earth.

Asteroid Impacts

If a large **asteroid** hits the Earth, it may trigger a **mass extinction**. This likely happened at the end of the Cretaceous period, around 65 million years ago. An asteroid 10 kilometers (6 miles) in diameter struck the Yucatan Peninsula in southeastern Mexico. About 85% of all species present on Earth at that time became extinct, including the dinosaurs. Dust that was kicked high into the atmosphere came together as rocks and fell to the ground. The organisms that survived had to endure extreme cold, as dust blocked the Sun for many years. Photosynthesis slowed down and the planet cooled to levels that were intolerable for many species.

Milankovitch Cycles

The most extreme climate of recent Earth history was the Pleistocene. Scientists attribute a series of ice ages to variation in the Earth's position relative to the Sun, known as **Milankovitch cycles.**

The Earth goes through regular variations in its position relative to the Sun:

1. The shape of the Earth's orbit changes slightly as it goes around the Sun. Our orbit varies from more circular to more elliptical in a cycle lasting between 90,000 and 100,000 years. When the orbit is more elliptical, there is a greater difference in solar radiation between winter and summer.
2. The planet wobbles on its axis of rotation. At one extreme of this 27,000 year cycle, the Northern Hemisphere points toward the Sun, when the Earth is closest to the Sun. Summers are much warmer and winters are much colder than now. At the opposite extreme, the Northern Hemisphere points toward the Sun when it is farthest from the Sun. This results in chilly summers and warmer winters.
3. The planet's tilt on its axis varies between 22.1° and 24.5°. Seasons are caused by the tilt of Earth's axis of rotation, which is at a 23.5° angle now. When the tilt angle is smaller, summers and winters differ less in temperature. This cycle lasts 41,000 years.

When these three variations are charted out, a climate pattern of about 100,000 years emerges. Ice ages correspond closely with Milankovitch cycles. Since glaciers can only form over land, ice ages only occur when landmasses cover the polar regions. Therefore, Milankovitch cycles are also connected to plate tectonics.

Rising Atmospheric Greenhouse Gases

Greenhouse gases in the atmosphere trap the heat that radiates off the planet's surfaces. Therefore, a decrease in greenhouse gas levels lowers the average air temperature. An increase in greenhouse gases raises air temperature. Greenhouse gas levels have varied throughout Earth history. For example, CO_2 been present in Earth's atmosphere at concentrations less than 200 parts per million (ppm) and more than 5,000 ppm. But for 650,000 years or more, CO_2 has never risen above 300 ppm, during either glacial or interglacial periods. CO_2 levels are higher during interglacial than glacial periods (**Figure** 17.33).

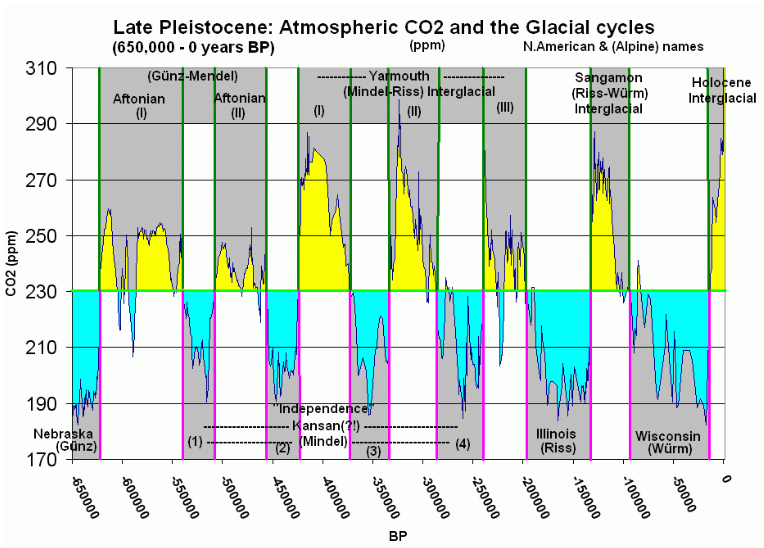

Figure 17.33: CO_2 is high during interglacial periods, when temperatures are high. CO_2 is low during glacial periods, when temperatures are low. BP means years before present. Glacial periods are shown in blue and interglacial periods are shown in yellow. Current carbon dioxide levels are at 387 ppm, the highest level for the last 650,000 years. (4)

Greenhouse gases are added to the atmosphere by natural processes, like volcanic eruptions, and the decay or burning of organic matter. Greenhouse gases are also removed from the atmosphere when CO_2 is absorbed by plant tissue. When plants die and are turned into fossil fuels - coal, oil, natural gas - deep in the Earth, the CO_2 they hold is stored with them. Storing CO_2 in the ground removes the greenhouse gas from the atmosphere, lowering Earth's average temperature.

Human activities are now releasing much of this stored CO_2 into the atmosphere. Although people have been burning wood and coal to meet their energy needs for hundreds of thousands of years, fossil fuel usage has increased dramatically in the past 200 years, since the Industrial Revolution. Fossil fuel use has skyrocketed in the past few decades as population has grown, and there are more and more cars, homes, and industries to power. Burning rainforests, to clear land for agriculture prevents the growing trees from removing CO_2 from the atmosphere and releases all the CO_2 stored in rainforest trees. With more people to feed, the destruction of rain forests has increased.

CO_2 is the most important greenhouse gas that human activities affect. And, after water vapor, CO_2 is the most abundant. But other greenhouse gases are increasing as well. Methane is released from raising livestock, rice production, and the incomplete burning of rainforest plants. Chlorofluorocarbons (CFC's) are human-made chemicals that were invented and used widely in the 20th century. Tropospheric ozone, mostly from vehicle exhaust, has more than doubled since 1976. All of these gases act as greenhouse gases as well as CO_2.

Global Warming

With more greenhouse gases trapping heat, average annual global temperatures are rising. This is known as **global warming.** There is now nearly 40% more CO_2 in the atmosphere than there was 200 years ago, before the Industrial Revolution. About 65% of that increase has occurred since the first CO_2 measurements were made on Mauna Loa Volcano, Hawaii in 1958 (**Figure** 17.34).

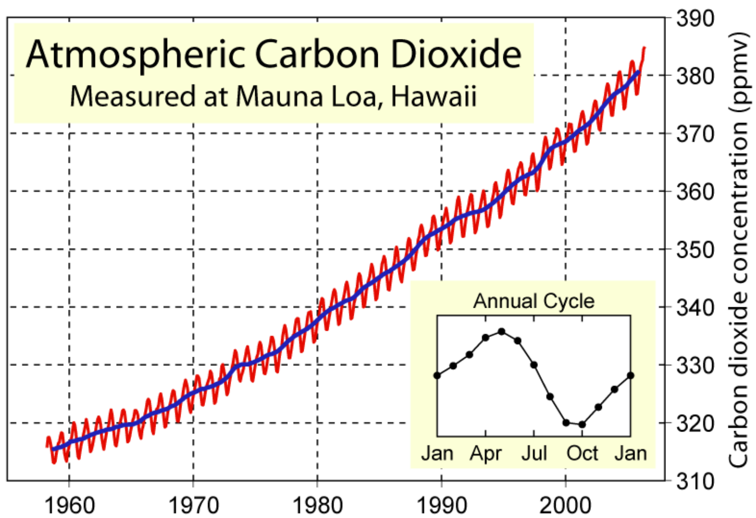

Figure 17.34: The Keeling Curve shows the upward trend in atmospheric CO_2 on Mauna Loa volcano since measurements began in 1958. The blue line shows yearly averaged CO_2. The red line shows seasonal variations in CO_2. (22)

The United States has been the largest emitter of greenhouse gases, with about 20% of total emissions in 2004 (**Figure** 17.35). China has been the second highest emitter (18.4%), followed by the European Union (11.4%). As a result of China's rapid economic growth, in early 2008 its CO_2 emissions probably surpassed those of the United States. However, it's also important to keep in mind that the US has only about 1/5 the population of China. Therefore, the average US citizen produces far more greenhouse gases than the average

Chinese person. If nothing is done to decrease the rate of CO_2 emissions, by 2030, CO_2 emissions are projected to be 63% greater than they were in 2002.

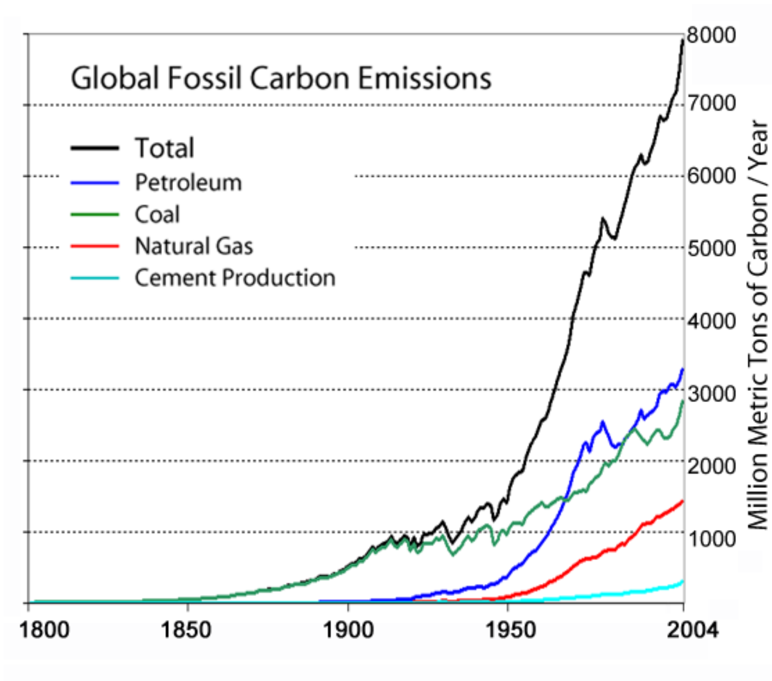

Figure 17.35: Global CO_2 emissions are rising rapidly. The industrial revolution began about 1850 and industrialization has been accelerating. (9)

How much CO_2 levels will rise in the next decades is unknown. It depends on how much CO_2emissions in developing nations increase. It also depends on how much technological advances or lifestyle changes increase or decrease emissions in developed nations. If nothing is done to control greenhouse gas emissions and they continue to increase at current rates, the surface temperature of the Earth can be expected to increase between 0.5°C and 2.0°C (0.9°F and 3.6°F) by 2050 and between 2° and 4.5°C (3.5° and 8°F) by 2100, with CO_2 levels over 800 parts per million (ppm)(**Figure** 17.36). On the other hand, if severe limits on CO_2 emissions begin soon, temperatures could rise less than 1.1°C (2°F) by 2100. Whatever the temperature increase, it will not be uniform around the globe. A rise of 2.8°C (5°F) would result in 0.6° to 1.2°C (1° to 2°F) at the equator, but up to 6.7°C (12°F) at the poles. So far, global warming has affected the North Pole more than the South Pole.

Changes in the Earth and organisms as a result of global warming are already being observed. While temperatures have risen since the end of the Pleistocene, 10,000 years ago, this rate of increase had been more rapid in the past century, and has even risen even faster since 1990. The eight warmest years on record have all occurred since 1998, and the 14 warmest years have occurred since 1990 (through 2007) (**Figure** 17.37).

As a result of these high temperatures, glaciers are melting and ice caps are breaking apart at

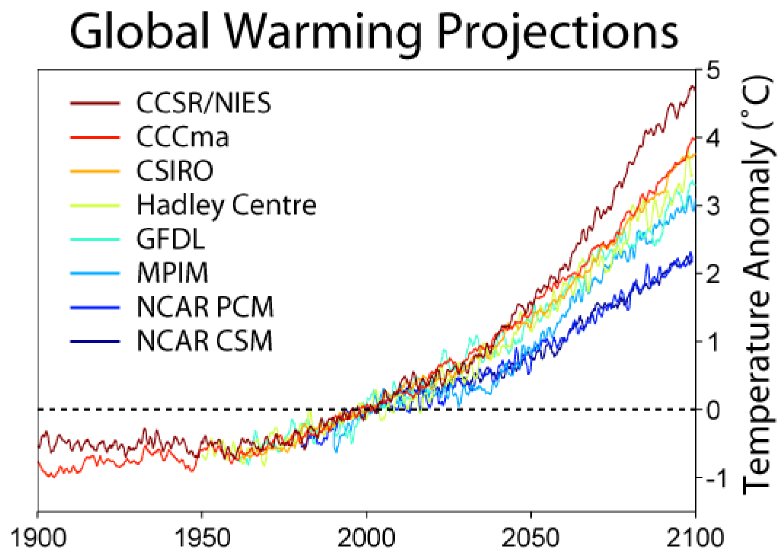

Figure 17.36: Various climate prediction models show how temperature is likely to rise by 2100. (24)

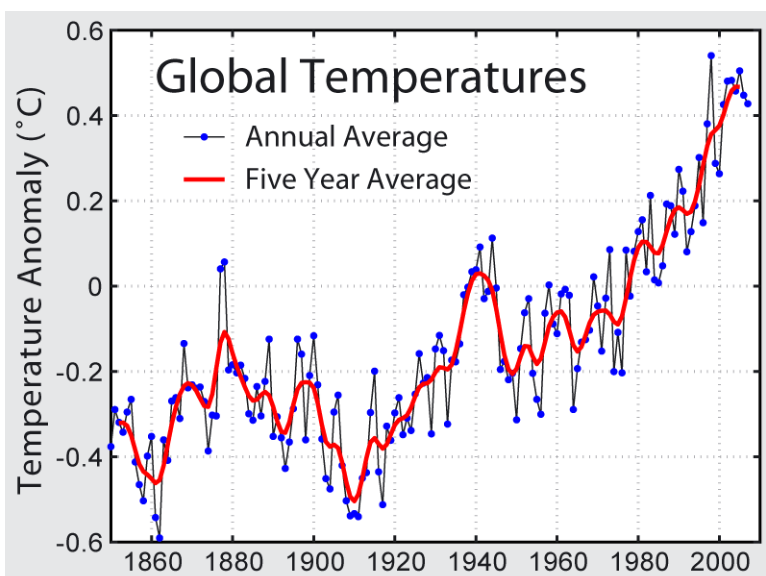

Figure 17.37: Recent temperature increases show how much temperature has risen since the Industrial Revolution began. (37)

the edges (**Figure** 17.38). Permafrost is melting, causing swamps in locations that were once frozen solid. Melting ice caps add water to the oceans, so sea level is rising (**Figure** 17.39). Also contributing to sea level rise is that water slightly expands as it warms — this expansion of water accounts for about one-quarter to one-half of the observed sea level change. Since warmer air can hold more moisture, storms are becoming more intense. Weather is therefore likely to be more severe with more heat waves and droughts. More rainfall sometimes results in increased flooding.

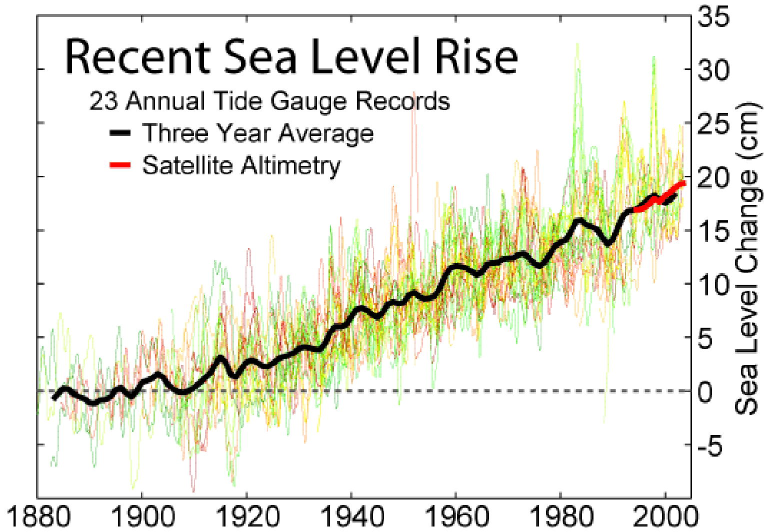

Figure 17.38: Sea level has been rising in recent decades. Twenty-three different geologically stable tide gauge sites with long-term records are represented here. (27)

Plants and animals are feeling the effects of the changing climate. Winters are shorter so some animals are changing their seasonal behaviors: migrating earlier in the spring, for example. Coral reefs are dying worldwide due in part to the increase in surface ocean temperatures. Forests are also dying in some places because warm weather has allowed insect pests to expand their ranges into areas that were once too cold. As surface seas warm, phytoplankton productivity has decreased. Some regions that were already marginal for agriculture are no longer farmable, because they have become too warm or dry.

As greenhouse gases increase, changes will be more extreme. Oceans will become slightly more acidic, making it more difficult for creatures with carbonate shells to grow, including coral reefs. A studying monitoring ocean acidity in the Pacific Northwest found ocean acidity increasing ten times faster than expected and 10 to 20 percent of shellfish (mussels) replaced by acid tolerant algae.

Plant and animal species seeking cooler temperatures will need to move poleward 100 to 150 km (60 to 90 miles) or upward 150 m (500 feet) for each 1.0°C (8°F) rise in global temperature. There will be a tremendous loss of biodiversity because forest species can't migrate that rapidly. Even if they could, human development would block their spread

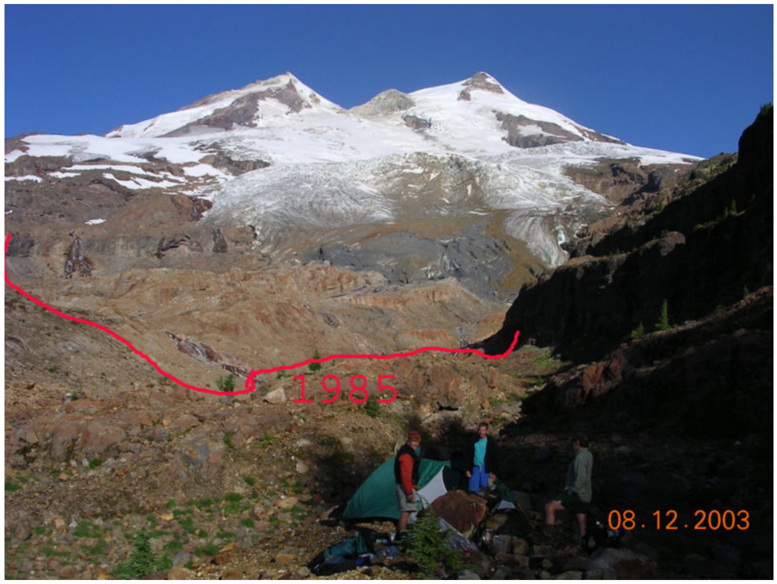

Figure 17.39: The Boulder Glacier has melted back tremendously since 1985. Other mountain glaciers around the world are also melting. (23)

and stop them from colonizing many new areas. Parks and wildlife refuges might be left protecting nothing. And biologists have already documented the extinction of high altitude species that have nowhere higher to go.

Decreased snowpacks, shrinking glaciers, and the earlier arrival of spring will all lessen the amount of water available in some regions of the world, including the western United States and much of Asia. Ice will continue to melt and sea level is predicted to rise 18 to 97 cm (7 to 38 inches) by 2100 (**Figure** 17.40). An increase this large will gradually flood coastal regions where about one-third of the world's population lives, forcing billions of people to move inland.

There will be more severe heat waves and heat-related illnesses and deaths. Drought could make many marginal regions uninhabitable. Some modelers predict that the Midwestern United States will become too dry to support agriculture and the areas that currently produce our best agriculture would move into Canada. In all, about 10 to 50% of current cropland worldwide may become unusable if CO_2 doubles.

Although scientists do not all agree, hurricanes are likely to become more severe and possibly more frequent. Hurricanes cause a tremendous loss of life in developing nations and a loss of property in developed ones. Tropical and subtropical insects will expand their ranges. This will result in the spread of tropical diseases such as malaria, encephalitis, yellow fever, and dengue fever.

You may notice that the numerical predictions above contain wide ranges. Sea level, for example is expected to rise somewhere between 18 and 97 cm — quite a wide range. This

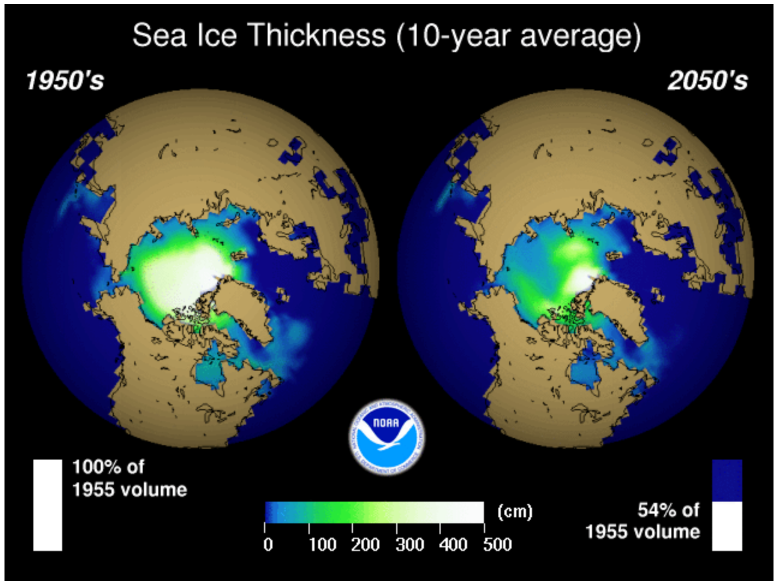

Figure 17.40: Sea ice thickness around the North Pole has been decreasing in recent decades and will continue to decrease in the coming decades. (13)

uncertainty is partly because scientists cannot predict exactly how the Earth will respond to increased levels of greenhouses gases. How quickly greenhouse gases continue to build up in the atmosphere depends in part on the choices we make.

Lesson Summary

- Climate has changed throughout Earth history. In general, when greenhouse gas levels are high, temperature is high.
- Greenhouse gases are now increasing due to human activities, especially fossil fuel use.
- We are already seeing the effects of these rising greenhouse gases in higher temperatures and changes to physical and biological systems.
- Society must choose to reduce greenhouse gas emissions or face more serious consequences.

Review Questions

1. Why is the climate currently warming?
2. Why does sea level rise and fall during interglacial and glacial periods?
3. How can the human history of Greenland be related to climate cycles?
4. Why did human civilization not develop significantly until the Pleistocene ended?
5. If climate has been much warmer in Earth history, why do we need to worry about global warming now?

6. When the weather along coastal California is especially rainy with many winter storms, what is likely to be happening in the equatorial Pacific in terms of the Southern Oscillation?
7. The Peruvian anchovy fishery collapsed in 1972. Using what you know about climate and food webs, can you devise an explanation for this event?
8. What two events must occur for there to be an ice age?
9. What human activities are responsible for increasing greenhouse gases in the atmosphere?
10. Why are CO_2 emissions projected to increase by so much during the next few decades?
11. What role do the developed nations play a role in increasing CO_2 emissions in the next few decades?
12. Why do storms increase in frequency and intensity as global temperatures increase?
13. Earth is undergoing some important changes, some of which are known about and monitored by satellites. Describe the sort of global change that satellites can monitor.
14. What will happen if sea level rises by 60 cm (2 feet0 by the end of this century? Which locations will be hardest hit?
15. What can be done to reduce greenhouse gas emissions?

Vocabulary

asteroid A chunk of rock or ice that moves through the solar system.

El Niño Part of the Southern Oscillation in which the trade winds weaken or reverse directions, and warm water accumulates on the ocean surface off of South America.

global warming The global increase in average global temperature that has been taking place due to human activities.

La Niña Part of the Southern Oscillation in which the trade winds are stronger than normal and surface water off of South America is cold

mass extinction An extinction in which 25% or more of the planet's species die out in a fairly short period of time.

Milankovitch cycles Cycles in Earth's position relative to the sun that affect global climate, resulting in a cycle of around 100,000 years.

Southern Oscillation A reversal of normal atmospheric low and high pressure conditions in the Pacific Ocean.

sunspot Sunspots are magnetic solar storms on the sun that cause solar radiation to decrease slightly. Sunspots come and go over an 11-year cycle.

Points to Consider

- Nearly all climate scientists agree that human activities are causing the accelerated warming of the planet that we see today. Why do you suppose that the media is still talking about the controversy in this idea when scientists are almost entirely in agreement?
- If greenhouse gas emissions must be lowered to avoid some of the more serious consequences of global warming, why have humans not done something to lower these emissions instead of letting them increase?
- In what ways can progress be made in reducing greenhouse gas emissions? Think about this on a variety of scales: for individuals, local communities, nations, and the global community.

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Chapter 18

Ecosystems and Human Populations

18.1 Ecosystems

Lesson Objectives

- Discuss the importance of chemical and physical factors to living organisms.
- Describe the role of different species in an ecosystem.
- Describe the function of an ecosystem, and how different species fill different roles in different ecosystems.
- Describe energy transfer from the lowest to the highest trophic level in a chain, including energy loss at every trophic level.
- Discuss how materials are cycled between trophic levels and how they can enter or leave a food web at any time.

Introduction

An ecosystem is made up of the living creatures and the nonliving things that those creatures need within an area. Energy moves through an ecosystem in one direction. Nutrients cycle through different parts of the ecosystem and can enter or leave the ecosystem at many points.

Biological Communities

A **population** consists of all individuals of a single species that occur together at a given place and time. A **species** is a single type of organisms that can interbreed and produce fertile offspring. All of the populations living together in the same area make up a **community.** An **ecosystem** is all of the living things in a community and the physical and chemical factors that they interact with. The living organisms within an ecosystem are its

biotic factors. Living things include bacteria, algae, fungi, plants (**Figure** 18.1) and animals, including **invertebrates** (**Figure** 18.2), animals without backbones and **vertebrates** (**Figure** 18.3), animals with backbones.

Figure 18.1: The horsetail *Equisetum* is a primitive plant. (16)

Physical and chemical features are **abiotic** factors. Abiotic factors include resources living organisms need like light, oxygen, water, carbon dioxide, good soil, and nitrogen, phosphorous and other nutrients. Abiotic factors also include environmental features that are not materials or living things, like living space and the right temperature range.

Organisms must make a living, just like a lawyer or a ballet dancer. This means that each individual organism must acquire enough food energy to live and hopefully reproduce. A species' way of making a living is called its **niche**. An example of a niche is making a living as a top carnivore, an animal that eats other animals, but is not eaten by any other animals. This niche can be filled by a lion in a savanna, a wolf in the tundra, or a tuna in the oceans.

Figure 18.2: Insects are among the many different types of invertebrates. (25)

Every species fills a niche, and niches are almost always filled in an ecosystem.

An organism's **habitat** is where it lives. The important characteristics of a habitat include climate, the availability of food, water and other resources, and other factors, such as weather. A habitat may be a hole in a cactus or the underside of a fern in a rainforest. It may be a large area of savanna.

Roles in Ecosystems

There are many different types of ecosystems (**Figure** 18.4). A few examples of some ecosystems are a rainforest, chaparral, tundra, and desert. These words are the same words used for biomes. This is because climate conditions determine which ecosystems are found in which location. A particular biome encompasses all of the ecosystems that have similar climate and organisms.

Different organisms live in each different type of ecosystems. Lizards thrive in deserts, but no reptiles can survive at all in polar ecosystems. Large animals generally do better in cold climates than in hot climates. Despite this, every ecosystem has the same general roles that living creatures fill. It's just the organisms that fill those niches that are different. For example, every ecosystem must have some organisms that produce food in the form of chemical energy. These organisms are primarily algae in the oceans, plants on land, and bacteria at deep sea hot springs.

The organisms that produce food are extremely important in every ecosystem. The most fundamental distinction between types of organisms is whether they are able to produce their own energy or not. Organisms that produce their own food are called **producers**. In contrast, organisms that use the food energy that was created by producers are named

Figure 18.3: A giraffe is an example of a vertebrate. (11)

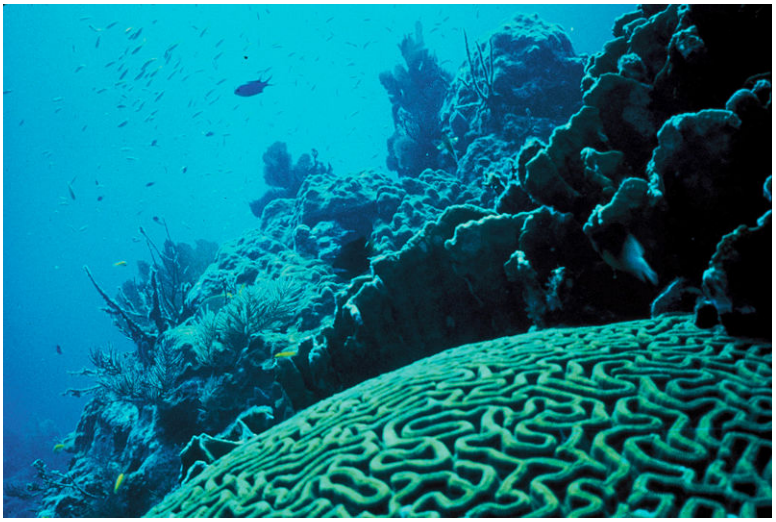


Figure 18.4: Coral reefs are complex and beautiful ecosystems. (6)

consumers.

There are two types of producers. Nearly all producers take energy from the Sun and make it into chemical energy (food) by the process of **photosynthesis**. Photosynthesizing organisms use carbon dioxide (CO_2) and water (H_2O) to produce sugar ($C_6H_{12}O_6$) and oxygen (O_2). This food can be used immediately or stored for future use.

A tiny group of producers create usable chemical energy from chemicals, without using any sunlight. At the bottom of the ocean, at deep-sea hot springs known as hydrothermal vents, a few types of bacteria break down chemicals to produce food energy. This process is called **chemosynthesis** (**Figure** 18.5).

There are many types of consumers. **Herbivores** eat producers directly (**Figure** 18.6). These animals break down the plant structures to get the materials and energy they need. Many other consumers eat animals. These are known as **carnivores**. Carnivores can eat herbivores or they can eat other carnivores. **Omnivores** eat plants and animals, as well as fungi, bacteria and organisms from the other kingdoms.

There are many types of feeding relationships between organisms. A **predator** is an animal that kills and eats another animal (**Figure** 18.7). The animal it kills is its **prey.**

Scavengers are animals that eat organisms that are already dead. Vultures and hyenas are just two types of scavengers. **Decomposers** break apart dead organisms or the waste material of living organisms, returning the nutrients to the ecosystem. Many decomposers are bacteria, but there are others as well, including fungi (**Figure** 18.8). Decomposers are recyclers; they make nutrients from dead organisms available for living organisms.

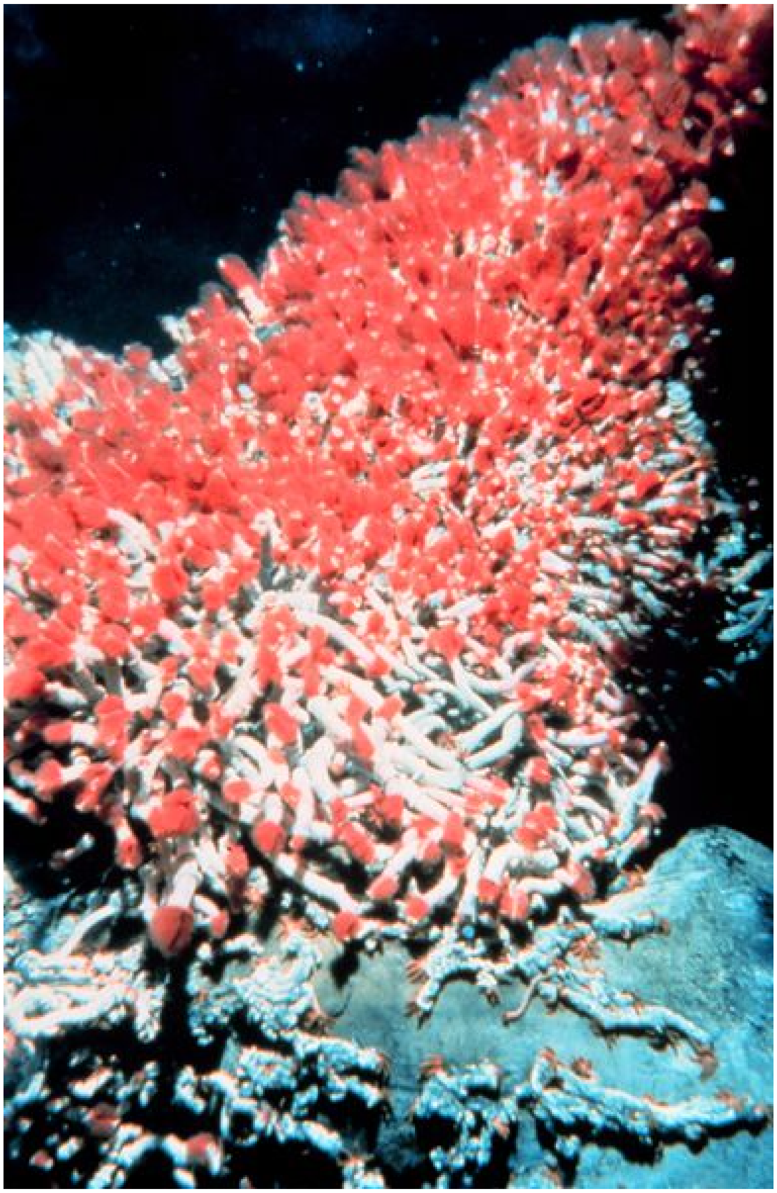


Figure 18.5: Tube worms have a symbiotic relationship with chemosynthetic bacteria. The bacteria provide the worms with food and the worm tubes provide the bacteria with shelter. (7)

Figure 18.6: Deer are herbivores. (19)

Figure 18.7: This South China Tiger is a predator. (22)

Figure 18.8: Fungi are decomposing this tree. (14)

Flow of Energy in Ecosystems

Energy cannot be created or destroyed. Energy can only be changed from one form to another. This is such a fundamental law in nature that it has its own name: **The Law of Conservation of Energy**. Plants do not create chemical energy from nothing. Instead, they create chemical energy from abiotic factors that include sunlight. So they transform solar energy into chemical energy. Organisms that use chemosynthesis start with chemical energy to create usable chemical energy. After the producers create the food energy, it is then passed on to consumers, scavengers, and decomposers.

Energy flows through an ecosystem in only one direction. Energy enters the ecosystem with the producers. In nearly all ecosystems, sunlight is the original energy source. This energy is passed from organisms at one **trophic level** or energy level, to organisms in the next trophic level. Producers are always the first trophic level, herbivores the second, the carnivores that eat herbivores the third, and so on.

An average of 90% of the energy that reaches a trophic level is used to power the organisms at that trophic level. They need it for locomotion, heating themselves, and reproduction. So animals at the second trophic level have only about 10% as much energy available to them as do organisms at the first trophic level. They use about 90% of what they receive, and so those at the third level have only 10% as much available to them as those at the second level. This 10% rule continues up the trophic levels, so much less energy is available at the next higher trophic level in an ecosystem.

The set of organisms that pass energy from one trophic level to the next is described as the **food chain** (**Figure** 18.9). In this simple depiction, all organisms eat at only one trophic level. Animals at the 3rd trophic level only eat from the 2nd trophic level and those at the 2nd eat only from the 1st. But many omnivores feed at more than one trophic level, with plants and animals in their diets.

Since only 10% of the energy is passed up the food chain, each level can support fewer organisms. A top predator, like a jaguar, must have a very large range in which to hunt so that it can get enough energy to live. Top carnivores are quite rare relative to herbivores for this reason. The result of this is that the number of organisms at each trophic level looks like a pyramid. There are many more organisms at the base of the pyramid, at the lower trophic levels than at the top of the pyramid, the higher trophic levels.

Food chains usually have only four or five trophic levels because there is not enough energy to support organisms in a sixth trophic level. Food chains of ocean animals are longer than those of land-based animals because ocean conditions are more stable. Organisms at higher trophic levels also tend to be larger than those at lower levels. The reason for this is simple: a whale must be able to eat a plankton, but the plankton does not have to be able to eat the whale. Sometimes multiple smaller predators will act together to take down a larger prey, so the organisms at the higher level are smaller than those at the lower level. This is true of a pack of wolves, which acts together as one to hunt a moose.

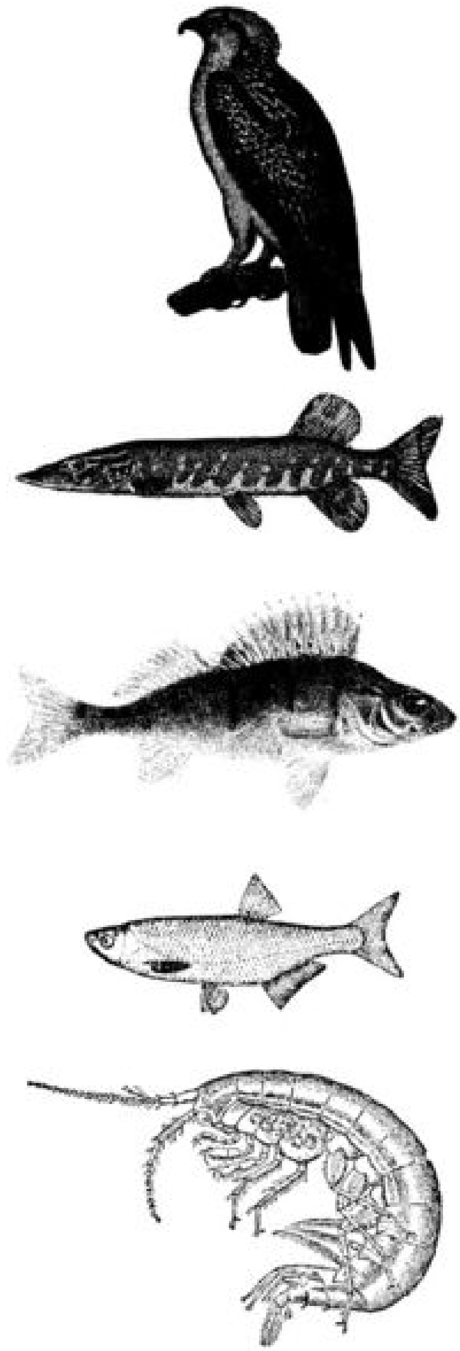


Figure 18.9: A simple food chain from a Swedish lake. Not pictured: algae eaten by the shrimp; Shrimp are eaten by a small fish, a bleak, which is eaten by a perch, which is eaten by a northern pike, which is eaten by an osprey. (17)

Since some organisms feed at more than one trophic level, the food chain does not adequately describe the passage of energy in an ecosystem. The more accurate representation is a **food web** (**Figure** 18.10). A food web recognizes that many organisms eat at multiple trophic levels. A food web includes the relationships between producers, consumers and decomposers.

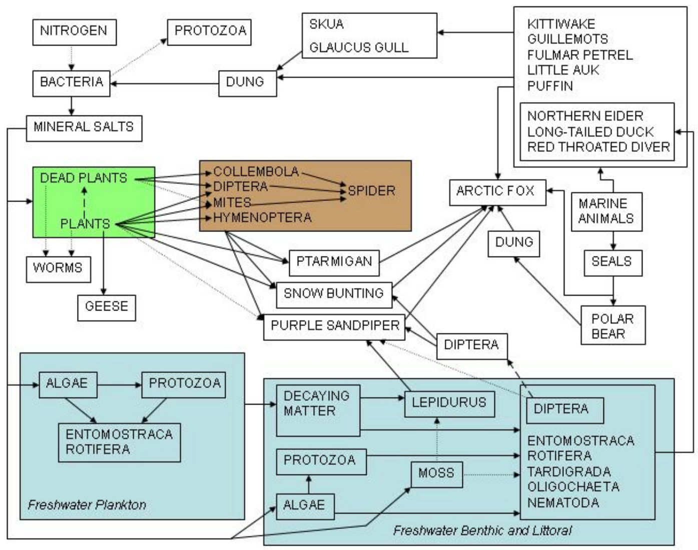


Figure 18.10: An arctic food web. Besides the living organisms, some abiotic components (nitrogen, mineral salts) and nonliving parts (dung) are included. (10)

All organisms depend on two global food webs that are interconnected. The base of one is phytoplankton, microscopic ocean producers. These tiny organisms are eaten by zooplankton. The zooplankton are tiny animals which in turn are eaten by small fish and then larger fish. Land plants form the base of the second food web. They are eaten by herbivores, that are eaten by carnivores and so on. Birds or bears that live on land may eat fish, which connects the two food webs. Humans are an important part of both of these food webs; we are at the top of a food web since nothing eats us. That means that we are top predators.

Flow of Matter in Ecosystems

The flow of matter in an ecosystem is not like energy flow. Matter can enter an ecosystem at any level and can leave at any level. It cycles freely between trophic levels and between the ecosystem and the physical environment. **Nutrients** are ions that are crucial to the growth of living organisms. Nutrients, like nitrogen and phosphorous, are important for plant cell growth. Animals use silica and calcium to build shells and skeletons. Cells need nitrates and phosphates to create proteins and other biochemicals. From nutrients, organisms make tissues and complex molecules like carbohydrates, lipids, proteins and nucleic acids.

Nutrients may enter an ecosystem from the breakdown of rocks and minerals. They enter the soil and are taken up by plants. Nutrients can be brought in from other regions, perhaps carried to a lake by a stream. When one organism eats another organism, it receives all of its nutrients. Nutrients can also cycle out of an ecosystem. Decaying leaves may be transported out of an ecosystem by a stream. Nutrients can blow out of an ecosystem on the wind.

Decomposers play a key role in making nutrients available to organisms. After scavengers eat dead organisms, they almost always leave some parts of the dead animal or plant behind. Decomposers complete the process of breaking down dead organisms. They convert dead organisms into nutrients and carbon dioxide, which they respire into the air. These left over nutrients are then available for other organisms to use. Without decomposers, life on Earth would not be able to continue. Dead tissue would remain as it is and eventually nutrients would run out. Decomposers break apart tissue and return the nutrients to the ground. Without decomposers, life on earth would have died out long ago.

Relationships Between Species

Species have different types of relationships with each other. **Competition** occurs between species that are trying to use the same resources. When there is too much competition, one species may move or adapt so that it uses slightly different resources. It may live at the tops of trees and eat leaves that are somewhat higher on bushes, for example. If the competition does not end, one species will die out. Each niche can only be inhabited by one species.

Some relationships between species are beneficial to at least one of the two interacting species. These relationships are known as **symbiosis** and there are three types. In **mutualism**, the relationship benefits both species (**Figure** 18.11). Most plant-pollinator relationships are mutually beneficial. The pollinator, such as a hummingbird, gets food. The plant get its pollen caught in the bird's feathers, so that pollen is spread to far away flowers helping them reproduce.

In **commensalism**, the relationship is beneficial to one species, but does not harm or help the other (**Figure** 18.12). A bird may build a nest in a hole in a tree. This neither harms nor benefits the tree, but it provides the bird and its young with protection.

In **parasitism**, the parasite species benefits and the host is harmed (**Figure** 18.13). Parasites do not usually kill their hosts because a dead host is no longer useful to the parasite. A visible example of parasite and host is mistletoe on an oak tree. The mistletoe gains water and nutrients through a root that it sends into the tree's branch. The tree is then supporting the mistletoe, but the tree is not killed, even though its growth and reproduction are slightly harmed by the parasite. Humans can host parasites, like the flatworms that cause schistosomiasis.

Figure 18.11: This hummingbird and flower each benefit from the mutualism of their relationship. (8)

Figure 18.12: The relationship between these barnacles and the humpback whale is an example of commensalism. The barnacles receive protection and get to move to new locations and the whale is not harmed. (26)

Figure 18.13: These tiny mites are parasitic on a harvestman. (23)

Lesson Summary

- Each species fills a niche within an ecosystem. Each ecosystem has the same niches, although the same species doesn't always fill them.
- Each ecosystem has producers, consumers, and decomposers. Decomposers break down dead tissue to make nutrients available for living organisms.
- Energy is lost at each trophic level, so top predators are scarce. Feeding relationships are much more complicated than a food chain, since some organisms eat from multiple trophic levels.
- As a result, food webs are needed to show all the predator/prey interactions in an ecosystem.

Review Questions

1. What is the difference between a population, a community and an ecosystem?
2. What is the difference between a niche and a habitat?
3. Why are the roles in different ecosystems the same but the species that fill them often different?
4. Why are there no producers in the deep sea ecosystem? Without producers, where does the energy come from? What is the ultimate source of the energy?
5. Is a predator an herbivore, carnivore or omnivore? How about a prey?
6. Biologists have been known to say that bacteria are the most important living things on the planet. Why would this be true?
7. Why are you so much more likely to see a rabbit than a lion when you're out on a hike?
8. How much energy is available to organisms on the 5^{th} trophic level compared with those on the 1st? How does this determine how long a food chain can be?
9. Why is a food web a better representation of the feeding relationships of organisms than a food chain?
10. Why is energy only transferred in one way in an ecosystem, but nutrients cycle around?
11. Why does a predator kill its prey but a parasite rarely kills its host?

Vocabulary

abiotic Nonliving features of an ecosystem include space, nutrients, air, and water.

biotic Living features of an ecosystem include viruses, plants, animals, and bacteria.

carnivore Animals that only eat other animals for food.

chemosynthesis The creation of food energy by breaking down chemicals.

commensalism A relationship between two species in which one species benefits and the other species is not harmed.

community All of the living creatures of an ecosystem; all of the populations of all of the species that live together.

competition A rivalry between two species, or individuals of the same species, for the same resources.

consumer An organism that does not create its own chemical energy, but uses other organisms for food.

decomposer An organism that breaks down the tissues of a dead organism into its various components, including nutrients that can be used by other organisms.

ecosystem All of the living things in a region and the physical and chemical factors that they need to live.

food chain An energy pathway that includes all organisms that are linked as they pass along food energy, beginning with a producer and moving on to consumers.

food web Interwoven food chains that show each organism eating from different trophic levels, which more closely reflects reality.

habitat Where an organism lives; habitats have distinctive features like climate or resource availability.

herbivore An animal that only eats producers.

invertebrate Animals without backbones.

mutualism A symbiotic relationship between two species in which both species benefit.

niche An organism's "job" within its community.

omnivore An organism that consumes both plants (producers) and other consumers (animals) for food.

parasitism A symbiotic relationship between two species in which there is a parasite and a host. The parasite gains nutrition from the host. The host in a parasitic relationship is harmed but usually not killed.

photosynthesis The process in which plants use carbon dioxide and water to produce sugar and oxygen: $6CO_2 + 12H_2O + \text{solar energy } C_6H_{12}O_6 + 6O_2 + 6H_2O$.

population All the individuals of a species that occur together in a given place and time.

predator An animal that kills and eats other animals.

prey An animal that could be killed and eaten by a predator.

producer An organism that creates chemical energy to be used as food. Most producers use photosynthesis but a very small number use chemosynthesis.

scavenger Animals that eat animals that are already dead.

species A classification of organisms that includes those that can or do interbreed and produce fertile offspring; members of a species share the same gene pool.

symbiosis Relationships between two species in which at least one species benefits.

trophic level Energy levels within a food chain or food web.

vertebrate Animals with backbones.

Points to Consider

- What happens if two species attempt to fill the same niche?
- There is at least one exception to the rule that each ecosystem has producers, consumers and decomposers. Excluding hydrothermal vent, what does the deep sea ecosystem lack?
- Where do humans fit into a food web?
- Most humans are omnivores, but a lot of what we eat is at a high trophic level. Since ecosystems typically can support only a few top predators relative to the number or lower organisms, why are there so many people?

18.2 The Carbon Cycle and the Nitrogen Cycle

Lesson Objectives

- Describe the short term cycling of carbon through the processes of photosynthesis and respiration.
- Identify carbon sinks and carbon sources.
- Describe short term and long term storage of carbon.
- Describe how human actions interfere with the natural carbon cycle.
- Describe the nitrogen cycle.

Introduction

Carbon is a very important element. It is not the most abundant element in the universe or even on the Earth, but it is the second most common element in the human body. You could not live without carbon. If something you eat has protein or **carbohydrates** or fats, then it contains carbon. When your body breaks down that food to produce energy, you breathe out carbon dioxide. Carbon is also a very important element on Earth. Carbon is provided by the environment, moves through organisms and then returns to the environment again. When all this happens in balance, the ecosystem remains in balance too. In this section, let's follow the path of a carbon atom over many years and see what happens.

Nitrogen is also a very important element. Nitrogen must be converted to a useful form so that plants can grow. Without "fixed" nitrogen, plants and therefore animals could not exist as we know them.

Short Term Cycling of Carbon

The short term cycling of carbon begins with carbon dioxide and the process of **photosynthesis**. Our atmosphere is mostly made of nitrogen and oxygen, but there is a small amount of carbon dioxide in the air too. Plants and **algae** use this carbon dioxide, along with water and energy from sunlight to produce their own food. This is a little miracle that is happening everywhere around you each and every day. Plants and algae have the ability to take the inorganic carbon in carbon dioxide and make it into organic carbon, which is food. That is something that we cannot do at all! Imagine the difference between what would happen if you tried to eat a piece of coral or a shell and what happens when we eat sugar. We can't get energy from the bits of rock at all, but you know how quickly sugar can be used for energy in our bodies.

Through photosynthesis, carbon dioxide plus water and energy from sunlight is transformed into food with oxygen given off as a waste product. Chemists write shorthand equations for different types of chemical reactions. The equation for photosynthesis looks like this (**Figure**

18.14):

$$6\,CO_2 + 6\,H_2O + \text{Energy from sunlight} \rightarrow C_6H_{12}O_6 + 6\,O_2$$

carbon dioxide water glucose (sugar) oxygen

Figure 18.14: (3)

The amazing transformation that has happened here is changing energy from sunlight into chemical energy that plants and animals can use as food (**Figure** 18.15).

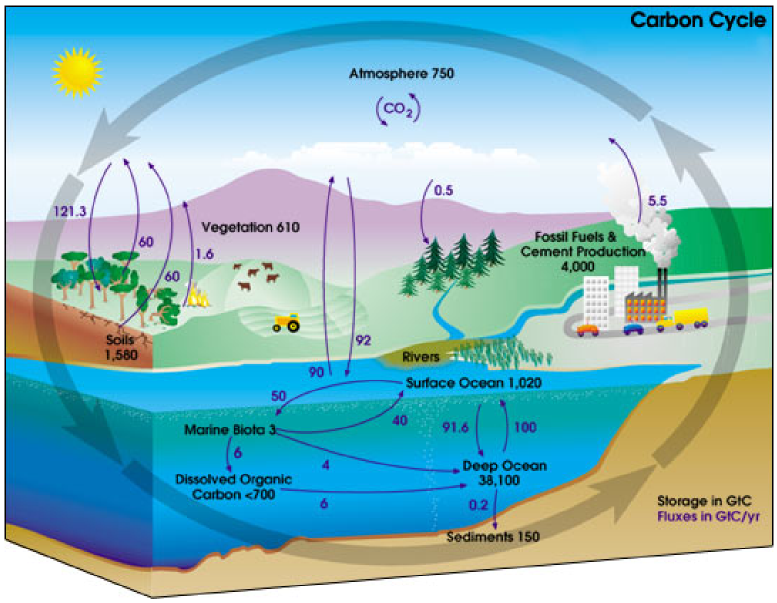


Figure 18.15: This diagram of the carbon cycle shows some of the places a carbon atom might be found. The black numbers indicate how much carbon is stored in various reservoirs, in billions of tons ("GtC" stands for gigatons of carbon; figures are circa 2004). The purple numbers indicate how much carbon moves between reservoirs each year. The sediments, as defined in this diagram, do not include the ˜70 million GtC of carbonate rock and kerogen. (18)

Carbon Can Also Cycle in the Long Term

As described above, an individual carbon atom could cycle very quickly if the plant takes in carbon dioxide to make food and then is eaten by an animal, which in turn breathes out carbon dioxide. Carbon might also be stored as chemical energy in the cells of the plant or the animal. If this happens, the carbon will stay stored as part of the organic material that makes up the plant or animal until it dies. Some of the time, when a plant or animal dies, it decomposes and the carbon is released back into the environment. Other times, the organic material of the organism is buried and transformed over millions of years into coal, oil, or natural gas. When this happens, it can take millions of years before the carbon becomes available again.

Another way that carbon is stored for long periods of time happens when carbon is used by ocean organisms. Many ocean creatures use calcium carbonate ($CaCO_3$) to make their shells or to make the reef material where coral animals live. When algae die, their organic material becomes part of the ocean sediments, which may stay at the bottom of the ocean for many, many years. Over millions of years, those same ocean sediments can be forced down into the mantle when oceanic crust is consumed in deep ocean trenches. As the ocean sediments melt and form magma, carbon dioxide is eventually released when volcanoes erupt.

Carbon Sinks and Carbon Sources

We can think of different areas of the ecosystem that use and give back carbon as **carbon sources** and **carbon sinks**. Carbon sources are places where carbon enters into the environment and is available to be used by organisms. One source of available carbon in the environment happens when an animal breathes out carbon dioxide. So carbon dioxide added to our atmosphere through the process of respiration is a carbon source. Carbon sinks are places where carbon is stored because more carbon dioxide is absorbed than is emitted. Healthy living forests and our oceans act as carbon sinks.

In the natural situation, the amount of carbon dioxide in the atmosphere is very low. This means that we can quickly change the amount of carbon dioxide in our atmosphere. Scientists can use data from air bubbles trapped in the ice of glaciers to determine what the natural level of carbon dioxide was before the Industrial Revolution, when humans began to use lots of fossil fuels. Measurements of the different gases in the air bubbles tell us that the natural level of carbon dioxide was about 280 parts per million. Today the amount of carbon dioxide in our atmosphere is 388 parts per million and that amount continues to rise every year. Scientists have been making measurements in the middle of the Pacific Ocean, far from any large land areas for fifty years. The graph (**Figure** 18.16) of this data shows that the amount of carbon dioxide has been steadily increasing every year.

Human Actions Impact the Carbon Cycle

Humans have changed the natural balance of the carbon cycle because we use coal, oil, and natural gas to supply our energy demands. Remember that in the natural cycle, the carbon that makes up coal, oil, and natural gas would be stored for millions of years. When we burn coal, oil, or natural gas, we release the stored carbon in the process of combustion. That means that combustion of fossil fuels is also a carbon source.

The equation for combustion of propane, which is a simple **hydrocarbon** looks like this (**Figure** 18.17):

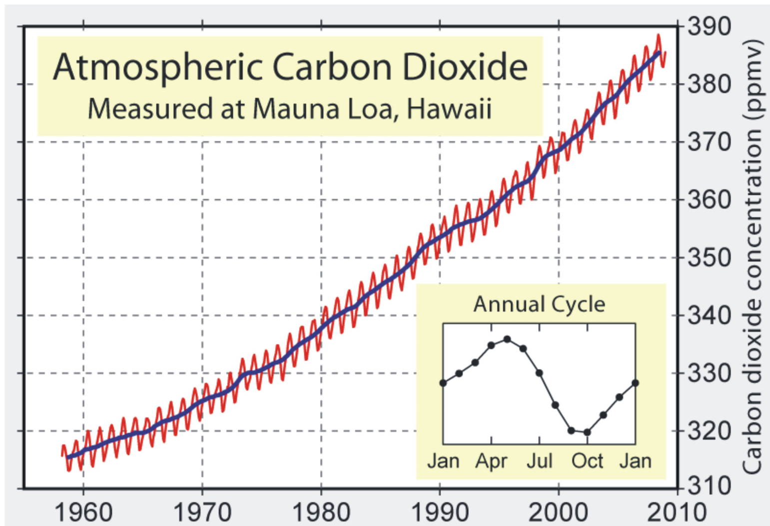


Figure 18.16: The Keeling curve of atmospheric CO_2 concentrations measured at Mauna Loa Observatory. (4)

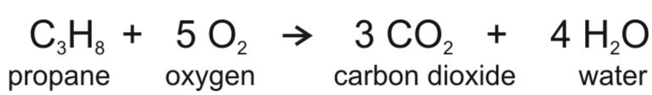


Figure 18.17: (20)

The equation shows that when propane burns, it uses oxygen and the result is carbon dioxide and water. So each time we burn a fossil fuel, we increase the amount of carbon dioxide in the atmosphere. Another way that carbon dioxide is being added to our atmosphere is through the cutting down of trees, called **deforestation** (**Figure** 18.18). Trees are very large plants, which naturally use carbon dioxide while they are alive. When we cut down trees, we lose their ability to absorb carbon dioxide and we also add the carbon that was stored in the tree into the environment. Healthy living forests act as a carbon sink, but when we cut them down, they are a carbon source.

Figure 18.18: This forest in Mexico has been cut down and burned to clear forested land for agriculture. (21)

Coal, oil, and natural gas as well as calcium carbonate rocks and ocean sediments are long term carbon sinks for the natural cycling of carbon. When humans extract and use these resources, combustion makes them into carbon sources.

Why Do We Need to Know About the Carbon Cycle?

You may wonder why scientists study the carbon cycle or why we would be concerned about such small amounts of carbon dioxide in our atmosphere. Carbon dioxide is a **greenhouse gas** (**Figure** 18.19). Different gases in our atmosphere absorb infrared energy, the longer wavelengths of the Sun's reflected rays. These gases hold onto heat energy that would otherwise radiate out into space. As the heat is held in our atmosphere, it warms the Earth. This is just like what happens in a greenhouse. The glass that makes up the greenhouse holds in heat that would otherwise radiate out.

When our atmosphere holds onto more heat than it would in the natural situation, it produces

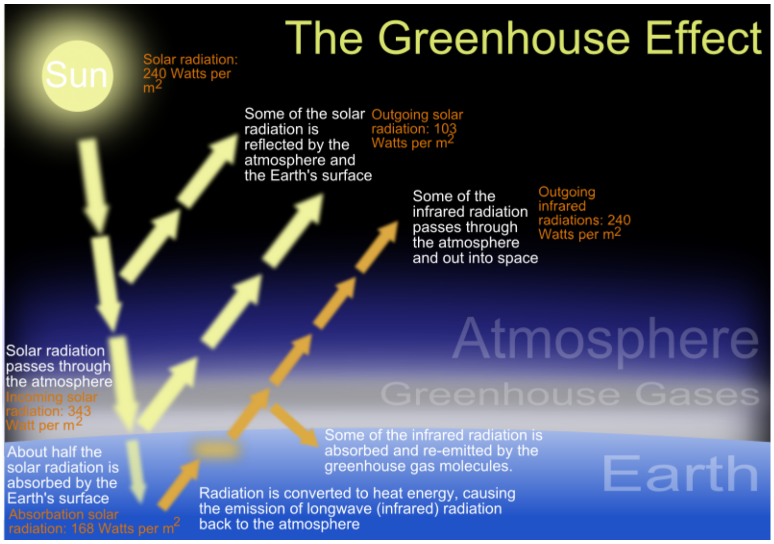


Figure 18.19: This diagram explains the role of greenhouse gases in our atmosphere. (24)

global warming. As our Earth continues to warm, there are many potential consequences. One possibility is that the current weather patterns will change. With rain falling in different areas, we won't be able to grow crops in the same regions which will impact our ability to grow food. Another possibility is that our polar ice caps will melt. We can already see this happening today. Glaciers all over the world are retreating as they melt away. Another possible consequence is that some species of plants and animals could become extinct. Polar bears have recently been added to the endangered species list as threatened because they need sea ice in order to hunt (**Figure** 18.20).

Figure 18.20: Polar bears depend on sea ice for hunting. (13)

As continental glacial ice melts, this will cause sea levels to rise, which will cause flooding of low lying coastal areas. That would be a big problem because many of our biggest cities are along coastlines.

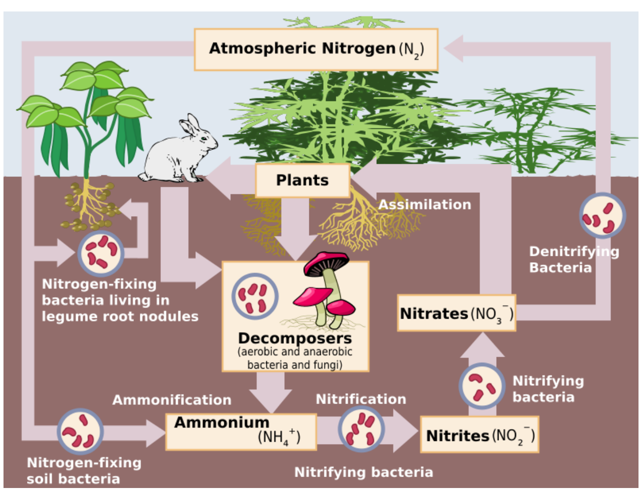
The Nitrogen Cycle

Nitrogen (N2) is also vital for life on Earth as an essential component of organic materials. Nitrogen is found in all amino acids, proteins, and nucleic acids such as DNA and RNA. Chlorophyll molecules in plants, which are used to create food by photosynthesis forming the basis of the food web, contain nitrogen.

Although nitrogen is the most abundant gas in the atmosphere, it is not in a form that plants can use. To be useful, nitrogen must be "fixed," or converted into a more useful form. Although some nitrogen is fixed by lightning or blue-green algae, much is modified by bacteria in the soil. These bacteria combine the nitrogen with oxygen or hydrogen to create nitrates or ammonia.

Nitrogen fixing bacteria either live free or in a symbiotic relationship with leguminous plants (peas, beans, peanuts). The symbiotic bacteria use carbohydrates from the plant to produce ammonia that is useful to the plant. Plants use this fixed nitrogen to build amino acids, nucleic acids (DNA, RNA) and chlorophyll. When these legumes die, the fixed nitrogen they contain fertilizes the soil.

Animals eat plant tissue and create animal tissue. After a plant or animal dies or an animal excretes waste, bacteria and some fungi in the soil fix the organic nitrogen and return it to the soil as ammonia. Nitrifying bacteria oxidize the ammonia to nitrites, other bacteria oxide the nitrites to nitrates, which can be used by the next generation of plants. In this way, nitrogen does not need to return to a gas. Under conditions when there is not oxygen, some bacteria can reduce nitrates to molecular nitrogen.



Usable nitrogen is sometimes the factor that limits how many organisms can grow in an ecosystem. Modern agricultural practices increase plant productivity adding nitrogen fertilizers to the soil. This can have unintended consequences as excess fertilizers run off the land, end up in water, and then cause nitrification of ponds, lakes and nearshore oceanic areas. Also, nitrogen from fertilizers may return to the atmosphere as nitrous oxide or ammonia, both of which have deleterious effects. Nitrous oxide contributes to the breakdown of the ozone layer and ammonia contributes to smog and acid rain.

Lesson Summary

- The carbon cycle begins with the process of photosynthesis, which transforms inorganic carbon into organic carbon.
- Our forested areas and our oceans are carbon sinks. When carbon is trapped in ocean sediments, or fossil fuels, it is stored for millions of years.
- Humans have changed the natural carbon cycle by burning fossil fuels, which releases carbon dioxide to the atmosphere. Burning of fossil fuels and deforestation are carbon sources.
- One potential consequence of increased carbon dioxide in the atmosphere is global warming.
- The nitrogen cycle begins with nitrogen gas in the atmosphere then goes through nitrogen-fixing micro organisms to plants, animals, decomposers and into the soil.

Review Questions

1. Describe the process of photosynthesis.
2. How can carbon cycle very quickly back into the environment?
3. Name two ways that carbon is stored for a very long time in the natural cycle.
4. Describe what makes a carbon sink and what makes a carbon source and give an example of each.
5. Name two ways that humans interfere with the natural carbon cycle.
6. Do we need carbon dioxide in our atmosphere?
7. Is global warming something that could impact you in your lifetime?

Vocabulary

algae Photosynthetic organisms in the ocean; includes one celled organisms and seaweeds.

carbohydrates An organic compound that supplies energy to the body; includes sugars, starches and cellulose.

carbon sink An area of an ecosystem that absorbs more carbon dioxide than it produces.

carbon source An area of an ecosystem that emits more carbon dioxide than it absorbs.

deforestation Cutting down and/or burning trees in a forested area.

greenhouse gas Gases like carbon dioxide that absorb and hold heat from the sun's infrared radiation.

global warming Warming of the Earth brought about by adding additional greenhouse gases to the atmosphere.

hydrocarbon An organic compound that contains only hydrogen and carbon.

photosynthesis The process using carbon dioxide, water, and energy from sunlight by which plants and algae produce their own food.

18.3 Human Populations

Lesson Objectives

- Describe how changes in a limiting factor can alter the carrying capacity of a habitat.
- Discuss how humans have increased the carrying capacity of Earth for our species and how we may have exceeded it.
- Discuss how human activities like agriculture and urbanization have impacted the planet.
- Describe what sustainable development is.

Introduction

Improvements in agriculture, sanitation, and medical care have enabled the human population to grow enormously in the last few 100 years. As the population grows, consumption, waste, and the overuse of resources also grow. People are beginning to discuss and carry out sustainable development that decreases the impact humans have on the planet.

Populations

The population size of a species depends on the biotic and abiotic factors present in that ecosystem. Biotic factors include the amount of food that is available to that species and the number of organisms that use that species as food. For life to thrive, a specific amount of abiotic factors are necessary. For example, too little water may cause land plants or animals to become dehydrated. Too much water, however, may cause drowning.

A population grows when the number of births is greater than the number of deaths. It shrinks, if deaths exceed births. For a population to grow, there must be ample resources and no major problems. A population can shrink either because of biotic or abiotic limits. An increase in predators, the emergence of a new disease, or the loss of habitat are just three possible problems that will decrease a population. A population may also shrink if it grows too large for the resources required to support it.

When the number of births equals the number of deaths, the population is at its **carrying capacity** for that habitat. In a population at its carrying capacity, there are as many organisms of that species as the habitat can support. The carrying capacity depends on biotic and abiotic factors. If these factors improve, the carrying capacity increases. If the factors become less plentiful, the carrying capacity drops. If resources are being used faster than they are being replenished, then the species has exceeded its carrying capacity. If this occurs, the population will then decrease in size.

Every stable population has one or more factors that limit its growth. A **limiting factor** determines the carrying capacity for a species. A limiting factor can be any biotic or abiotic factor: a nutrient, space, and water availability are examples. The size of a population is tied to its limiting factor. If the limiting factor decreases, the population decreases. If the limiting factor increases, the population increases. If a limiting factor increases a lot, another factor will most likely become the new limiting factor.

This may be a bit confusing so let's look at an example of limiting factors. Say you want to make as many chocolate chip cookies as you can with the ingredients you have on hand. It turns out that you have plenty of flour and other ingredients, but only two eggs. You can make only one batch of cookies, because eggs are the limiting factor. But then your neighbor comes over with a dozen eggs. Now you have enough eggs for seven batches of cookies, and enough other ingredients but only two pounds of butter. You can make four batches of cookies, with butter as the limiting factor. If you get more butter, something else will be limiting.

Species ordinarily produce more offspring than their habitat can support. If conditions improve, more young survive and the population grows. If conditions worsen, or if too many young are born, there is competition between individuals. As in any competition, there are some winners and some losers. Those individuals that survive to fill the available spots in the niche are those that are the most fit for their habitat.

Human Population Growth

Human population growth over the past 10,000 years has been tremendous (**Figure** 18.21). The human population was about 5 million in 8000 B.C., 300 million in A.D. 1, 1 billion in

1802, 3 billion in 1961, and 6.7 billion in 2008. As the human population continues to grow, different factors may emerge limiting human population in different parts of the world. Space may be a limiting factor or having enough clean air, clean water or food to feed everyone are concerns we are already facing.

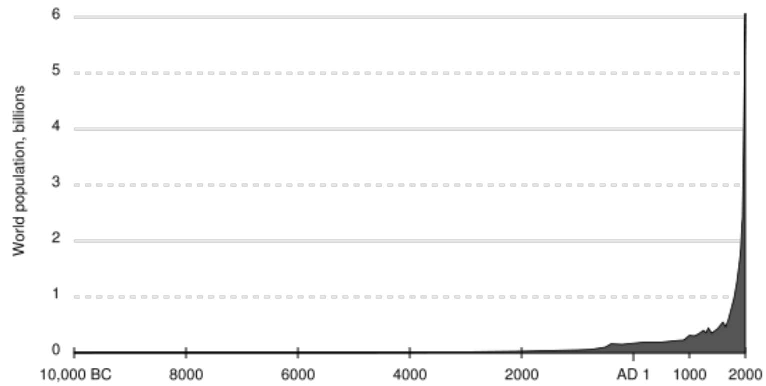


Figure 18.21: Human population from 10,000 BC through 2000 AD showing the exponential increase in human population that has occurred in the last few centuries. (5)

Not only has the population increased, but the rate of growth has also increased (**Figure** 18.22). It took all of human history for the population to reach the first 1 billion people, in around 1802. The second billion was added 125 years later, in 1927. It took 33 years for there to be 3 billion people in 1960, and only 15 years for there to be 4 billion people in 1975. Another billion was added by 1987, just twelve years later, and it took only another twelve years for the population to reach 6 billion people in 1999. Estimates are that the population will reach 7 billion in 2012, 13 years after reaching 6 billion.

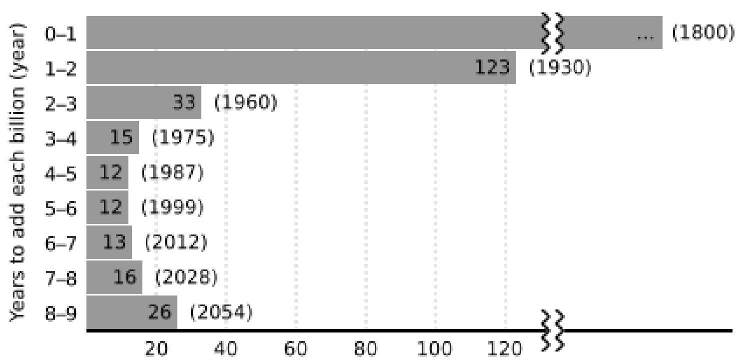


Figure 18.22: The amount of time between the addition of each one billion people to the planet's population including speculation about the future. (9)

Although population continues to grow rapidly, the rate of growth has declined. Still, it is likely that there will be between 9 and 10 billion people sharing this planet by the middle of the century. The total added will be about 2.5 billion people, which is more than were even in existence as recently as 1950.

With so many more people on the planet than ever before, we must ask whether humans now are exceeding Earth's carrying capacity for our species. Many anthropologists say that the carrying capacity of humans on the planet without agriculture is about 10 million. This population was reached about 10,000 years ago. At the time, people lived together in small bands of hunters and gatherers. Commonly women gathered nuts and vegetables and men hunted animals and fished. People within a band shared their resources. Although they had trading networks with outside groups, trading was limited by what could reasonably be carried. For the most part, people relied on the resources that they could find where they lived.

As you can see, human populations have blown past this hypothetical carrying capacity. By using our brains, our erect posture, and our hands, we have been able to do things that no other species has ever done. About 10,000 years ago, we developed the ability to grow our own food. Farming allowed us to grow the plants we wanted to eat and to have food available year-round. We domesticated animals to have meat when we wanted. With agriculture, people could settle down, so that they no longer needed to carry all their possessions. They could develop better farming practices and store food for when it was difficult to grow. Agriculture allowed people to settle in towns and cities. Early farmers could grow only enough food for their families, with perhaps a bit extra to sell, barter, or trade. More advanced farming practices allowed a single farmer to grow food for many more people. Being freed from having to gather or grow food allowed people to do other types of work.

The next major stage in the growth of the human population was the Industrial Revolution, which started in the late 1700's. Increased efficiency in farming freed up large numbers of people available to work in factories. This major historical event marks when products were first mass produced and when fossil fuels were first widely used for power.

Every major advance in agriculture allowed global population to increase. Irrigation, the ability to clear large swaths of land for farming efficiently, and the development of farm machines powered by fossil fuels allowed people to grow more food and transport it to where it was needed. Currently about 70% of the world's fresh water is used for agriculture.

The biggest advance in agriculture in recent decades is called the **Green Revolution**. It is this advance that has allowed the population to grow so rapidly. The first focus of the Green Revolution was to improve crops. A tremendous increase in the use of artificial fertilizers, nutrients that help plants to grow and chemical pesticides, chemicals that kill pests followed. About 23 times more fertilizer and 50 times more pesticides are used around the world than just 50 years ago. Most agricultural work is now done by machines: plowing, tilling, fertilizing, picking, and transporting (**Figure** 18.23). About 17% of the energy used each year in the US is for agriculture.

The Green Revolution has increased the productivity of farms immensely. A century ago,

Figure 18.23: Rows of a single crop and heavy machinery are normal sights for modern day farms. (15)

a single farmer produced enough food for 2.5 people, but now a farmer can feed more than 130 people. Due to this increased productivity, the Green Revolution is credited for feeding 1 billion people that would not otherwise have been able to live.

The flip side of this is that for the population to continue to grow, more advances in agriculture will be needed. We've increased the carrying capacity for humans by our genius: growing crops, trading for needed materials, and designing ways to exploit resources that are difficult to get at, like groundwater. The question is, even though we have increased the carrying capacity of the planet, have we now exceeded it? Are humans on Earth experiencing **overpopulation**?

There are many different opinions about human population growth. In the eighteenth century, Thomas Malthus predicted that human population would continue to grow until we had exhausted our resources. At that point, humans would become victims of famine, disease or war. Some scientists think that the carrying capacity of the planet is around 1 billion people, not the almost 7 billion people we have today. How did we get to where we are today? Many of our limiting factors have changed as we have used our intelligence and technology to expand our resources. Can we continue to do this into the future? Do we now have more people and more impacts on our environment than the Earth can handle?

Humans and the Environment

Along with the increases in food that have come from the Green Revolution have come enormous impacts on the planet. More food has allowed the human population to explode. Natural landscapes have been altered to create farmland and cities. Already, half of the ice free lands have been converted to human uses. Estimates are that by 2030, that number will be more than 70%. Forests and other landscapes have been cleared for farming or urban areas. Rivers have been dammed and the water is transported by canals for irrigation and domestic uses. Ecologically sensitive areas have been altered: wetlands are now drained and coastlines are developed.

Modern agricultural practices produce a lot of pollution (**Figure** 18.24). Some pesticides are toxic. Fertilizers drain off farmland and introduce nutrients into lakes and coastal areas, causing fish to die. Farm machines and vehicles used to transport crops produce air pollutants. Pollutants enter the air, water, or are spilled onto the land. Moreover, many types of pollution easily moves between air, water, and land. As a result, no location or organism—not even polar bears in the remote Arctic—is free from pollution.

The increased numbers of people have other impacts on the planet. Humans do not just need food. They also need clean water, secure shelter, and a safe place for their wastes. These needs are met to different degrees in different nations and among different socioeconomic classes of people. For example, about 1.2 billion of the world's people do not have enough clean water for drinking and washing each day (**Figure** 18.25).

A large percentage of people expect much more than to have their basic needs met. For about one-quarter of people, there is an abundance of food, plenty of water, and a secure home. Comfortable temperatures are made possible by heating and cooling systems, rapid transportation is available by motor vehicles or a well developed public transportation system, instant communication takes place by phones and email, and many other luxuries are available that were not even dreamed of only a few decades ago. All of these need resources to produce and fossil fuels to power. Their production, use and disposal all produce wastes. Many people refer to the abundance of luxury items in these people's lives as **over-consumption**. People in developed nations use 32 times more resources than people in the developing countries of the world.

There are many problems worldwide that result from overpopulation and over-consumption. One such problem is the advance of farms and cities into wild lands, which diminishes the habitat of many organisms. In addition, water also must be transported for irrigation and domestic uses. This means building dams on rivers or drilling wells to pump groundwater. Large numbers of people living together need effective sanitation systems. Many developing countries do not have the resources to provide all of their citizens with clean water. It is not uncommon for some of these children to die of diseases related to poor sanitation. Improving sanitation in many different areas—sewers, landfills, and safe food handling—are important to prevent disease from spreading.

Figure 18.24: Pesticides are hazardous in large quantities and some are toxic in small quantities. (1)

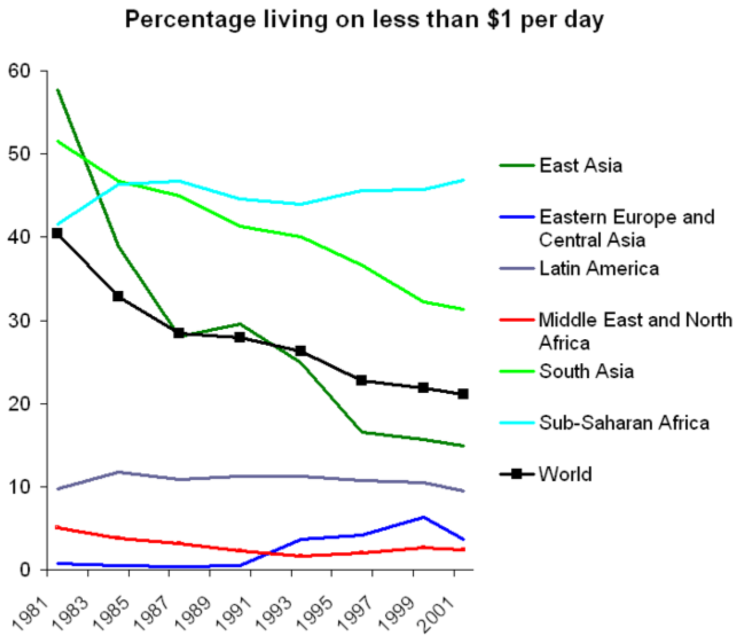


Figure 18.25: The percentage of people in the world that live in abject poverty is decreasing somewhat globally, but increasing in some regions, like Sub-Saharan Africa. (12)

Wildlife is threatened by fishing, hunting and trading as population increases. Besides losing their habitat as land is transformed, organisms are threatened by hunting and fishing as human population grows. Hunting is highly regulated in developed nations, but many developing nations are losing many native animals due to hunting. Wild fish are being caught at too high a rate and many ocean fish stocks are in peril.

Humans also cause problems with ecosystems when they introduce species that do not belong in a habitat. **Invasive species** are sometimes introduced purposefully, but often they arrive by accident like rats on a ship. Invasive species often have major impacts in their new environments. A sad example is the Australian Brown Tree Snake that has wiped out 9 of the 13 native species on the island of Guam (**Figure** 18.26).

Pollution is a by-product of agriculture, urbanization, and the production and consumption of goods. Global warming is the result of fossil fuel burning.

Let's return to the question of whether humans have exceeded Earth's carrying capacity for our species. Carrying capacity is exceeded if resources are being used faster than they are being replenished. It is also exceeded if the environment is being damaged.

The answer to our original question therefore appears to be yes. Many resources are being used far in excess of the rate at which they are being replaced. The best farmland is already in use and more marginal lands are being developed. Most rivers in the developed nations

Figure 18.26: An Australian Brown Tree Snake perched on a post in Guam. (2)

and many in developing nations are already dammed. Groundwater is being used far more rapidly than it is being replaced. The same is true for fossil fuels and many mineral resources. Forests are being chopped down; and wild fish are being overharvested. Human have caused the rate of extinction of wild species to increase to about at least 100 times the normal extinction rate.

In addition, the stability of the environment decreases as landscapes are transformed, organisms die out and the planet becomes polluted. Although many more people are alive in the world than ever before, many of these people do not have secure lives. Many people in the world live in poverty, with barely enough to eat. They often do not have safe water for drinking and bathing. Diseases kill many of the world's children before they reach five years of age.

Sustainable Development

A topic generating a great deal of discussion these days is **sustainable development**. This is development that attempts to help people out of poverty, while protecting the environment, without using natural resources faster than they can be replaced. It is development that allows people to use resources no faster than the rate at which they are regenerated.

One of the most important steps to achieving a more sustainable future is to reduce human population growth. This has been happening in recent years. Studies have shown that the birth rate decreases as women become educated. Educated women tend to have fewer and healthier children.

Science can be an important part of sustainable development. When scientists understand how Earth's natural systems work, they can recognize how people are impacting them. Scientists can work to develop technologies that can be used to solve problems wisely. An example of a practice that can aid sustainable development is fish farming, as long as it is done in environmentally sound ways. Engineers can develop cleaner energy sources to reduce pollution and greenhouse gas emissions.

Citizens can change their behavior to reduce the impact they have on the planet by demanding products that are produced sustainably. When forests are logged, new trees should be planted. Mining should be done so that the landscape is not destroyed. People can consume less and think more about the impacts of what they do consume.

Lesson Summary

- Populations of organisms are kept to a habitat's carrying capacity by factors that limit their growth.
- By developing agriculture and other technologies, the human population has grown well past any natural population limits.
- Many people on Earth live in poverty, without enough food or clean water or shelter.
- Overpopulation and over-consumption are causing resources to be overused and much pollution to be generated.
- Society must choose development that is more sustainable, in order to secure a long term future for our species and the other species that we share the planet with.

Review Questions

1. If phosphorous is limiting to a species in an ecosystem and the amount of phosphorous is increased, what will happen to the population of that species? What will happen to the carrying capacity?
2. Name some factors that could cause a population to increase. Try to include as many types of factors as possible.
3. In terms of numbers of births and deaths, explain in detail why you think human population is growing so tremendously?
4. If all people on Earth were allowed only to replace themselves (that is, each person could only have one child or each couple two children), what would happen to the planet's population in the next decade? Would it decrease, increase, or remain exactly the same as it is now?
5. What role has agriculture played in human population and why?
6. Discuss the good and bad points about the Green Revolution.
7. In the United States, 17% of energy is used for agriculture? How is this possible, if plants photosynthesize with sunlight?
8. What is more threatening to the future of the planet: overpopulation or overconsump-

tion? How does an increase in the standard of living for people living in poverty affect the planet?
9. What evidence is there that humans are exceeding Earth's carrying capacity for our species?
10. What is sustainable development?

Vocabulary

carrying capacity The number of individuals of a given species a particular environment can support.

Green Revolution Changes in the way food is produced since World War II that have resulted in enormous increases in production.

invasive species A species of organism that spreads in an area where it is not native, and negatively impacts the native vegetation. People often introduce invasive species either purposefully or by accident.

limiting factor The one factor that limits the population of a region. The limiting factor can be a nutrient, water, space, or any other biotic or abiotic factor that species need.

over-consumption Resource use that is unsustainable in the long term; obtaining many more products than people need.

overpopulation When the population of an area exceeds its carrying capacity or when long-term harm is done to resource availability or the environment.

pesticide A chemical that kills a certain pest that would otherwise eat or harm plants that humans want to grow.

sustainable development Economic development that helps people out of poverty, use resources at a rate at which they can be replaced, and protects the environment.

Points to Consider

- How much impact on the planet does an infant born in the United States have during its lifetime, compared with one born in Senegal?
- How does consuming less impact global warming?
- Can ordinary people really make a difference in changing society toward more sustainable living?

Image Sources

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Chapter 19

Human Actions and the Land

19.1 Loss of Soils

Lesson Objectives

- Explain how human actions accelerate soil erosion.
- Describe ways that we can prevent soil erosion.

Introduction

Have you ever seen muddy rain or snow falling from the sky? Can you imagine what it might be like if the water that came down as rain and snow was muddy and brown? In May 1934, a huge wind storm picked up and blew away massive amounts of **topsoil** from the Central United States (**Figure** 19.1). The wind carried the soil eastward to Chicago. Some of the soil then fell down to the ground like a snowstorm made of mud. The rest of it continued blowing eastward, and reached all the way to New York and Washington, D.C. That winter, states like New York and Vermont actually had red snow because of all the dusty soil in the air.

A little less than one year later, in April 1935, another such storm happened (**Figure** 19.2). It was called a Black Blizzard. It made the day turn dark as night; people could not see right in front of them because of all the soil blown up by the wind storm. The storm caused tremendous damage and led to many people leaving the central United States to find other places to live. Many people became sick from breathing the soil in the air.

These storms are sometimes called the Dust Bowl storms. They continued on and off until about 1940. They are extreme examples of soil erosion, which is the process of moving soil from one place to another. Soil erosion is a serious problem because it takes away a valuable

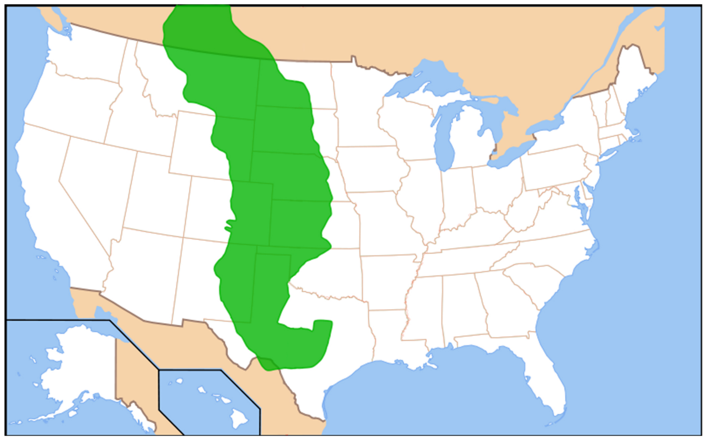

Figure 19.1: Soil loss from the dust storms of 1934 and 1935 came mostly from the states shown here in green in the Central United States. The soil blew all the way to the east coast of the United States. (10)

Figure 19.2: This wind storm blew huge amounts of soil into the air in Texas on April 14, 1935. (8)

resource that we need to grow food. Several factors contributed to the Dust Bowl storms. First, farmers in the Central United States had plowed grasslands there to grow food crops. They left the crop fields bare in the winter months. This left the soil exposed to wind. Secondly, a long drought in the 1930's left the exposed soil especially dry. When the spring winds began blowing, the dry exposed soil was easily picked up and blown away.

We learned many lessons from the Dust Bowl storms. Today, we encourage farming practices that keep the soil covered even during the winter, so that it is not exposed and vulnerable to erosion. We have also learned of ways to prevent erosion in cities and towns as well as on farmlands. In this lesson, you will learn about some human activities that lead to erosion. You will then learn some of the specific ways we can prevent soil erosion.

Causes of Soil Erosion

Soil erosion occurs when water, wind, ice or gravity moves soil from one place to another. Running water is the leading cause of erosion, since it can easily take soil with it as the water flows downhill or moves across the land. Wind is the next leading cause of erosion. Just as in the Dust Bowl storms of the 1930's, wind can blow soil many hundreds of kilometers away. Soil is especially vulnerable to erosion if it is bare or exposed. Plants therefore serve a tremendous role in preventing soil erosion. If the soil is covered with plants, erosion is slowed down. But when soil is bare, the rate of erosion speeds up tremendously. What are some human activities that leave the soil exposed and speed up erosion? We speed up erosion through the following actions:

- Agriculture
- Grazing animals
- Logging and mining
- Construction
- Recreational activities, like driving vehicles off-road or hiking

Agriculture, is probably the most significant human action that accelerates, or speeds up, erosion (**Figure** 19.3). We first plow the land to plant fields of crops. This takes away the natural vegetative cover of an area and replaces it with rows of crop plants mixed with bare areas. It also creates an area where there may not be anything growing in the winter, because in most areas, food crops only grow in the spring and summer. The bare areas of a field are very susceptible to erosion. Without anything growing on them, the soil is easily picked up and carried away. The fields also experience more erosion in the winter if no plants are growing on them and they are just left as bare soil. In addition, farmers sometimes make deep grooves in the land with their tractor tires. These grooves act like small channels that give running water a path. This speeds up erosion from water.

Some parts of the world use an agricultural practice called slash and burn. This involves cutting and burning forests to create fields and **pastures**. It is one of the worldwide leading

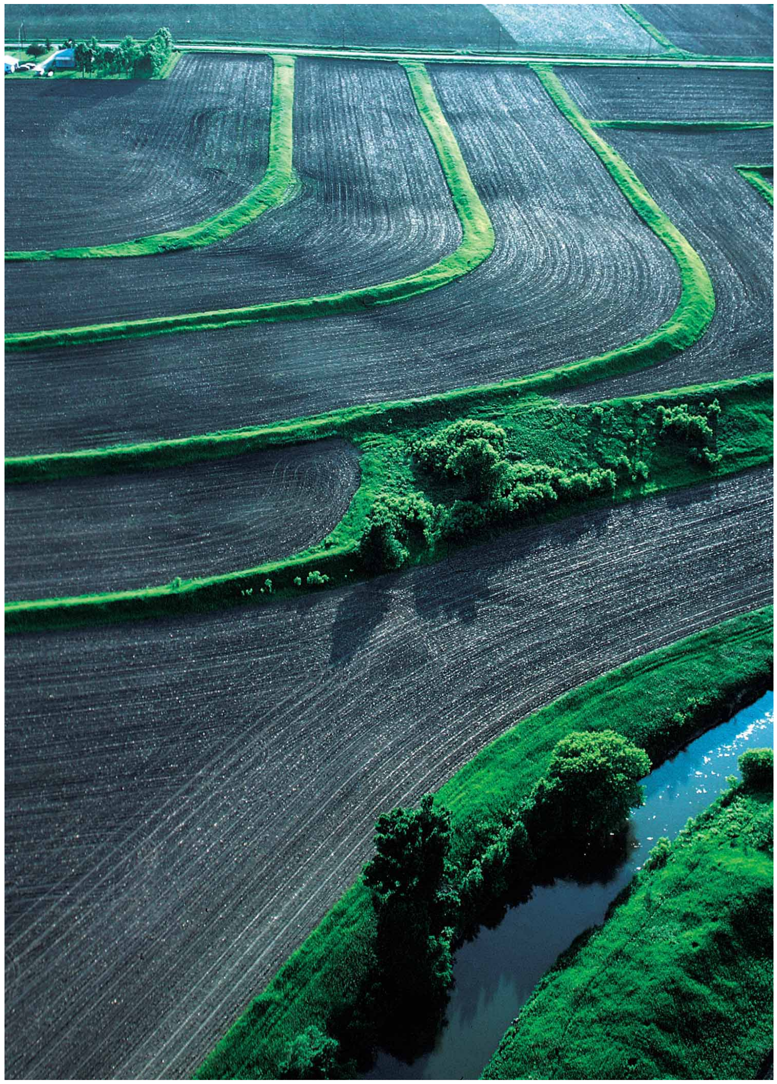

Figure 19.3: The bare areas of farmland are especially vulnerable to erosion. (12)

causes of excessive soil erosion. It is most commonly practiced in developing countries in tropical areas of the world, as people create more land for agriculture.

Grazing animals are animals that live on large areas of grassland (**Figure** 19.4). They wander over the area and eat grasses and shrubs. They can remove large amounts of the plant cover for an area. If too many animals graze the same land area, once the tips of grasses and shrubs have been eaten, they will use their hooves to pull plants out by their roots.

Figure 19.4: Grazing animals can cause erosion if they are allowed to overgraze and remove too much or all of the vegetation in a pasture. (11)

When an area is logged, large areas of trees are cut down and removed for human use (**Figure** 19.5). When the trees are taken away, the land is left exposed to erosion. Even more importantly, logging results in the loss of **leaf litter**, or dead leaves, bark, and branches on the forest floor. Leaf litter decreases because no trees are left to drop leaves or other plant parts to the ground. The leaf litter plays an important role in protecting forest soils from erosion.

Mining is another activity that speeds up erosion (**Figure** 19.6). When we mine we are digging in the Earth for mineral resources, like copper or silver. The huge holes dug by mining operations leave large amounts of ground exposed. In addition, most of the rock removed when mining is not actually the precious mineral, but **tailings**, or unwanted rock that is left next to the mine after the valuable minerals are removed. These tailings are usually piled up next to a mine, and are easily eroded downhill.

Constructing human buildings and roads also causes much soil erosion. This **development** involves changing forest and grassland into cities, buildings, roads, neighborhoods, and other human-made features. Any time we remove natural vegetation, we make the soil more susceptible to erosion. In addition, features like roads, sidewalks, and parking lots do not let

Figure 19.5: Logging exposes large areas of land to erosion. (9)

Figure 19.6: This large coal mining pit in Germany, and other mines like it, are major causes of erosion. (4)

water run through them into the ground because they are hard and **impermeable** (**Figure** 19.7). Since the water cannot enter the ground, it then runs over the ground faster than usual. This can speed up water erosion.

Figure 19.7: Urban areas and parking lots result in less water entering the ground. Therefore, more water runs over the land and quickly forms channels that can speed up erosion. (6)

Humans also cause erosion through recreational activities, like hiking and riding off-road vehicles. An even greater amount of erosion occurs when people drive off-road vehicles over an area. The area eventually develops bare spots where no plants can grow. Erosion becomes a serious problem in these areas.

Human-caused Erosion

Some erosion is a natural process and has always happened on Earth. However, human activities like those discussed above, have accelerated soil erosion, which may occur about 10 times faster than its natural rate. As the human population grows, we increase our impact on soil erosion. In order to support Earth's human population, we need to create more and more farmland, we develop more areas and build more cities, and we use much more of the land for recreation. Human population growth can lead to degradation of the natural environment.

Human impact on erosion differs throughout the world. In developed countries like the United States, we have learned good agricultural practices that greatly slow down agriculture's impact on erosion. However, we still experience much erosion from the development of urban areas and construction of new cities. In developing countries, many people are very poor and just want to be able to grow food and make a simple living. They carry out slash and burn agriculture because it quickly gives them land to grow food crops on. Poverty is a big contributing factor to environmental problems like soil erosion in developing countries.

Preventing Soil Erosion

Soil is a renewable, natural resource necessary for growing food. However, it renews itself slowly: it can take hundreds or thousands of years to replenish lost soil. When we lose valuable soil, we also lose an important natural resource. Many of the farmers affected by the Dust Bowl storms of the 1930's lost their homes because they could no longer grow crops and earn money to live, once their topsoil had all blown away. While agriculture can cause erosion, it is also necessary for human life. We have learned many good agricultural practices that reduce erosion, instead of speeding it up.

Table 19.1 shows some seps that we can take to prevent erosion. Which of these things can you do in your own personal life? Can you think of any other steps we can take to slow down erosion? Notice that many of the things listed here involve ways that we use the land. Land use always requires humans to make choices.

Table 19.1:

Source of Erosion	Strategies for Prevention
Agriculture	• Leave leaf litter on the ground in the winter • Grow **cover crops**, special crops grown in the winter to cover the soil • Plant tall trees around fields to buffer the effects of wind • Drive tractors as little as possible • Use drip irrigation that puts small amounts of water in the ground frequently • Avoid watering crops with sprinklers that make big water drops on the ground • Keep fields as flat as possible to avoid soil eroding down hill

Table 19.1: (continued)

Source of Erosion	Strategies for Prevention
Grazing Animals	• Move animals throughout the year, so they don't consume all the vegetation in one spot • Keep animals away from stream banks, where hills are especially prone to erosion
Logging and Mining	• Reduce the amount of land that we log and mine • Reduce the number of roads that are built to access logging areas • Avoid logging and mining on steep lands • Cut only small areas at one time and quickly replant logged areas with new seedlings
Development	• Reduce the amount of land that we turn into cities, urban areas, parking lots, etc. • Keep as much "green space" in cities as possible, such as strips of trees where plants can grow • Invest in and use new technologies for parking lots that make them permeable to water in order to reduce runoff of water
Recreational Activities	• Avoid using off-road vehicles on hilly lands • Stay on designated trails

Table 19.1: (continued)

Source of Erosion	Strategies for Prevention
Building Construction	• Avoid building on steep hills • Grade surrounding land to distribute water rather than collecting it in one place • Where water collects, drain to creeks and rivers • Landscape with plants that minimize erosion

Lesson Summary

- Soil erosion is a natural process, but human activities have greatly accelerated soil erosion.
- We accelerate erosion through agriculture, grazing, logging and mining, development, and recreation.
- Soil is an important natural resource necessary for plant growth and should be kept safe from erosion as much as possible.
- There are many ways that we can slow down or prevent erosion, but practicing these involves making decisions about how we use land resources. It also requires striking a balance between economic needs and the needs of the environment.

Review Questions

1. Many farmers harvest their crops in the fall and then let the leftover plant material stay on the ground over winter. How does this help prevent erosion?
2. List five ways human activity has accelerated soil erosion.
3. How do urban areas contribute to soil erosion?
4. What is the connection between poverty and soil erosion in developing countries?
5. What is one way you can prevent soil erosion when you are hiking?
6. You often see stone barriers or cage-like materials set up along coastal shores and river banks. How do you think these serve to prevent erosion? Why are areas like this prone to erosion?
7. How can your own activities affect the environment, especially soil erosion?
8. What can we do to help solve environmental problems in developing countries? What responsibility do you have to help solve this problem?

Further Reading / Supplemental Links

- People who lived during the Dust Bowl talk about their experiences, the Ganzel Group http://www.livinghistoryfarm.org/farminginthe30s/water_02.html

- Video of the Dust Bowl http://www.weru.ksu.edu/vids/dust002.mpg

Vocabulary

cover crop A special crop grown by a farmer in the wintertime to reduce soil erosion. Cover crops often also add nitrogen to the soil.

development The construction of new buildings, roads, and other human-made features in a previously natural place.

impermeable Not allowing water to flow through it.

leaf litter Dead leaves, branches, bark, and other plant parts that accumulate on the floor of a forest.

pasture Land that is used for grazing animals.

topsoil The very important top few inches of soil, where much of the nutrients are found necessary for plant growth; Part of the A horizon

Points to Consider

- Is soil a renewable resource or a nonrenewable resource? Explain the ways it could be either.
- Could humans live without soil?
- What could you do to help to conserve soil?

19.2 Pollution of the Land

Lesson Objectives

- Define hazardous waste and describe its sources.
- Describe some of the impacts of hazardous waste on human health and on the environment.
- Detail some ways that we can control hazardous wastes.

Introduction

Sometimes human activities lower the quality or **degrade** the land by putting hazardous substance in the soil and water. A well-known example of this is the story of Love Canal in New York. The story began in the 1950's, when a local chemical company put dangerous chemicals in steel drum containers. They buried the containers in Love Canal, an abandoned waterway near Niagara Falls, New York (**Figure** 19.8). They then covered the containers with soil and sold the land to the local school system.

Figure 19.8: Steel barrels like these were used to contain the hazardous chemicals at Love Canal. After several years, they began to leak the chemicals into the soil and groundwater, which caused many people to become sick. (7)

The school system built a school on the land. The city of Niagara Falls also built more than 800 homes near Love Canal. Several years later, people who lived there began to notice bad chemical smells in their homes. Children developed burns after playing in the soil, and they were often sick. A woman living in the area, named Lois Gibbs, organized a group of citizens called the 'Love Canal Homeowners Association' to try to find out why their children kept getting sick (**Figure** 19.9). They discovered that their homes and school were sitting on top of the site where the dangerous chemicals had been buried. They believed that the old steel drums used to contain the dangerous chemicals were leaking and making them and their children sick. They demanded that the government take action to clean up the area and remove the chemicals.

By 1979, the United States government fully realized that the old drums were indeed leaking dangerous chemicals into the soil and water where the people lived and went to school. The government gave money to many of the people to move somewhere safer and began

Figure 19.9: A resident of Love Canal protests the hazardous waste contamination in her neighborhood. (2)

cleaning up the site. The work of Lois Gibbs was important in bringing the problem of hazardous chemical pollution to peoples' attention. After the Love Canal problem, the U. S. government created a law called the **Superfund Act**. This law requires companies to be responsible for hazardous chemicals that they put into the environment. It also requires them to pay the money needed to clean up polluted sites, which can often be hundreds of millions of dollars. As a result, companies today are more careful about how they deal with hazardous substances.

This lesson describes some of the sources of hazardous wastes throughout the world. It then discusses the effects these wastes have on human health and the environment. Finally, this lesson covers ways that we can control hazardous wastes.

What is Hazardous Waste?

Hazardous waste is any waste material that is dangerous to human health or that degrades the environment. Hazardous waste materials include substances that are:

1. Toxic: something that causes serious harm, death or is poisonous.
2. Chemically active: something that causes dangerous or unwanted chemical reactions, like dangerous explosions.
3. Corrosive: something that destroys other things by chemical reactions.
4. Flammable: something that easily catches fire and may send dangerous smoke into the air.

Hazardous waste may be solid or liquid. It comes from many sources, and you may be surprised to learn that you probably have some sources of hazardous waste right in your own home. Several cleaning and gardening chemicals are hazardous if not used properly. These include chemicals like drain cleaners and **pesticides** that are toxic to humans and many other creatures. When we use, store, and dispose of them, we have to be careful. We have to protect our bodies from exposure to them and make sure they do not enter the environment (**Figure** 19.10). If they are thrown away or disposed of improperly, they become hazardous to the environment. Others sources of hazardous waste are shown in **Table** 19.2.

Table 19.2:

Type of Hazardous Waste	Example	Why it is Hazardous
Chemicals from the automobile industry	Gasoline, used motor oil, battery acid, brake fluid	Toxic to humans and other organisms; often chemically active; often flammable
Batteries	Car batteries, household batteries	Contain toxic chemicals; are often corrosive

Table 19.2: (continued)

Type of Hazardous Waste	Example	Why it is Hazardous
Medical wastes	Surgical gloves, wastes contaminated with body fluids such as blood, x-ray equipment	Toxic to humans and other organisms; may be chemically active
Paints	Paints, paint thinners, paint strippers, wood stains	Toxic; flammable
Dry cleaning chemicals	Many various chemicals	Toxic; many cause cancer in humans
Agricultural chemicals	Pesticides, herbicides, fertilizers	Toxic to humans; can harm other organism; pollute soils and water

Impacts of Hazardous Waste

Many hazardous waste materials have serious impacts on human health. They often cause cancer and can also cause birth defects. They can make people sick for very long times. Breathing the air or drinking the water that is contaminated with hazardous waste is a major health threat.

Two chemicals that are especially toxic in the environment are lead and mercury. Lead harms people by damaging their brain and nervous system. Lead is especially harmful in children under the age of six; about 200 children die every year from lead poisoning. Lead was once a common ingredient in gasoline and paint (**Figure** 19.11). In the 1970's and 1980's, the United States government passed laws completely banning lead in gasoline and paint. This has prevented the lead poisoning of millions of children in the United States. However, several other countries still use gasoline with lead in it. Also, homes built before the 1970's may contain paint that has lead in it. These still pose a threat to human health.

Mercury is a pollutant affecting the whole world (**Figure** 19.12). Mercury enters the environment from volcanic eruptions, burning coal and from waste products like old batteries and electronic switches. It is also found in old discarded electronic appliances like television sets. Like lead, mercury also damages the brain and impairs nervous system function. Mercury often accumulates in fish, so people and other animals that eat the fish then are in danger of getting the mercury in their own bodies.

Preventing Hazardous Waste Pollution

The United States is currently the world's largest producer of hazardous wastes. However, as China becomes more industrialized, it may take over the number one spot. Countries with

Figure 19.10: This farm worker wears special clothes for protection from the hazardous pesticide in the container. (1)

Figure 19.11: In the United States, automotive gasoline must now be unleaded, or free from lead. (3)

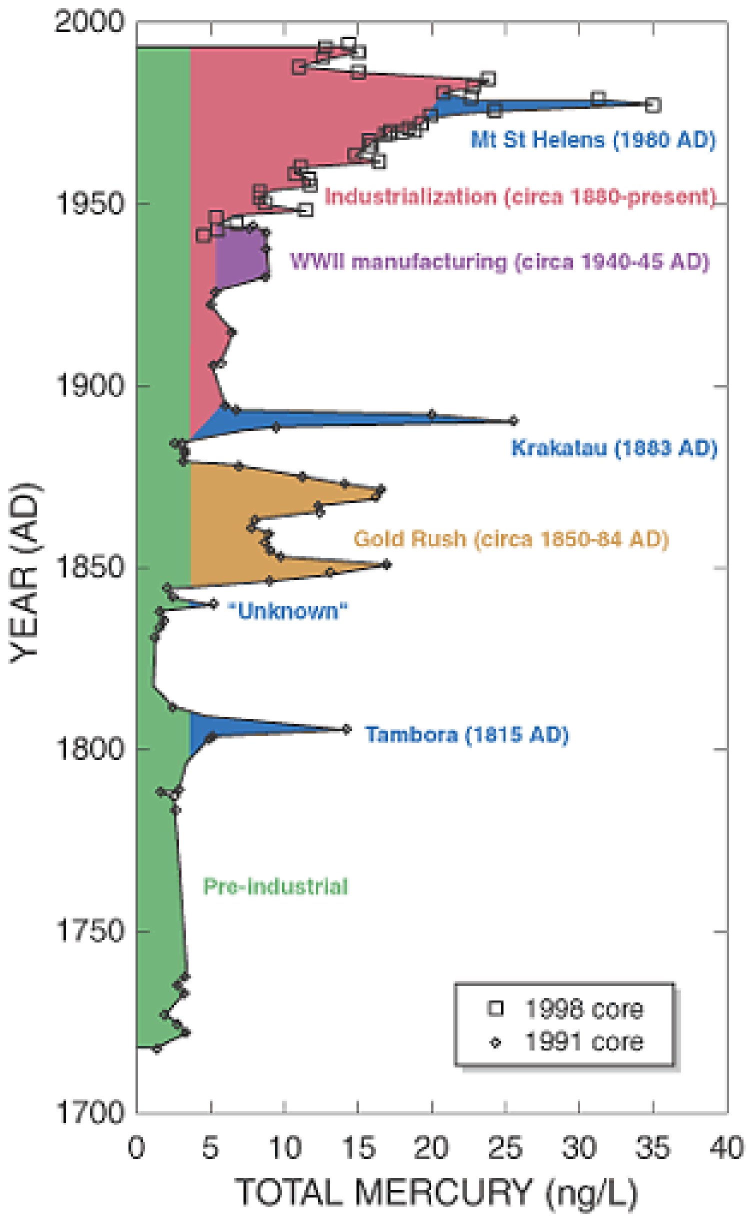

Figure 19.12: This graph shows historic increases of mercury in the atmosphere. Events in blue are volcanic eruptions. Events in brown, purple and pink are human-caused. Notice the effect of industrialization on mercury levels in the atmosphere (the red region of the graph). (5)

more industry produce more hazardous waste than those with little industry. Hazardous wastes can enter the air when we burn things like batteries containing mercury or old tires. Hazardous waste can enter the water when chemicals are dumped on the ground, or are buried and then leak. Substances buried in the ground often leak from their containers after a number of years. The chemicals then move through the soil until they reach groundwater. Hazardous chemicals are especially dangerous once they reach our groundwater resources. Sites like the one at Love Canal are now referred to as **Superfund sites**. They are found throughout the country. Many of them have been identified and cleaned up. We now have strict laws to prevent new sites like the Love Canal site from ever forming in the first place.

In the United States, we have several laws that help control hazardous waste. The Resource Conservation and Recovery Act requires any company that produces hazardous materials to keep careful track of what happens to it. The government has passed special rules for how these materials can be disposed of. Companies must ensure that hazardous waste is not allowed to enter the environment in dangerous amounts. They have to protect their workers from the hazards of the materials. They must keep a record of how they dispose of hazardous wastes, and show the government that they did so in a safe way.

Individual people can also do much to control hazardous wastes. We can choose to use materials that are not hazardous in the first place. We can make sure that we dispose of materials properly. We can control the amount of pesticides that we use. We can make sure to not pour toxic chemicals over the land, or down the drain or toilet, or even into the trashcan. We can also use hazardous materials less often. We can find safer alternatives for many of the chemicals we use. For example, we can use vinegar and water to clean windows instead of the usual glass-cleaning chemicals.

Lesson Summary

- Hazardous wastes are dangerous to human health and the environment. They come from many sources, such as household chemicals, gasoline, paints, old batteries, discarded appliances, and industrial chemicals.
- Once in the air or buried on land, they can cause human health problems or even death and degrade the environment for other organisms.
- Developed countries like the United States produce most of the world's hazardous waste.
- We have passed laws that require careful disposal of hazardous materials and that make their producers financially responsible for them if they pollute the environment.

Review Questions

1. How does the United States Superfund Act help control hazardous wastes?
2. What is the difference between corrosive and flammable?

3. Organic farming is a method of growing food crops with natural alternatives to chemical pesticides. How does organic farming help control hazardous wastes?
4. What is one disadvantage of storing hazardous wastes in barrels buried deep in the ground?
5. Scientists who work with hazardous wastes often wear special clothing like gloves and masks. Why do you think they wear these items?
6. Which do you think is easiest and hardest to keep track of: hazardous waste that is present as a gas, liquid, or solid? Why?

Further Information / Supplemental Links

- Love Canal Pathfinder, Nathan Tallman http://www.nathantallman.org/pathfinders/lovecanal.html

- Superfund Sites Where You Live http://www.epa.gov/superfund/sites/index.htm

Vocabulary

degrade To lower the quality of something.

pesticides Chemicals used to kill or harm unwanted pests such as insects that damage food crops.

superfund act A law passed by the US Congress in 1980 that held companies responsible for any hazardous chemicals that they might create.

superfund site A site where hazardous waste has been spilled. Under the Superfund act, the company that created the hazardous waste is responsible for cleaning up the waste.

Points to Consider

- What are the best ways to either prevent or safely dispose of hazardous materials?
- If humans are the ones who mostly create hazardous materials, whose responsibility is it to clean them up?
- Is it important for each generation to leave the world a safe place? If one generation doesn't do this, who pays the price?

Image Sources

(1) USDA. http://commons.wikimedia.org/wiki/Image:Hazardous-pesticide.jpg. Public Domain.

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Chapter 20

Human Actions and Earth's Resources

20.1 Use and Conservation of Resources

Lesson Objectives

- Discuss some natural resources used to make common objects.
- Describe some ways to conserve natural resources.

Figure 20.1: The Monongahela National Forest in West Virginia supplies us with many natural resources, including, timber, wildlife, coal, gas, recreation, and fishing. (5)

Introduction

In the Monongahela National Forest of West Virginia (**Figure** 20.1), scientists have a mystery to solve: the mystery of the missing plant **nutrients**, which are substances in the soil that plants need to grow. For several years, the trees there have not grown as well as they should. Soil scientists believe that the soil is missing many of the important nutrients that the trees and other plants there need to grow. They have conducted many years of research to determine why the nutrients are disappearing and why the trees are not growing like they should.

Mary Lusk was one of the soil scientists who worked to solve the mystery of the missing nutrients in the forest. She gathered samples of the soil and tested it for important nutrients. She saw that the soil has very low levels of plant nutrients, such as magnesium and calcium. If these nutrients are not in the soil, the trees cannot grow well. She wondered why the soil had such low levels of these nutrients. After a little more research, she developed the hypothesis that air pollution from nearby factories has been putting chemicals in the environment that are removing the nutrients from the soil. In a sense, the pollution is "snatching" the nutrients and carrying them out of the soil.

Scientists in the Monongahela National Forest are still researching the missing plant nutrients. They are trying to learn what they can do to help keep the nutrients in the soil, so the trees will grow better. The forest is an important natural resource. A natural resource is something from nature that we depend on. We depend on the Monongahela National Forest for many reasons, including:

- Recreation, such as hiking, camping, and picnics.
- The forest is vital habitat for many animals, including 9 endangered species and 50 different species of rare plants.
- The forest contains 207 kilometers (129 miles) of streams for fishing, particularly trout fishing.
- Hunters use the forest for hunting deer, squirrels, turkeys, rabbits, mink, and foxes.
- The forest contains materials that we use, such as coal, gas, limestone, and gravel.
- The forest has abundant hardwood trees used for **timber**, which is sold for over 7 million dollars a year.

Like the Monongahela National Forest, we use many parts of the Earth for many reasons (**Figure** 20.2). We depend on materials from the Earth for food, water, building materials, timber, recreation, and energy. However, human activities can degrade these natural resources, just like air pollution from factories is speeding up the loss of soil nutrients in West Virginia (**Figure** 20.3). We need to **conserve** our natural resources so they will always be around. When we practice conservation, we make sure resources will be available in the future, both for ourselves and for other organisms.

Figure 20.2: We use Earth's resources for many purposes, including recreation and natural beauty. (8)

Figure 20.3: Severe pollution can lead to drastic environmental damage and loss of natural resources. This forest in Europe was damaged by air pollution. (3)

Renewable versus Non-Renewable Resources

Natural resources may be classified as renewable or non-renewable. Renewable resources are those that can be regenerated, which means new materials can be made or grown again at the same rate as they are being used. For example, trees are a renewable resource because new trees can be grown to replace trees that are cut down for use. Other examples of renewable resources include soil, wildlife, and water. However, some resources, like soil, have very slow rates of renewal, so we still need to conserve them. It is also important to realize that while these resources are in most cases renewable, we can still pollute them, damage them or over-use them to the point that they are not fit for use anymore. Fish are considered a renewable resource because we can take some fish but leave others to reproduce and create new fish for later use. Imagine, however, what can happen if we over-fish, or take too many fish at one time. If we over-harvest our trees or wildlife resources, we may not leave enough to let the resource renew itself.

Non-renewable resources are resources that renew themselves at such slow rates that, practically, they cannot be regenerated. Once we use them up, they are gone for good - or at least for a very, very long time. Coal, oil, natural gas and minerals are non-renewable resources. It takes millions of years for these materials to form, so if we use them to the point of depletion, new resources will not be made for millions more years. We can run out of these resources.

Common Materials We Use From the Earth

What do a CD, a car, a book, a soda can, a bowl of cereal, and the electricity in your home all have in common? They are all made using natural resources. For example, a CD and a soda can are made of metals that we mine from the Earth. A bowl of cereal comes from wheat, corn, or rice that we grow in the soil. The milk on the cereal comes from cows that graze on fields of grass. We depend on natural resources for just about everything that we eat and use to keep us alive, as well as the things that we use for recreation and luxury. In the United States, every person uses about 20,000 kilograms (40,000 pounds) of minerals every year for a wide range of products such as cell phones, TV's, jewelry, and cars. **Table** 20.1 shows some common objects, the materials they are made from and whether they are renewable or non-renewable.

Table 20.1:

Common Object	Natural Resources Used	Are These Resources Renewable or Non-renewable?
Cars	15 different metals, such as iron, lead, and chromium to make the body	Non-renewable

Table 20.1: (continued)

Common Object	Natural Resources Used	Are These Resources Renewable or Non-renewable?
Jewelry	Precious metals like gold, silver, and platinum; Gems like diamonds, rubies, emeralds, turquoise	Non-renewable
Electronic Appliances (TV's, computers, DVD players, cell phones, etc.)	Many different metals, like copper, mercury, gold	Non-renewable
Clothing	Soil to grow fibers such as cotton Sunlight for the plants to grow Animals for fur and leather	Renewable
Food	Soil to grow plants Wildlife and agricultural animals	Renewable
Bottled Water	Water from streams or springs Petroleum products to make plastic bottles	Non-renewable and Renewable
Gasoline	Petroleum drilled from wells	Non-renewable
Household Electricity	Coal, natural gas, solar power, wind power, hydroelectric power	Non-renewable and Renewable
Paper	Trees Sunlight Soil	Renewable
Houses	Trees for timber Rocks and minerals for construction materials, for example, granite, gravel, sand	Non-renewable and Renewable

Human Population and Resource Use

As the human population grows, so does the use of our natural resources. A growing population creates a demand for more food, more clothing, more houses and cars, etc. Population growth puts a strain on natural resources. For example, nearly 500 people move into the

Tampa, Florida area every week (**Figure** 20.4). Tampa's population is growing quickly. The Tampa area may have over 3 million people by 2010. One of Tampa's rivers, the Hillsborough River, is pumped for drinking water to support all the people. Too much water is being taken from the river. The river is becoming salty, as water from the near-by Gulf of Mexico starts to take the place of the **freshwater** being pumped out. This hurts wildlife and may eventually make the river water unsuitable for human use. Many other examples like this are taking place worldwide.

Figure 20.4: Downtown Tampa, Florida is growing at an enormous rate. The growing human population puts a strain on natural resources, like rivers and other bodies of water. (1)

Resource Availability

You can see from the table above that many of the resources we depend on are non-renewable. We will not be able to keep taking them from the Earth forever. Also, non-renewable resources vary in their availability. Some are very abundant and others are rare. Precious gems, like diamonds and rubies, are valuable in part because they are so rare. They are found only in small areas of the world. Other materials, like gravel or sand are easily located and used. Whether a resource is rare or abundant, what really determines its value is how easy it is to get to it and take it from the Earth. If a resource is buried too deep in the Earth or is somehow too difficult to get, then we don't use it as much. For example, the oceans are filled with an abundant supply of water, but it is too salty for drinking and it is difficult to get the salt out, so we do not use it for most of our water needs.

Resource availability also varies greatly among different countries of the world. For example, 11 countries (Algeria, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates, and Venezuela) have nearly 80% of all the world's oil (**Figure** 20.5). However, none of these is the world's biggest user of oil. In fact, the biggest users of oil, the United States, China, and Japan, are all located outside this oil-rich region. This difference in availability and use of resources can be a source of economic and political trouble throughout the world. Nations that have abundant resources often **export** them to other countries, while countries that lack a resource must **import** it from somewhere else.

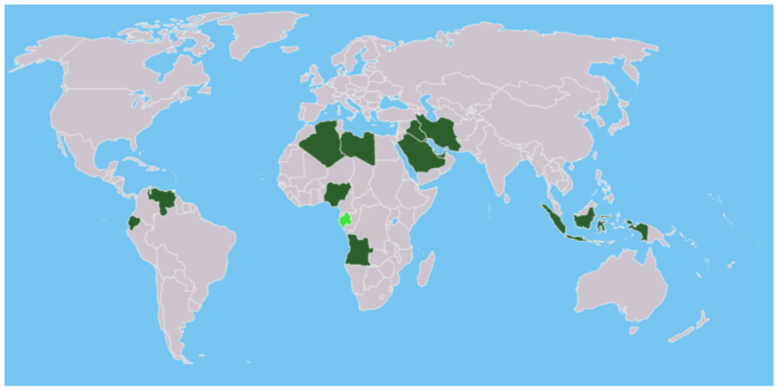

Figure 20.5: The nations in green are the 11 biggest producers of worldwide oil. They have almost 80% of the world's current oil supply, even though the United States, China, and Japan are the world's biggest users of oil. (7)

In developed countries like the United States and most of Europe, we often use many more natural resources than we need just to live. We have many luxury and recreational materials made from resources. We also tend to throw things away quickly because we can afford to replace them. Discarding materials not only leads to more resource use, but it also leads to more waste that has to be disposed of in some way. Pollution from discarded materials degrades the land, air, and water (**Figure** 20.6). As our cities and neighborhoods grow, we use more and more resources and produce more and more waste. Natural resource use is generally lower in developing countries because people cannot afford to use as much. Still, developing countries need to actively protect their resources by adopting sustainable practices as they develop.

Conserving Natural Resources

We need to conserve natural resources so that we can continue to use them in the future, and so that they will be safe for use. While renewable resources will not run out, they can become degraded or polluted. For example, water is a renewable resource, but we can pollute it to the point that it is not safe for use. Reducing use and recycling materials is a great way to conserve resources (**Figure** 20.7). Many people are also researching ways to find renewable alternatives to non-renewable resources. Here is a checklist of some things we can do to conserve resources:

Figure 20.6: Pollution from discarded materials degrades the environment and reduces the availability of natural resources. (6)

Figure 20.7: Recycling can help conserve natural resources. (2)

- Purchase less stuff (use items as long as you can, ask yourself if you really need something new.)
- Reduce excess packaging (for example, drink water from the tap instead of buying it in plastic bottles).
- Recycle materials like metal cans, old cell phones, and plastic bottles.
- Purchase products made from recycled materials.
- Keep air and water clean by not polluting in the environment.
- Prevent soil erosion.
- Plant new trees to replace ones that we cut down.
- Drive cars less, take public transportation, bicycle, or walk.
- Conserve energy at home (for example, by turning out lights when they are not needed).

Lesson Summary

- We use natural resources for many things. Natural resources give us food, water, recreation, energy, building materials, and luxury items.
- Many resources vary in their availability throughout the world. Some are rare, difficult to get or in short supply.
- We need to conserve our natural resources, protecting them from pollution and overuse.
- We can use materials less or recycle to conserve resources.
- We can also make efforts to reduce pollution and soil erosion in order to conserve resources.

Review Questions

1. List five general things we get from natural resources.
2. We depend on forests as habitat for wildlife. How does this make a forest an important resource for people?
3. How could human life be affected if a large amount of soil erosion affected our soil resources?
4. How does discarding products lead to more resource use?
5. How does choosing to walk or ride a bicycle instead of riding in a car help conserve resources?

Further Reading / Supplemental Links

- Maps of Renewable Resources in the United States http://www.nrel.gov/gis/maps.html
- What to Recycle [* Maps of Renewable Resources in the United States http://www.nrel.gov/gis/maps.html

Vocabulary

conserve To keep things safe and ensure that they will always be around.

export To send out to another country.

import To receive from another country.

macronutrients Nutrients that are needed by an organism in a large amount.

non-renewable A resource that cannot be regenerated; once it is used up, it cannot be replaced within a human lifetime.

timber Trees that are cut for wood to be used for building or some other purpose.

nutrients Substances that a living thing needs to grow.

renewable A resource that can be regenerated, new ones can be made or grown to replace ones that get used.

Points to Consider

- Could a renewable resource ever become nonrenewable?
- How many resources do you use every day?
- Which is more sustainable: using renewable resources or nonrenewable resources? Why?

20.2 Energy Conservation

Lesson Objectives

- Discuss why it takes energy to get energy and why some forms of energy are more useful than others.
- Describe some ways to conserve energy or to use energy more efficiently.

Introduction

Imagine that someone offers you a $100 bill that you can use for whatever you want. That would be a pretty good deal, wouldn't it? Now imagine that the person attaches a condition to their offer: in order to get the $100 bill you have to pay them $75. You would still come out ahead, but this time you would only be getting $25. Does it make sense to spend money to get money? That depends on how much you get back for what you spend.

Getting and using natural energy sources is a lot like spending money to get money. We use a lot of energy just to get energy (**Figure** 20.8). We have to find an energy source, extract it from the Earth, transport it to the places where it will be used, and often process or convert it into a different form of energy. All of these steps of getting energy require energy use themselves. For example, we use petroleum to make gasoline for our cars. To get the petroleum, we often have to build huge drilling facilities and drill down hundreds of meters into the Earth. It takes energy to do this. We then use trucks or ships to transport the oil all over the world, which also takes energy. We then have to heat the petroleum to its boiling point to make different products from it, like gasoline and automotive oil and this takes even more energy.

In this lesson, you will learn that different sources of energy all require adding some other energy before they can be made useful. You will be able to compare various sources of energy in terms of their usefulness. You will also learn some ways that we can conserve energy or use it more efficiently.

Obtaining Energy

It takes energy to get energy. Net energy is the amount of useable energy available from a resource after subtracting the energy used to extract it from the Earth and make it useable by humans. We just discussed someone giving you $100 but requiring you to pay them back $75. In this case, your net pay would be $25, or $100 minus $75. Net energy is calculated the same way. For example, for every 5 barrels of oil that we take from the Earth, we have to use 1 barrel for the extraction and refining process. This leaves us a net supply of only 4 barrels (5 barrels minus 1 barrel).

Remember that oil is a non-renewable resource. Imagine what would happen if the energy needed to extract and refine oil increased. What might happen if it took 4 barrels of oil being used to get 5 barrels of new oil? Then our net supply would only be 1 barrel. Our supply of oil would begin to dwindle away even faster than the current rate.

We sometimes use the expression **net energy ratio** to demonstrate the difference between the amount of energy available in a resource and the amount of energy used to get it. If we get 10 units of energy from a certain amount of oil, but use 8 units of energy to extract, transport, and refine the oil, then the net energy ratio is 10/8 or 1.25. A net energy ratio larger than 1 means that we are still getting some usable energy. A net energy ratio smaller

Figure 20.8: It takes energy to get energy. This is an oil platform used for drilling oil from deep underground. It took lots of energy to build the platform and to run it. (9)

than one means there is an overall energy loss. **Table** 20.2 shows several energy sources commonly used for heating our homes and schools. It shows their net energy ratios. Higher ratios mean that the source provides more useable energy than those with lower ratios.

Table 20.2:

Energy Source	Net Energy Ratio
Solar Energy	5.8
Natural Gas	4.9
Petroleum	4.5
Coal-fired Electricity	0.4

Notice from the table that renewable solar energy gives you much more net energy than other sources and that coal-fired electricity actually consumes more energy than it produces. Why do you think this is so? Burning coal for electricity requires a large input of energy to get energy. We have to find the coal, mine the coal, transport the coal, and build power plants to burn the coal (**Figure** 20.9). All of these take energy and reduce the net energy available for us to use. Solar energy, however, requires very little energy to get in the first place. We don't have to mine it or transport it in trucks. Sunshine is abundant globally and can be used in the same place where it is collected.

Figure 20.9: Transporting coal requires a large input of energy. It takes energy to run the train that transports the coal. (4)

Energy Efficiency

The discussion above on net energy shows you that it takes energy to get energy and that some sources of energy require more input than others to get usable energy. After we get the energy, we then use it for some purpose. Energy efficiency is a term that describes how much usable energy we have available to do work from every unit of energy that we use. Higher energy efficiency is desirable because it means we are wasting less energy and getting more use out of the energy sources that we take from the Earth. Higher energy efficiency also lets us extend our non-renewable sources and make them last longer.

Nearly 85% of the energy used in the United States comes from non-renewable fossil fuels. Since these exist in limited supplies, we need to be especially concerned about using them efficiently. Sometimes our choices affect energy efficiency. For example, transportation needs require huge amounts of energy. Forms of transportation such as cars and airplanes are less efficient than transportation by boats and trains. Fluorescent light bulbs are more efficient than regular, incandescent light bulbs. Hydroelectric power plants are more efficient than nuclear fission reactors.

Energy Conservation

Energy conservation involves reducing or eliminating the unnecessary use of energy. This improves energy efficiency. Energy conservation saves us money and it also ensures that our energy supplies will last longer. There are two main ways to conserve energy: use less energy and use energy more efficiently. The pie chart (**Figure** 20.10) shows how energy is used in the United States.

Almost one-half of the energy used in the United States is for transportation and home use. This means that individual people can do much to conserve energy on a national basis. **Table** 20.3 shows some ways that we can decrease energy use and use energy more efficiently in transportation, residences, industries, and office settings.

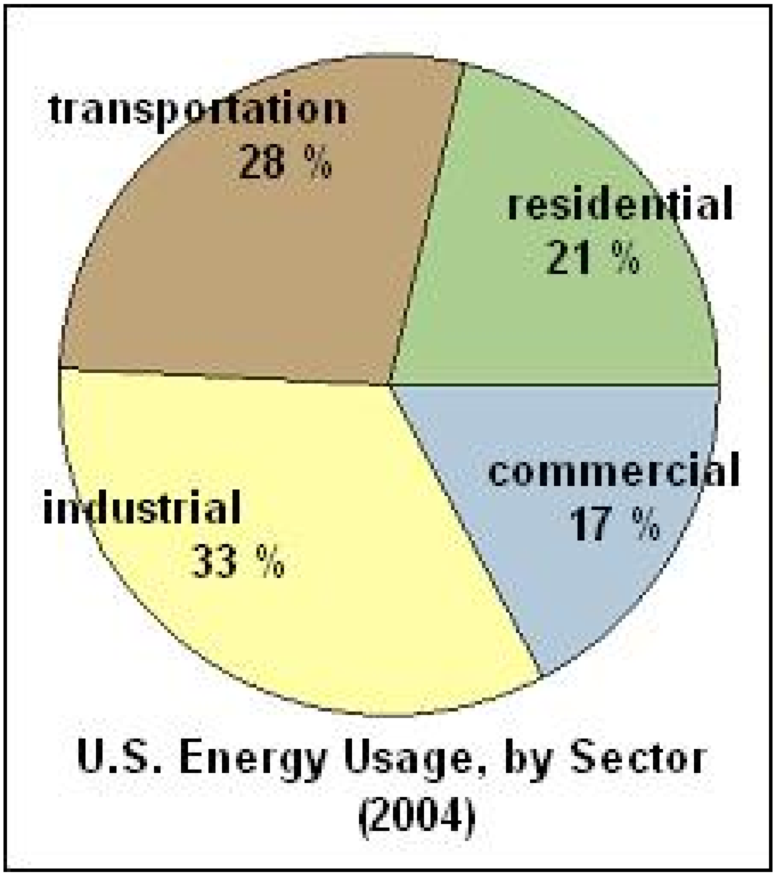

Figure 20.10: This pie chart shows how energy is used in the United States. (10)

Table 20.3:

Where Energy is Used	How We Can Use Less Energy	How We Can Use Energy More Efficiently
Transportation	• Ride a bike or walk instead of taking a car • Reduce the number of trips you make • Use public transportation	• Increase fuel efficiency in cars • Buy and drive smaller cars • Build cars from lighter and stronger materials • Drive at speeds at or below 90 kilometers per hour (55 miles per hour)
Residential	• Turn off lights when not in a room • Only run appliances when necessary • Unplug appliances when not in use • Wear a sweater instead of turning up heat • Read a book or play outside instead of watch TV • Rely on sunlight instead of artificial light	• Replace old appliances with newer more efficient models • Insulate your home • Make sure windows and doors are well sealed • Use LED bulbs if available, or **compact fluorescent** light bulbs (and dispose of properly!)
Industrial	• Recycle materials like soda cans and steel • Reduce use of plastic, paper, and metal materials	• Practice conservation in factories • Reuse materials • Design equipment to be more efficient

Table 20.3: (continued)

Where Energy is Used	How We Can Use Less Energy	How We Can Use Energy More Efficiently
Commercial (businesses, shopping areas, etc.)	• Turn off appliances and equipment when not in use	• Use fluorescent lighting • Set thermostats to automatically turn off heat or air conditioning when buildings are closed

Using less energy or using energy more efficiently will help conserve our energy resources. Since many of the energy resources we depend upon are non-renewable, we need to make sure that we waste them as little as possible.

Lesson Summary

- It takes energy to get energy. We use the term 'net energy' to refer to the amount of energy left for use after we expend energy to get, transport and refine other forms of energy.
- Once the energy is available, we use it for some purpose, but sometimes do so inefficiently.
- We can conserve energy resources by reducing energy use.
- We can also use energy more efficiently by getting more work out of the energy that we use.
- Examples of this include driving smaller cars and using fluorescent light bulbs.

Review Questions

1. Define net energy?
2. Why does solar power have a higher net energy ratio than coal-fired electricity?
3. Coal-fired electricity has a net energy ratio of 0.40. Explain why this means that getting electricity from burning coal is an undesirable option for energy use.
4. What are two ways you can use less energy in your home?
5. Why is it especially important to not waste energy from fossil fuels?
6. Trains are much more efficient than trucks in transporting items around. Why do you think this might be so?

Vocabulary

energy The ability to do work which we can get from a fuel.

extraction The process of taking oil out of the Earth.

fluorescent A type of lighting that uses less energy than regular light bulbs.

net energy ratio The ratio between the useful energy present in a type of fuel, and the energy used to extract and process the fuel.

refining The process of removing impurities from oil and to make it usable.

Points to Consider

- If it takes energy to get energy, then what are the best choices for types of energy?
- Put each of these actions in order from most important to least: choosing a sustainable form of energy, increasing energy efficiency, conserving energy use. Explain the order you chose.
- Could everyone in the world use as much energy as a person in the United States does each day? Why or why not?

Image Sources

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Chapter 21

Human Actions and Earth's Waters

21.1 Humans and the Water Supply

Learning Objectives

- Learn how humans use water.
- Discuss how much water is taken up by each water use.
- Explain the difference between consumptive and non-consumptive water uses.
- Discuss three of the most serious issues humans face today, including shortages of fresh water, lack of safe drinking water and water pollution.

- Discuss why humans are facing water shortages.
- Discuss how water shortages can lead to disputes and even battles between states and countries bordering on the same water source.
- Explain why one fifth of the human population does not have access to safe drinking water.
- Describe the relationship between disease and exposure to unsafe drinking water.
- What is the origin of California's fresh water supply?

Human Uses of Water

All forms of life need water to survive. As humans, we need water to drink or we need to get it from the foods we eat. We also use water for agriculture, industry, household uses, and recreation. Water is continually cycled and recycled through the environment.

Some ways that we use water consume a lot of water that then is lost to the ecosystem and some ways we use water put less demand on our water supplies. Understanding how water cycles and is replaced is important, especially when we look for ways to use less water.

Currently, agricultural uses the most water. Considering different methods of irrigation and times of day to water crops can improve this situation. Farming, growing crops and raising livestock uses more than two thirds of the water used by humans globally.

When water is used but not recycled, the water use is called consumptive. That water is lost to the ecosystem. When excess water is captured or recycled, it is called non-consumptive. As we move to a more sustainable future, we want to be sure as much of our water use is non-consumptive as possible.

What is the most important thing for all life on Earth? Not gold or diamonds. It is water! From the smallest bacteria to the largest trees, all forms of life on Earth depend on water for survival. As humans, we could not survive for more than a few days without drinking water or getting water from the foods we eat.

In addition to our basic survival need for water to drink, people also use freshwater for agriculture, industry and household needs. Across the world, different communities also use water for many kinds of recreational and environmental activities.

Which human activity uses the most water? Not showers, baths, washing dishes or other household uses. On average, agriculture uses more than two thirds of the water that humans use across the world. Industry and household uses average 15% each. Recreational use and environmental uses average 1% each. (See **Figure** 21.1)

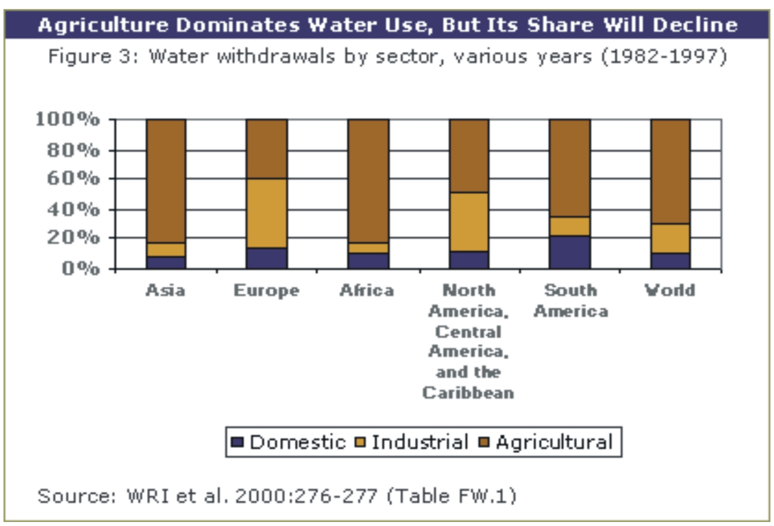


Figure 21.1: Proportion of water used for home, industrial, and agricultural purposes across the world. (3)

Some ways that people use water do not use up the water. When you swim in a lake, you do not use up the water. The water is still in the lake when you climb out. In some cases, water can be recycled for reuse. For example, the water you use to brush your teeth or take a bath can be collected through your household pipes and the sewer system, purified and then redistributed for reuse. These are examples of **non-consumptive water use.** By recycling water, we ultimately reduce our overall water consumption.

Unlike the previous examples, water sprinklers are called **consumptive,** because much of the water is lost to the air as evaporation. None of the lost water can be captured and reused.

Agricultural Water Uses

Have you ever watched huge sprinklers watering large fields of crops (**Figure** 21.2)? If you have, try to imagine how much water it takes to water a field compared to taking a shower or bath. You may be surprised to learn that agriculture uses more than two thirds (69%) of the water humans use, globally. http://authors.ck12.org/wiki/index.php/File:Ear-2101-02.jpg

Figure 21.2: Agricultural Water Use: Overhead sprinklers need to use large quantities of water on crops because much of the water is lost to evaporation and runoff. (25)

Two of the most popular irrigation methods are overhead sprinklers and trench irrigation. Trench irrigation systems are just that: trench canals that carry water from a water source to the fields. Farmers often chose these methods because they relatively inexpensive. Unfortunately, they are also wasteful of water. Roughly fifteen to thirty-six percent of the water never reaches the crops, because it evaporates into the air or is lost as runoff. When rain or irrigation water is not absorbed by the soil, often it washes valuable soil away.

Giving up irrigation is not a choice for most farmers. A farmer living in a dry region, such as a desert, needs irrigation, just to grow crops. A farmer living in a wetter place would use irrigation to produce more crops or to grow more profitable crops. In some cases, farmers can choose to grow crops that match the amount of rain that falls in that region naturally.

Figure 21.3: Drip Irrigation uses a series of pipes and tubes to deliver water to the base of each plant. Because little water is lost to evaporation and runoff, this method uses less water than sprinklers and trenches. (2)

Instead of giving up irrigation, farmers can use less water by choosing more efficient irrigation methods, such as **drip irrigation** (**Figure** 21.3). This irrigation system uses pipes and tubes to deliver small amounts of water directly to the soil at the roots of each plant or tree. It wastes less water than sprinklers and trenches, because almost all of the water goes directly to the soil and plant roots.

You might wonder why any farmer would not switch to efficient irrigation methods, since they would save so much water. There are two reasons. First, drip irrigation and other efficient irrigation methods cost more than trenches and sprinklers. Second, in some countries, such as the United States, the government pays for much of the cost of the water that is used for agriculture. Because, farmers do not have to pay the full price of the water they use, they do not have any financial reason or **incentive** to use less water.

Aquaculture

Aquaculture is the name for the type of farming you might do if you were raising fish, shellfish, algae or aquatic plants (**Figure** 21.4). This is a farming practice where plants and animals that live in water are raised. As the supplies of fish from lakes, rivers, and the oceans dwindle, people are getting more fish from aquaculture. Raising fish instead of hunting for them is a different way of increasing our food resources. The next time you pass the fish display in the grocery store, look for labels for “farm raised” fish. These fish would have been raised in an aquaculture setting.

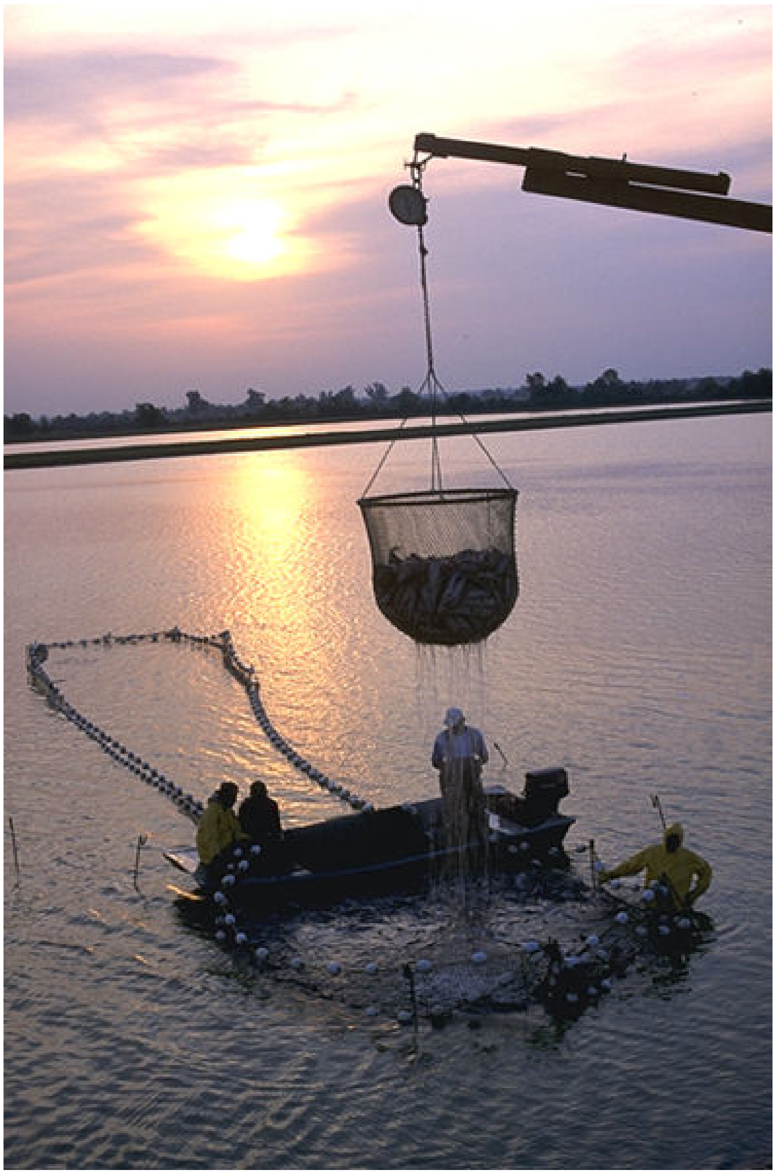


Figure 21.4: Aquaculture: Workers at a fish farm harvest fish they will sell to stores. (24)

Some of the most productive aquaculture farming takes place in wetland areas along coastlines. Rivers and streams carry nutrient-rich water into these wetlands, so fish and other animal life thrives. A good supply of nutrients is important when raising a large community of plants or animals. We need to be careful about the wastes that are added to our coastal waters when we increase plant and animal populations in these areas. Aquaculture can be considered a non-consumptive use of water, as long as we keep our coastal waters in good condition.

Industrial Water Use

Figure 21.5: Industrial water use: A power plant in Poland sits on the edge of a lake with easy access to water for cooling and other purposes. (8)

However, industrial water use accounts for an estimated fifteen percent of worldwide water use. Industries include power plants that use water to cool their equipment, and oil refineries that use water for chemical processes (**Figure** 21.5). Industry also uses water in many manufacturing processes. Looking at water use in a completely different way, hydroelectric power plants are built along rivers and streams to generate energy. This is a very efficient way to use water that is also non-consumptive.

Household Use

Starting from when you wake up in the morning, count the ways you use water at home (**Figure** 21.6). You will need to count the water you drink, water used in cooking, bathing, flushing toilets, and even gardening. You will be surprised to notice how many times a day you use water. Have you ever had to go without water? The United States is a developed country. In developed countries, people use a lot of water each day. People living in lesser

Figure 21.6: Domestic water use. (20)

developed countries use far less water than people in the United States. Globally, household or personal water use is estimated to account for fifteen percent of world-wide water use.

Some household water uses are considered non-consumptive, because water is recaptured in sewer systems, treated and returned to surface water supplies for reuse. Watering lawns with sprinklers is an exception. Just like sprinkler irrigation on farms, yard sprinklers are consumptive and use large amounts of water.

We all have many ways to lower the amount of water we use at home. Hardware stores sell water-efficient home products, such as drip irrigation to water lawns and gardens, low flow shower heads and low flow toilets. What other ways can you use less water at home?

Recreational Use

Figure 21.7: Recreational Water: Many recreational activities, such as swimming and fishing, are non-consumptive water activities; which won't deplete the water supply. (22)

Which sports use water? Swimming, fishing, and boating are easy examples to think about (**Figure** 21.7). Do you think playing golf requires water? Actually it does, because we irrigate the golf course in order to keep it nice and green! The amount of water that most recreational activities use is low: less than one percent of all the water we use.

Most recreational water uses are non-consumptive. That would include swimming, fishing, and boating. We can swim, fish, and boat without reducing the water supply. The same is not true for playing golf, which is the biggest recreational water consumer. Golf courses require large amounts of water. Water used for golf courses is generally consumptive, since most of it is lost to evaporation, soil, and runoff.

Environmental Use

Figure 21.8: Environmental Water Use: Wetlands and other environments depend on clean water to survive. Water shortages are a leading cause of global biodiversity loss. (14)

Environmental uses include activities to create habitat for wildlife, such as building lakes and fish ladders to help fish spawn (**Figure** 21.9). Most environmental uses are non-consumptive; they account for even less water use than recreation.

California Water Resources

California has a rich water supply from many sources. The winter snow pack in the Sierra Nevada and other mountain ranges feeds rivers that crisscross the state. Many of these streams feed into the Sacramento River in the northern part of the Central Valley, and the San Joaquin River in the southern portion (**Figure** 21.9). Virtually all of these rivers are dammed, some more than once, to supply power and water to the cities and farmland of the state.

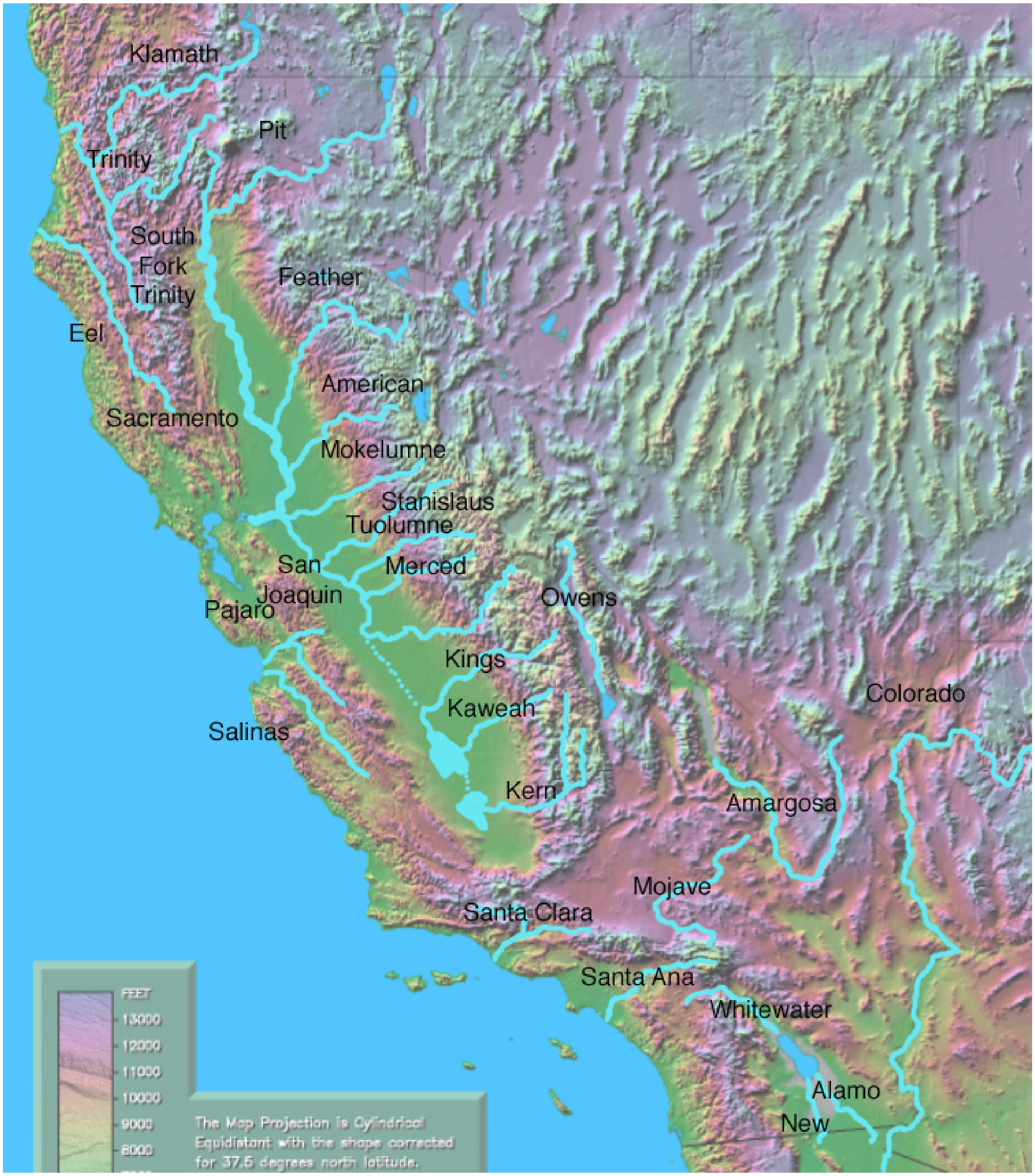


Figure 21.9: California rivers. (6)

Groundwater is also an important source of water in California. In a normal year about 40% of the state's water supply comes from groundwater. In a drought year, the number can rise to 60% or more. The largest groundwater reservoirs are found in the Central Valley where thousands of years of snow melt has fed the aquifers. In many locations, much more groundwater is used each year than is available to recharge the aquifer. Subsidence of the land is common in these regions.

Despite these vast water sources, the states large population and enormous agricultural landscape put a strain on the water supply. Water rights in California are complex and controversial. Although about 75% of the water resources are in the northern one-third of the state, the largest usage, about 80%, is in the southern two-thirds. Besides projects that exist to distribute water within the state, a large source of water is the Colorado River, which California must share with five other states and Mexico. The distribution of water resources in the Western United States will be a topic of much discussion in the coming decades.

Lesson Summary

- Human water use can be lumped into five categories. The uses are arranged in order of greatest to the least amounts of total water use on Earth:

- Agriculture (sixty-nine percent)
- Industry uses (fifteen percent of global water use)
- Home and Personal use (fifteen percent)
- Recreation uses (less than one percent)
- Environmental use (less than one percent)

- Despite California's abundant water supply from surface streams and groundwater, the state has a number of water rights issues that will be important long into the future.

Review Questions

1. Describe the three water uses that consume the most fresh water.
2. Explain why humans are limited to using less than one percent of all the water on Earth for our needs.
3. List two reasons why human water use has increased tremendously during the past century.
4. Describe four consequences of water shortages.
5. What does the phrase 'water is more valuable than gold' mean?
6. Describe why some water uses are called consumptive.
7. Describe drip irrigation and why it wastes less water than irrigating with sprinklers.
8. Describe why droughts are more serious in arid regions of the world than in wetter regions.

9. What is the origin of California's fresh water sources?

Vocabulary

consumptive Water use where water is 'lost' to evaporation.

drip irrigation Pipes & tubes that deliver small amounts of water directly to the soil at the roots.

incentive A financial benefit for taking a particular action.

non-consumptive Water use that does not 'use up' the water supply.

Points to Consider

- How could fresh water be more valuable than gold or a diamond?
- Which human activity uses more water than all other activities combined?
- Why don't all farmers use drip irrigation and other water efficient irrigation methods?

21.2 Problems with Water Distribution

Learning Objectives

- Explain why water shortages are increasingly frequent throughout the world.
- Discuss why 1.1 billion people (one fifth of the people on Earth) do not have access to safe drinking water.
- Explain why humans can use less than one percent of all water on Earth.
- Discuss the ways in which human water demands are unsustainable.

Introduction

Humans are facing a worldwide water crisis according to the United Nations. The crisis includes worldwide shortages of fresh water that humans can access, scarcity of safe drinking water supplies and water pollution.

World Water Supply and Distribution

Water is everywhere. More than 70% of the Earth's surface is covered by water. The Earth has a limited supply of water that we can use. There are supplies of freshwater in lakes, rivers, streams, swamps, reservoirs, and even underground water rich regions of soil and rock, called **aquifers.** Almost anywhere you stand, there is water somewhere beneath you. Sometimes that water is just several meters below you, sometimes it is deeper within the Earth.

Still, this supply of freshwater is less than 1% of all of the water on Earth. Why is so little water available for human use? Two reasons:

- For most of our needs, humans cannot use saltwater, which makes up 97-98% of all water on Earth.
- Humans cannot use most of the freshwater on Earth, because is frozen in glaciers and icebergs, mainly in Greenland and Antarctica (**Figure** 21.10).

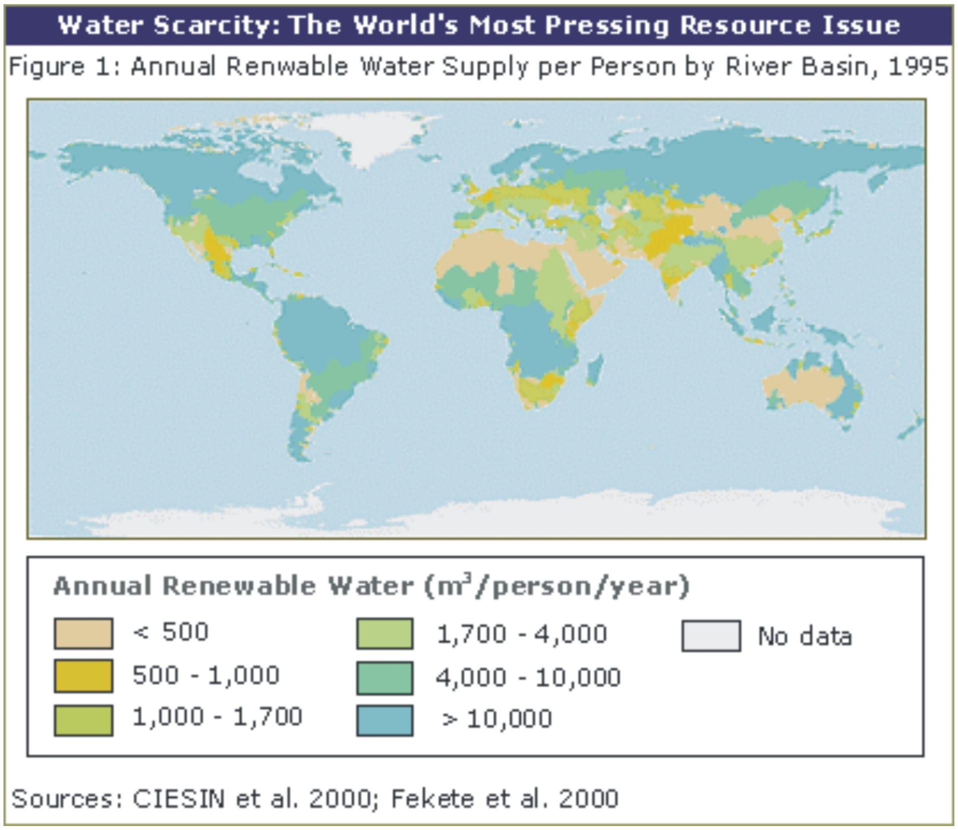
Figure 21.10: Most fresh water on Earth is in the form of frozen icebergs and glaciers. (11)

A common misconception is that water shortages can be solved by desalination, removing salt from seawater. This is because the desalination process requires so much energy and is so costly, that it is not an economical way to increase freshwater resources.

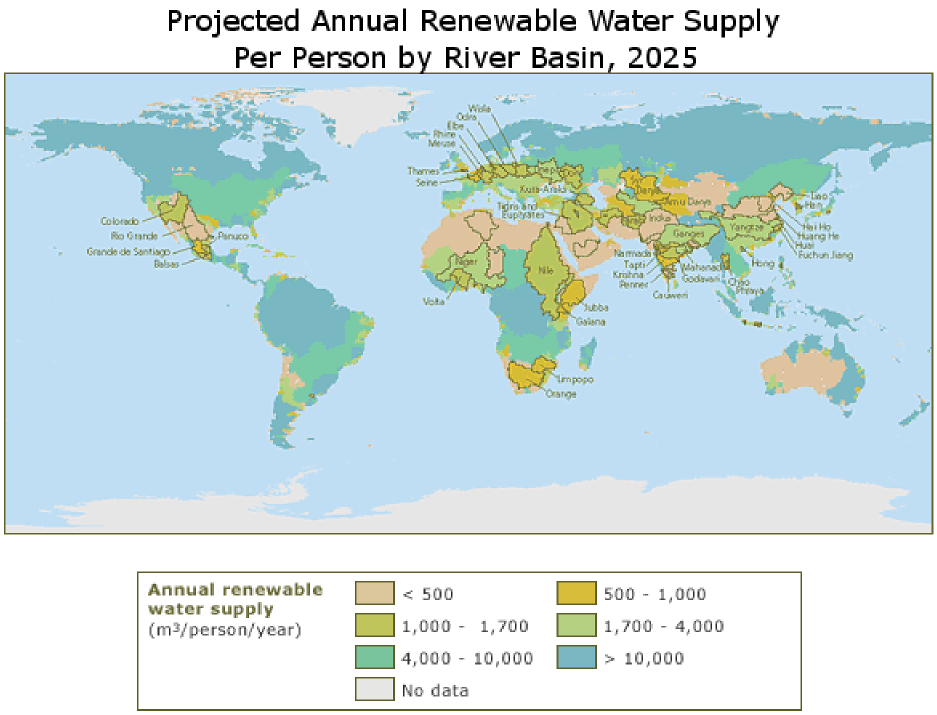
Water Distribution

Look closely at the climates of different regions around the Earth. Some places have water rich climates, while many others do not. Roughly 40% of the land on Earth is arid or semiarid, which means it receives little or almost no rainfall.

Water Distribution: Water is unevenly distributed across the world. The blue areas are the most water rich regions of the world. The salmon pink areas are desert areas. (Source: http://earthtrends.wri.org/maps_spatial/maps_detail_static.php?map_select=264&theme=2. CC-BY-SA)



Projected Water Distribution in 2025: The blue areas are the most water rich regions of the world. The salmon pink areas are desert areas. (Source: http://earthtrends.wri.org/maps_spatial/maps_detail_static.php?map_select=265&theme=2. CC-BY-SA)



Global warming affects patterns of rainfall and water distribution. As the Earth warms, regions that currently receive an adequate supply of rain may shift. Regions of Earth that normally are low pressure areas may become areas where high pressure dominates. That would completely change the types of plants and animals that can live successfully in that region.

In 1995, about 40% of the world's population faced water scarcity (**Figure** 21.11). Scientists believe that by the year 2025, nearly half of the world's people won't have enough water to meet their daily needs. Nearly one quarter of the people in the world will have less than 500 m^3 of water per person to use in an entire year. A cubic meter of water equals 1,000 liters. That means in certain areas of the world, many people will have less water available in a year than some people in the United States use in one day.

Water Shortages

Water Shortages Projections for 2025

As we continue to use our precious freshwater supplies, scientists expect that we will encounter several different types of problems. We currently irrigate our crops using supplies of groundwater in aquifers underground. When we have used up these groundwater supplies, we will not be able to grow as many different types of crops or we will have lower yields of the crops we grow. Using our freshwater often adds many different types of dissolved

Nearly Half the World Will Live With Water Scarcity by 2025

Figure 2: Global Renewable Water Supply per Person, 1995 and 2025 (projected)

Water Supply (m3/person /year)	1995 Population (millions)	1995 Percent of Total	2025 Population (millions)	2025 Percent of Total
<500	1,077	19.0	1,783	24.5
500-1,000	587	10.4	624	8.6
1,000-1,700	669	11.8	1,077	14.8
Subtotal	2,333	41.2	3,484	47.9
>1,700	3,091	54.6	3,494	48.0
Unallocated	241	4.2	296	4.0
Total	5,665	100.0	7,274	100.0

Source: WRI. The 2025 estimates are considered conservative because they are based on the United Nations' low-range projections for population growth, which has population peaking at 7.3 billion in 2025 (UNDP 1999:3). In addition, a slight mismatch between the water runoff and population data sets leaves 4 percent of the global population unaccounted in this analysis.

Figure 21.11: Water Supply Compared to Population. (4)

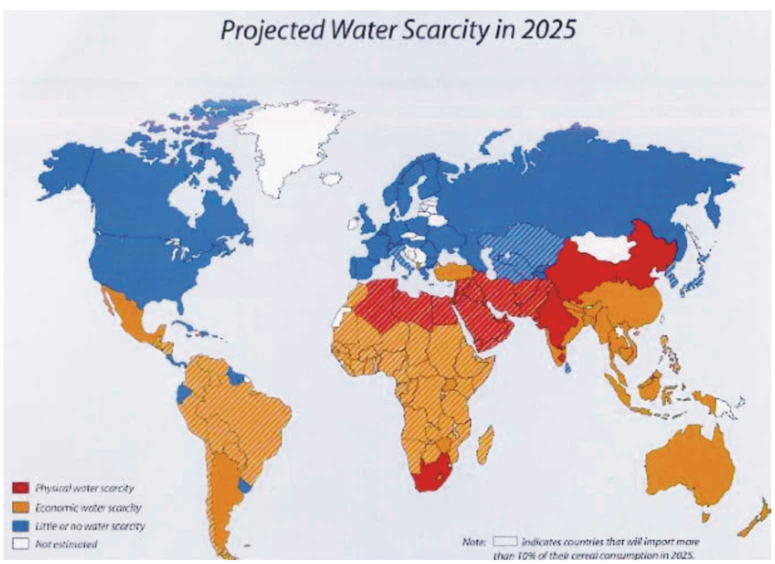


Figure 21.12: Water Scarcity Projections: If world-wide water use and population growth continues to grow at the current rate many people in the world will face serious water shortages. (23)

materials to the freshwater supply. This use may lead to pollution of our water resources and cause harm not only to humans but to many life forms, reducing our biodiversity. Most importantly, as our water supplies become scarce, there will be conflicts between individuals who have enough clean water and those who do not (**Figure** 21.12). As with any limited resource, this conflict could produce warfare.

Two of the most serious problems facing humans today are shortages of fresh water and the lack of safe drinking water.

Humans use six times as much water today as we did a hundred years ago. As the number of people on Earth continues to rise, our demand for water grows. Also, people living in developed countries use more water per person than individuals in lesser developed countries. This is because most of our activities today, such as farming, industry, building, and lawn care, are all water-intense practices, practices that require large amounts of water.

Droughts occur when for months or years, a region experiences unusually low rainfall (**Figure** 21.13). Periods of drought naturally make water shortages worse. Human activities, such as deforestation, can contribute to how often droughts occur. Trees and other land plants add water back into the atmosphere through transpiration. When trees are cut down, we break this part of the water cycle. Some dry periods are normal and can happen anywhere in the world. Droughts are a longer term event and can have serious consequences for a region. Because it is difficult to predict when droughts will happen, it is difficult for countries to predict how serious water shortages will be each year.

Water shortages hurt human health, agriculture and the environment. What happens when water supplies run out? In undeveloped regions in the world, people are often forced to move to a place where there is water. This can result in serious conflicts, even wars, between groups of people competing for water.

Water disputes happen in developed countries as well. Water-thirsty regions may build aqueducts, large canals or pathways to import water from other locations. For example, several cities in **arid** regions of the United States import water from the Colorado River. So much water is taken from the river that it can end as just a trickle when it reaches Mexico. Years ago, Mexico could depend on the river supplying water for irrigation and other uses. Today that water resource is gone from importing water upstream.

Some of the biggest legal battles in the United States have been over water rights, including access to the Colorado River. Water disputes may have lead to some of the earliest wars known.

Figure 21.13: Extended periods with lower than normal rainfall cause droughts. (21)

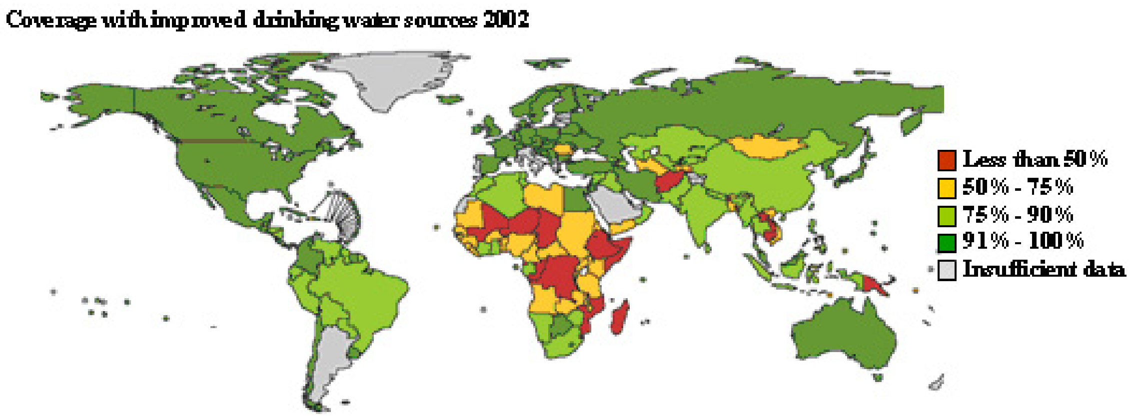


Figure 21.14: Access to improved drinking water and progress towards achieving the internationally agreed goals on water and sanitation. (1)

Problems with Water Quality

Scarcity of Safe Drinking Water

The next time you get water from your faucet, imagine life in a country that cannot afford the technology to treat and purify water. What would it be like if your only water came from a polluted river where sewage was dumped? Your only choice would be to drink polluted water. One fifth of all people in the world, more than 1.1 billion people, do not have access to safe water for drinking, personal cleanliness and domestic use. Unsafe drinking water can carry many disease-causing agents, such as infectious bacteria, toxic chemicals, radiological hazards, and parasites.

One of the leading causes of death worldwide is waterborne disease, disease caused by unsafe drinking water. It is also the leading cause of death for children under the age of five. Many children die when they only have unsafe drinking water and lack of clean water for personal hygiene. About eighty-eight percent of all diseases are caused by drinking unsafe water. At any given time, half of the world's hospital beds are occupied by patients suffering from a waterborne disease. The water you get from a faucet is safe because it has gone through a series of treatment and purification processes to remove contaminants.

Economic Considerations

A glass of water may be free in a restaurant, but this does not reflect its value as a resource. Water is often regarded as more valuable than gold, because human survival depends on having steady access to it.

Water scarcity can have dire consequences for the people, the economy and the environment. Without adequate water:

- Crops and livestock dwindle and people go hungry.
- Industrial, construction and economic development is halted.
- The risk of regional conflicts over scarce water resources rises.
- Ultimately some people die from lack of water.

Finding safe drinking water poses further challenges. What does it take for a country to provide its people with access to safe drinking water? It takes sophisticated technology to purify water, which removes harmful substances and **pathogens,** disease-causing organisms. Most developing countries lack the finances and the technology needed to supply their people with purified drinking water.

Water resources are so valuable, that wars have been fought over water rights throughout history. In many cases, water disputes add to tensions between countries where differing national interests and withdrawal rights have been in conflict (**Figure** 21.15).

Figure 21.15: The states and Canadian Provinces surrounding the Great Lakes have created a pact to control water in the lakes, preventing other states from over-draining the lakes. (9)

Some of today's greatest tensions are happening in places where water is scarce. Water disputes are happening along 260 different river systems that cross national boundaries including water disputes between:

- Iraq, Iran, and Syria
- Hungary and Czechoslovakia
- North and South Korea
- Iran and Syria
- Israel and Jordan
- Egypt and Ethiopia

International water laws, such as the Helsinki Rules, help interpret water rights among countries.

Lesson Summary

- Water is a renewable resource, but it is not unlimited. Humans are limited to less than one percent of the water on Earth. Also, water is not evenly distributed across the globe.

- Water is so valuable that countries have fought each other over water rights throughout history. Water shortages and water pollution have become so serious across the world, that some organizations call our water status a "water crisis." The crisis is blamed on overpopulation, overuse of water, pollution, and global warming.

- Undeveloped countries are rarely able to afford water treatment and purification facilities, unless other countries and international organizations help.

Review Questions

1. If most of the Earth is covered with water, how can there be water shortages?
2. Why are waterborne diseases more common in less developed countries than developed countries?
3. Why does the United Nations describe the current water status today as a crisis?
4. How do droughts affect water supplies?
5. Why do water disputes happen?
6. Give two reasons why water shortages are happening around the world today?

Vocabulary

aquifer Regions of soil or rock that are saturated with water.

arid Regions without enough water for things to grow.

drought A long period of lower than normal rainfall for a particular region.

pathogen Disease causing organisms.

Points to Consider

- What can we do to help the one fifth of the people on Earth who do not have access to safe drinking water?
- How can we reduce water shortages due to overuse, overpopulation, and drought?
- Water is so valuable that wars have been fought over it throughout history. Could conserving freshwater now help avoid future wars?

21.3 Water Pollution

Learning Objectives

- Discuss the risks that water pollution poses to human and environmental health.
- Explain where fresh and saltwater pollution come from.
- Discuss how pathogen born diseases are caused by water pollution.
- Describe why conserving water and protecting water quality is important to human health and the environment.
- Describe how water pollution reduces the amount of safe drinking water available.
- Discuss who is responsible for preventing and cleaning up water pollution.

Freshwater and ocean pollution are serious global problems that affect the availability of safe drinking water, human health and the environment. Waterborne diseases from water pollution kill millions of people in undeveloped countries every year.

Sources of Water Pollution

Water pollution can make our current water shortages even worse than they already are. Imagine that all of your drinking water came from a river polluted by industrial waste and sewage. In undeveloped countries throughout the world, raw sewage is dumped into the same water that undeveloped people drink and bathe in. Without the technology to collect, treat and distribute water, people do not have access to safe drinking water. Throughout the world, more than 14,000 people die every day from waterborne diseases, like cholera which is spread through polluted water.

Even in developed countries that can afford the technology to treat water, water pollution affects human and environmental health.

Water pollution includes any contaminant that gets into lakes, streams and oceans. The most widespread source of water contamination in undeveloped countries is raw sewage dumped into lakes, rivers and streams. In developed countries, the three main sources of water pollution are:

- Agriculture, including fertilizers, animal waste and other waste, pesticides, etc.
- Industry, including toxic and nontoxic chemicals
- Municipal uses, including yard and human waste

Figure 21.16: Municipal and agricultural pollution. (15)

Types of Water Pollution

Municipal Pollution

Wastewater usually contains many different contaminants. This makes it difficult for the Environmental Protection Agency (EPA) to identify the main source when toxic chemicals are found in wastewater. The pollution coming from homes, stores and other businesses is called municipal pollution (**Figure** 21.16). Contaminants come from:

- Sewage disposal (some sewage is inadequately treated or untreated)
- Storm drains
- Septic tanks: sewage from homes
- Boats that dump sewage
- Yard runoff (See agriculture discussion of fertilizer waste)

Industrial Pollution

Many kinds of pollutants from factories and hospitals end up in our air and waterways (**Figure** 21.17). Some of the most hazardous industrial pollutants include:

- Radioactive substances from nuclear power plants, as well as medical and scientific

Figure 21.17: Industrial Waste Water: Polluted water coming from a factory in Mexico. The different colors of foam indicate various chemicals in the water and industrial pollution. (17)

uses.

- Other chemicals in industrial waste, such as heavy metals, organic toxins, oils, and solids.
- Chemical waste from burning high sulfur fossil fuels that cause acid rain.
- Inadequately treated or untreated sewage and solid wastes from inappropriate waste disposal.
- Oil and other petroleum products from supertanker spills and offshore drilling accidents.
- Heated water from industrial processes such as power stations.

Agricultural Pollution

Agriculture includes crops, livestock and poultry farming. Most agricultural contaminants are carried by runoff that carries fertilizers, pesticides, and animal waste into nearby waterways (**Figure** 21.18). Soil and silt erosion also contribute to surface water contamination.

Animal wastes expose humans and the environment to some of the most harmful disease causing organisms or pathogens. These include bacteria, viruses, protozoa, and parasites. Pathogens are especially harmful to humans, because they can cause many illnesses including typhoid and dysentery as well as minor respiratory and skin diseases.

You may be surprised to learn that even the fertilizers we use on our lawns and farm fields are extremely harmful to the environment. Fertilizers from lawns and farm fields wash into

Figure 21.18: Many types of agriculture add pollutants to groundwater. (12)

nearby rivers, lakes and the oceans. Fertilizers contain nitrates that promote tremendous plant growth in the water. Consequences of this accelerated plant growth include:

- Lakes, rivers and bays become clogged with a carpet of aquatic plants that block light from entering the water.
- Without light reaching plants in the water below, these organisms die.
- As the plants die, their decomposition uses up all the oxygen in the water. Without enough dissolved oxygen in the water, large numbers of plants, fish and bottom-dwelling animals die.

Every year you can see **dead zones**, hundreds of kilometers of ocean without fish or plant life (**Figure** 21.19). These dead zones occur in the Gulf of Mexico and other river delta areas due to water polluted with fertilizers. In 1999, a dead zone in the Gulf of Mexico reached over 7,700 square miles.

Ocean Water Pollution

Most (80 %) of ocean pollution comes as runoff from agriculture, industry, and domestic uses (**Figure** 21.20). These same kinds of runoff also pollute freshwater. The remaining 20% of water pollution comes from oil spills and people dumping sewage directly into the water.

Coastal pollution can make coastal water unsafe for humans and wildlife. After rainfall, there can be enough runoff pollution that beaches are closed to prevent the spread of disease from pollutants.

A large proportion of the fish stocks we rely on for food live in the coastal wetlands. Coastal runoff from farm waste often carries water-borne organisms that cause lesions that kill fish. Humans who come in contact with polluted waters and affected fish can also experience

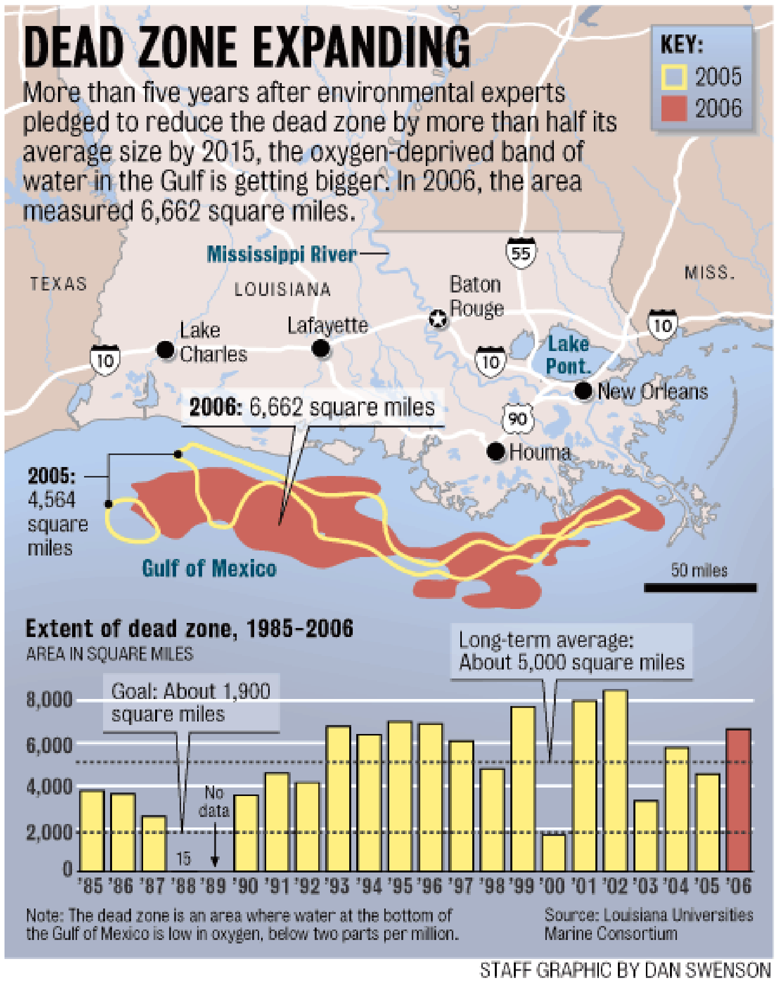


Figure 21.19: Agricultural Waste Water: A Dead Zone is a large area of water where fertilizer runoff pollutes farms and yards, ultimately killing off aquatic life. The size of the dead zone in the Gulf of Mexico varies at different times of the year. (13)

Figure 21.20: In some areas of the world, ocean pollution is all too obvious. (5)

harmful symptoms. More than one-third of the shellfish-growing waters of the United States are adversely affected by coastal pollution.

Thermal Water Pollution

Thermal pollution is anything that causes water temperatures to rise or fall (**Figure** 21.21). For example, power plants and other industries often use water to cool equipment. Once the water absorbs heat from a power plant or industry, the heated water is returned to the natural environment at a higher temperature. Cold water pollution can be observed when very cold water is released from reservoirs.

Figure 21.21: The Macquarie perch is now extinct in most of its upland river habitats partially due to thermal pollution by dams. (7)

Why would changing water temperature harm the environment? Fish and other aquatic organisms are often vulnerable to even small temperature changes. Heated water kills fish and other organisms by decreasing oxygen supply in the water. Frigid water has a severe effect on fish (particularly eggs and larvae), macro invertebrates and river productivity.

Lesson Summary

- Industrial, agricultural, and municipal sources produce harmful water pollutants such as toxic chemicals, radiological agents, and animal wastes. Thousands of people die from waterborne diseases every year.

Review Questions

1. What do the initials 'EPA' stand for?
2. What is runoff and why is it a problem?

3. Who is responsible for reducing water pollution?
4. Explain what a dead zone is and where you might find one?
5. What is the leading cause of death for children around the world?

Vocabulary

dead zone A region hundreds of kilometers wide without fish or plant life due to lack of oxygen in the water.

thermal pollution Water pollution created by added heat to water.

Points to Consider

- Water pollution not only harms human health and the environment. Consider how this reduces the amount of water available to humans.
- Fifty percent of all infectious diseases are caused by water pollution. What can be done to reduce the number of pathogens that reach our freshwater supplies?
- Ocean pollution harms some of the most productive sources of marine life. How can we change our behaviors to protect marine life?

21.4 Protecting the Water Supply

Learning Objectives

- Describe several ways water can be conserved.
- Discuss how water is treated to eliminate harmful particles.
- State what governments and international organizations can do to reduce water pollution.

Water Treatment

The goal of water treatment is to make water suitable for such uses as drinking water, medicine, agriculture and industrial processes.

People living in developed countries suffer from few waterborne diseases and illness, because they have extensive water treatment systems to collect, treat, and redeliver clean water to their people. Many undeveloped nations have few or no water treatment facilities.

Water treatment is any process used to remove unwanted contaminants from water (**Figure** 21.22). Water treatment processes are designed to reduce harmful substances such as suspended solids, oxygen-demanding materials, dissolved inorganic compounds, and harmful

Figure 21.22: Wastewater Treatment: Most wastewater treatment facilities separate contaminants from water by passing wastewater through a series of settlement containers. At each step, solids and particles are separated from water. Chemical and biological agents are also used to remove any remaining impurities. (10)

bacteria. Ideally, water treatment produces both liquids and solid materials that are not harmful the natural environment.

Water can contain hundreds of contaminants. Not all treatment processes are able to remove all of these particles and not all treated water is pure enough to qualify as safe drinking water. **Sewage treatment** is any process that removes contaminants from sewage or wastewater. **Water purification** is any process used to produce drinking water for humans by removing contaminants from untreated water. Purification processes remove bacteria, algae, viruses, and fungi, unpleasant elements such as iron and sulphur, and man-made chemical pollutants.

The choice of treatment method used depends on the kind of wastewater being treated. Most wastewater is treated using a series of steps, increasingly purifying the water at each step. Treatment usually starts with separating solids from liquids. Water may then be filtered or treated with chlorine. With each subsequent step, the water has fewer contaminants and the effluent is increasingly pure.

Reducing Water Pollution

How can people reduce water pollution? And who is responsible for doing it?

People have two ways to reduce any kind of pollution: We can prevent people from polluting water. And, we can use science to clean contaminants from water that is already polluted.

Governments can:

- Pass laws to control pollution emissions from different sources, such as factories and agriculture.
- Pass laws that require polluters to clean up water they pollute.
- Provide money to build and run water treatment facilities (and fund research to improve water quality technology).
- Educate the public, teach them how to prevent and clean up water pollution.
- Enforce laws.

The United Nations and other international groups have established organizations to improve global water quality standards. Some international organizations provide developing nations with the technology and education to collect, treat, and distribute water. Another priority is educating the people in these countries about how they can help improve the quality of the water they use.

In the United States, legislators passed the Clean Water Act which gives the Environmental Protection Agency the authority to sets standards for water quality for industry, agriculture and domestic uses (**Figure** 21.23).

Figure 21.23: Scientists control water pollution by sampling the water and studying the pollutants are in the water. (19)

One of the toughest problems is enforcement, catching anyone who is not following water regulations. Scientists are working to create methods to accurately track the source of water pollutants. Monitoring (tracking) methods allow the government to identify, catch and punish violators.

Who is responsible for reducing water pollution? Everyone who pollutes water is responsible for helping to clean it up. This includes individuals, communities, industries, and farmers.

Just a few of the things you can do to protect water quality include:

- Find approved recycling or disposal facilities for motor oil and household chemicals so these substances do not end up in the water.
- Use lawn, garden, and farm chemicals sparingly and wisely.
- Repair automobile or boat engine leaks immediately.
- Keep litter, pet waste, leaves, and grass clippings out of gutters and storm drains.

Controlling Ocean Pollution

Controlling seawater pollution and fresh water pollution are similar, but not exactly the same. We can try to prevent polluters from further spoiling the ocean and we can require polluters to clean up any pollution they cause. Government and international agencies can pass laws, provide funding, and enforce laws to prevent and clean up ocean pollution (**Figure** 21.24).

Several national and international agencies monitor and control ocean pollution. The agencies include the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency, the Department of Agriculture as well as other federal and state agencies.

When runoff pollution does cause problems, NOAA scientists help track down the exact causes and find solutions. This organization is also one of many organizations trying to educate the public on ways to prevent ocean pollution.

Conserving Water

As human population growth continues, water conservation will become increasingly important globally (**Figure** 21.25). Yet, the methods to conserve water are likely to differ between developing nations and developed countries.

For example, some people in undeveloped countries use so little water, that they may not gain much water by reducing their personal use. Meanwhile, large quantities of water can be conserved in the United States by finding ways to stop overconsumption of water.

At Earth Summit 2002 many governments approved a Plan of Action to address the scarcity of water and safe drinking water in developing countries. One goal of this plan is to cut in half, the number of people without access to safe drinking water by 2015.

Developed countries have many options to reduce water consumption. A farmer can cut water consumption drastically by using more efficient irrigation methods. People also have many opportunities to reduce our personal and household water demand with such measures as low flow shower heads, toilets that use less water, and drip irrigation to water lawns.

Figure 21.24: Many forms of marine pollution can be controlled by regulation such as the pumping of ballast water from ships. (16)

Figure 21.25: Low flow showerheads reduce the amount water used during showers. (18)

During prolonged droughts and other water shortages, some communities ration water use and prohibit such water intensive uses as watering lawns during the day and hosing down sidewalks. Often legislation is needed to provide incentives for individuals to reduce their water consumption.

Lesson Summary

- Many technologies are available to conserve water as well as to prevent and treat water pollution. Yet, most undeveloped countries cannot afford the technology they need to collect, treat and distribute water to their people.

- Developing countries may be able to afford water treatment systems, but people still need incentives to use conservation steps.

Review Questions

1. What is the purpose of water treatment and purification?
2. How can governments and international organizations help to reduce water pollution?
3. Name three things that a person could do to reduce pollution? Use lawn, garden or farming chemicals sparingly or use short term, specific chemicals, rather than long term broad spectrum chemicals. Repair engine leaks immediately. Keep litter, pet waste, leaves and grass clippings out of storm drains. Use an approved recycling center to dispose of motor oil and household chemicals and batteries.

4. Name three ways that you could reduce your personal water use.

Further Reading / Supplemental Links

- The American Association for the Advancement of Science, *AAAS Atlas of Population and Environment.* University of California Press, 2000.
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- http://www.epa.gov/lawsreg/laws/cwa.html
- http://en.wikibooks.org/wiki/Main_Page

Vocabulary

sewage treatment; Any process that removes contaminants from sewage or wastewater.

water purification Any process used to produce safe drinking water by removing contaminants.

Points to Consider

- Who is responsible for controlling water pollution?
- What can governments and international organizations do to control pollution?
- It is usually cheaper to dump polluted water without spending money to treat and purify the water. What incentives would convince industry to control water pollution?

Image Sources

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Chapter 22

Human Actions and the Atmosphere

22.1 Air Pollution

Lesson Objectives

- Describe the different types of air pollutants.
- Discuss what conditions lead some cities to become more polluted than others.
- Describe the sources of air pollutants.

Introduction

Earth's atmosphere supports life by providing the necessary gases for photosynthesis and respiration. The ozone layer protects life on Earth from the Sun's ultraviolet radiation. People also use the atmosphere as a dump for waste gases and particles. Pollutants include materials that are naturally-occurring but present in larger quantities than normal. In addition, pollutants consist of human-made compounds that have never before been found in the atmosphere. Pollutants dirty the air, change natural processes in the atmosphere, and harm living things. Excess greenhouse gases raise global temperatures.

Air Quality

Air pollution problems began centuries ago when fossil fuels began to be burned for heat and power. The problem grew into a crisis in the developed nations in the mid-20th century. Coal smoke and auto exhaust combined to create toxic smog that in some places caused lung damage and sometimes death. In Donora, Pennsylvania in October 1948, 20 people died and 4,000 became ill when coal smoke was trapped by an inversion. Even worse, in London in December 1952, the "Big Smoke" killed 4,000 people over five days, and it is likely that thousands more died of health complications from the event in the next several months (**Figure** 22.1).

Figure 22.1: A film crew recreates London smog in the Victorian Era. (2)

A different type of air pollution became a problem in Southern California after World War II. Although there was no coal smoke, cars and abundant sunshine produced **photochemical smog**. This smog is the result of a chemical reaction between some of the molecules in auto exhaust or oil refinery emissions, and sunshine. Photochemical smog consists of more than 100 compounds, most importantly ozone.

In the United States, these events led to the passage of the Clean Air Act in 1970. The act now regulates 189 pollutants. The six most important pollutants are ozone, particulate matter, sulfur dioxide, nitrogen dioxide, carbon monoxide, and the heavy metal lead. Other important regulated pollutants include benzene, perchloroethylene, methylene chloride, dioxin, asbestos, toluene, and metals such as cadmium, mercury, chromium, and lead compounds. Some of these will be discussed in the following section.

Besides human-caused emissions, air quality is affected by environmental factors. A mountain range can trap pollutants on its leeward side. Winds can move pollutants into or out of a region. Pollutants can become trapped in an air mass as a temperature inversion traps cool air beneath warm air. If the inversion lasts long enough, pollution can reach dangerous levels. Pollutants remain over a region until they are transported out of the area by wind, diluted by air blown in from another region, transformed into other compounds, or carried to the ground when mixed with rain or snow.

As a result of the Clean Air Act, air in the United States is much cleaner. Visibility is better and people are no longer incapacitated by industrial smog. Still, in the United States, industry, power plants and vehicles put 160 million tons of pollutants into the air each year. Some of this smog is invisible and some contributes to the orange or blue haze that affects many cities (**Figure** 22.2).

Table 22.1 lists the smoggiest cities in 2007: six of the 10 are in California. The state has the right conditions for collecting pollutants including mountain ranges that trap smoggy air, arid and sometimes windless conditions, and lots and lots of cars.

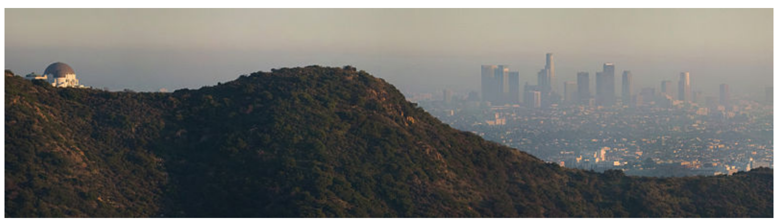

Figure 22.2: Smog over Los Angeles as viewed from the Hollywood Hills. (10)

Table 22.1: **Smoggiest Cities, 2007**

Rank	City, State
1	Los Angeles, California
2	Bakersfield, California
3	Visalia-Porterville, California
4	Fresno, California
5	Houston, Texas
6	Merced, California
7	Dallas-Fort Worth, Texas
8	Sacramento, California
9	New York, New York
10	Philadelphia, Pennsylvania

(*Source:* American Lung Association)

Types of Air Pollution

Most air pollutants enter the atmosphere directly; these are primary pollutants. Secondary pollutants become pollutants only after undergoing a chemical reaction. Primary pollutants include toxic gases, particulates, compounds that react with water vapor to form acids, heavy metals, ozone, and greenhouse gases. Ozone is one of the major secondary pollutants. It is created by a chemical reaction that takes place in exhaust and in the presence of sunlight.

Primary Pollutants

Some primary pollutants are natural, such as dust and volcanic ash, but most are caused by human activities. Primary pollutants are direct emissions from vehicles and smokestacks. Some of the most harmful pollutants that go directly into the atmosphere from human activities include:

- **Carbon oxides** include carbon monoxide (CO) and carbon dioxide (CO_2). Both are colorless, odorless gases. CO is toxic to both plants and animals. CO and CO_2 are both greenhouse gases.
- **Nitrogen oxides** are produced when nitrogen and oxygen from the atmosphere come together at high temperatures. This occurs in hot exhaust gas from vehicles, power plants or factories. Nitrogen oxide (NO) and nitrogen dioxide (NO_2) are greenhouse gases. Nitrogen oxides contribute to acid rain.
- **Sulfur oxides** include sulfur dioxide (SO_2) and sulfur trioxide (SO_3). These form when sulfur from burning coal reaches the air. Sulfur oxides are components of acid rain.
- **Particulates** are solid particles, such as ash, dust and fecal matter. They are commonly formed from combustion of fossil fuels, and can produce smog. In addition, particulate matter can contribute to asthma, heart disease, and some types of cancers.
- **Lead** was once widely used in automobile fuels, paint, and pipes. This heavy metal causes can cause brain damage or blood poisoning.
- **Volatile organic compounds** (VOCs) are mostly hydrocarbons, compounds made of hydrogen and carbon. Important VOCs include methane (a naturally occurring greenhouse gas that is increasing due to human activities), chlorofluorocarbons (human-made compounds that are being phased out because of their effect on the ozone layer), and dioxin (a byproduct of chemical production that serves no useful purpose, but is harmful to humans and other organisms).

Photochemical Smog

Any city can have photochemical smog, but it is most common in arid locations. A rise in the number of vehicles in cities worldwide has increased photochemical smog. This smog forms when car exhaust is exposed to sunlight. Nitrogen oxides are created in car combustion chambers. If there is sunshine, the NO_2 splits and releases an oxygen atom (O). The oxygen ion then combines with an oxygen molecule (O_2) to form ozone (O_3). This reaction can also go in reverse: Nitric oxide (NO) removes an oxygen atom from ozone to make it O_2. The direction the reaction proceeds depends on how much NO_2 and NO there is. If NO_2 is three times more abundant than NO, ozone will be produced. If nitrous oxide levels are high, ozone will not be created.

Ozone is an acrid-smelling, whitish gas. Warm, dry cities surrounded by mountains, such as Los Angeles, Phoenix, and Denver, are especially prone to photochemical smog (**Figure** 22.3). Photochemical smog peaks at midday on the hottest days of summer. Other compounds in addition to ozone are found in photochemical smog. Ozone is also a greenhouse gas.

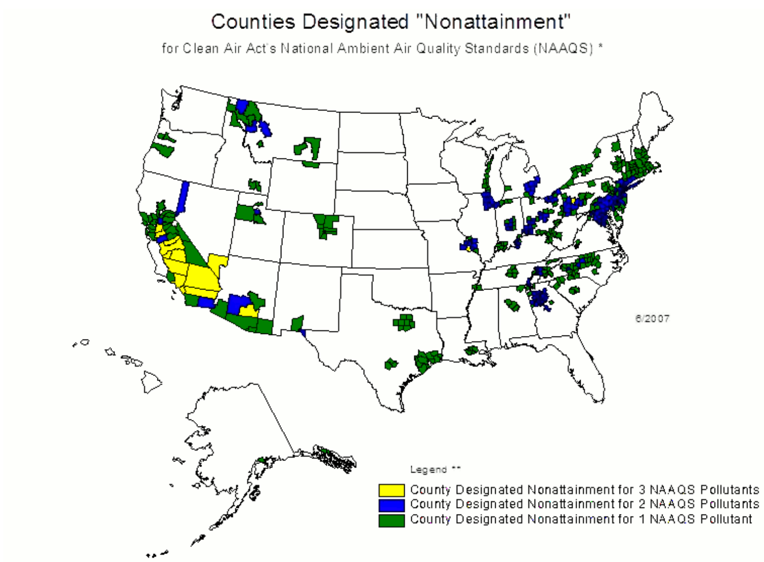

Figure 22.3: Counties with such high ozone levels that they do not attain federal air quality standards. (5)

Causes of Air Pollution

Most air pollutants come from burning fossil fuels or plant material. Some are the result of evaporation from human-made materials. Nearly half (49%) of air pollution comes from transportation, 28% from factories and power plants, and the remaining pollution from a variety of other sources.

Fossil Fuels

Fossil fuels are burned in most motor vehicles and power plants (**Figure** 22.4). They fuel manufacturing and other industries. Pure coal and petroleum can theoretically burn cleanly, emitting only carbon dioxide and water, which are both greenhouse gases. But most of the time, these fossil fuels do not completely burn, so these incomplete chemical reactions produce pollutants. In addition, few fossil fuels are pure and so other pollutants are usually released. These pollutants include carbon monoxide, nitrogen dioxide, sulfur dioxide and hydrocarbons.

Figure 22.4: A power plant and its emissions before emission control equipment was added. (8)

In large car-dependent cities such as Los Angeles and Mexico City, 80% to 85% of air pollution is from motor vehicles. Auto emissions are the most common source of ozone. Carbon monoxide is toxic in enclosed spaces like tunnels. Nitrous oxides come from the exhaust from a vehicle or a factory. Lead was once put in gasoline to improve engine knock, but is now banned in the United States. Still, enormous quantities of lead are released into the air every year from other sources.

A few pollutants come primarily from power plants or industrial plants. They pour out of smokestacks that burn coal or oil. Sulfur dioxide (SO_2) is a major component of industrial air pollution. It is released whenever coal and petroleum are burned. SO_2 mixes with H_2O in the air to produce sulfuric acid (H_2SO_4). The heavy metal mercury is released when coal and some types of wastes are burned. Mercury is emitted as a gas, but as it cools, it becomes a droplet. Mercury droplets eventually fall to the ground. If they fall into sediments, bacteria convert them to the most dangerous form of mercury: methyl mercury. Highly toxic, methyl mercury is one of the metal's organic forms.

Biomass Burning

Fossil fuels are ancient plants and animals that have been converted into usable hydrocarbons. Burning plant and animal material directly also produces pollutants. **Biomass** is the total amount of living material found in an environment. The biomass of a rainforest is the amount of living material found in that rainforest.

The primary way biomass is burned is by **slash-and-burn agriculture** (**Figure** 22.5). The rainforest is slashed down and then the waste is burned to clear the land for farming. Biomass from other biomes, like savannah, is also burned to clear farmland. The pollutants are much the same as from burning fossil fuels: CO_2, carbon monoxide, methane, particulates, nitrous oxide, hydrocarbons, and organic and elemental carbon. Burning forests increase greenhouse gases in the atmosphere by releasing the CO_2 stored in the biomass and also by removing the forest so that it cannot store CO_2 in the future. As with all forms of air pollution, the smoke from biomass burning often spreads far and pollutants can plague neighboring states or countries.

Figure 22.5: A forest that has been slash-and-burned to make new farmland. (7)

Particulates result when anything is burned. About 40% of the particulates that enter the atmosphere above the United States are from industry and about 17% are from vehicles. Particulates also occur naturally from volcanic eruptions or windblown dust. Like other pollutants, they travel all around the world on atmospheric currents.

Evaporation

Volatile organic compounds (VOCs) enter the atmosphere by evaporation. VOCs evaporate from human-made substances, such as paint thinners, dry cleaning solvents, petroleum, wood preservatives, and other liquids. Naturally occurring VOCs evaporate off of pine and citrus trees. The atmosphere contains tens of thousands of different VOCs, nearly 100 of which are monitored. The most common is methane, a greenhouse gas. Methane occurs naturally, but human agriculture is increasing the amount of methane in the atmosphere.

Lesson Summary

- Industrial pollution causes health problems and even death, though the Clean Air Act has decreased these health problems in the United States by forcing industry to clean their emissions.
- The increase in motor vehicles in arid cities has increased ozone and other secondary pollutants in these regions.
- Burning fossil fuels is the greatest source of air pollution.
- Biomass burning is also a large source, especially in places where slash-and-burn agriculture is practiced.

Review Questions

1. What is the difference between the type of smog experienced by cities in the eastern United States and that found in Southern California?
2. London has suffered from terrible air pollution for at least seven centuries. Why is the city so prone to its famous "London fog?" What did London do to get rid of its air pollution?
3. Imagine two cities of the same size with the same amount of industrialization and the same number of motor vehicles. City A is incredibly smoggy most of the time and City B usually has very little air pollution. What factors are important for creating these two different situations?
4. What might be a reason why the city of San Francisco and its metropolitan area not on the list of smoggiest cities for 2007?
5. Why are naturally-occurring substances, like particulates or carbon dioxide, sometimes considered pollutants?
6. How does ozone form from vehicle exhaust?
7. What are the necessary ingredients for ozone creation, excluding those that are readily available in the atmosphere? Why could there be a city with a lot of cars but relatively little ozone pollution?
8. Some people say that we need to phase out fossil fuel use and replace it with clean energy. Why is fossil fuel use becoming undesirable?

9. Mercury is not particularly toxic as a metal but it is very dangerous in its organic form. How does mercury convert from the metal to the organic form?
10. In what two ways does deforestation contribute to air pollution?

Vocabulary

lead A heavy metal found in a large number of products. Exposure to too much lead causes lead poisoning, which harms people's brain and blood.

mercury A heavy metal that enters the atmosphere primarily from coal-burning power plants. Mercury that has been converted to an organic form (methylmercury) is highly toxic.

ozone Three oxygen atoms bonded together in an O_3 molecule. Ozone in the lower atmosphere is a pollutant but in the upper atmosphere protects life from ultraviolet radiation.

particulates Particles like ash, dust and fecal matter in the air. Particulates may be caused by natural processes, such as volcanic eruptions or dust storms, or they may be caused by human activities, like burning fossil fuels or biomass.

photochemical smog This type of air pollution results from a chemical reaction between pollutants in the presence of sunshine.

slash-and-burn agriculture In the tropics, rainforest plants are slashed down and then burned to clear the land for agriculture.

volatile organic compounds (VOCs) Pollutants that evaporate into the atmosphere from solvents and other humanmade compounds. Some VOCs occur naturally.

Points to Consider

- Despite the Clean Air Act, the air over many regions in the United States is still not clean. Why?
- How do pollutants damage human health?
- In what ways does air pollution harm the environment?

22.2 Effects of Air Pollution

Lesson Objectives

- Describe the damage that is being done by smog.
- Discuss how acid rain is formed and the damage it does.
- Discus how chlorofluorocarbons destroy the ozone layer.

Introduction

People in developing countries often do not have laws to protect the air that they breathe. The World Health Organization estimates that 22 million people die each year from complications due to air pollution. Even in the United States, more than 120 million Americans live in areas where the air is considered unhealthy. This lesson looks at the human health and environmental problems caused by different types of air pollution.

Smog

All air pollutants cause some damage to living creatures and the environment. Different types of pollutants cause different types of harm. Particulates reduce visibility. For example, in the western United States, people can now ordinarily see only about 100 to 150 kilometers (60 to 90 miles), which is one-half to two-thirds the natural (pre-pollution) range on a clear day. In the East, visibility is worse. People can only see about 40 to 60 kilometers (25-35 miles), which is one-fifth the distance they could see without any air pollution.

Particulates reduce the amount of sunshine that reaches the ground. Since plants also receive less sunlight, there may be less photosynthesis. Particulates also form the nucleus for raindrops, snowflakes or other forms of precipitation. An increase in particles in the air seems to increase the number of raindrops, but often decreases their size. By reducing sunshine, particulates can also alter air temperature. In the three days after the terrorists attacks on September 11, 2001, jet airplanes did not fly over the United States. Without the gases from jet contrails blocking sunlight, air temperature increased 1°C (1.8°F) across the U.S (**Figure** 22.6). Imagine how much all of the sources of particulates combine to reduce temperatures.

Ozone damages some plants. Since ozone effects accumulate, plants that live a long time show the most damage. Some species of trees appear to be the most susceptible. If a forest contains ozone-sensitive trees, they may die out and be replaced by species that are not as easily harmed. This can change an entire ecosystem, since animals and plants may not be able to survive without the habitats created by the native trees.

Some crop plants show ozone damage. When exposed to ozone, spinach leaves become

Figure 22.6: Jet contrails block sunlight. (9)

spotted. Soybeans and other crops have reduced productivity. In developing nations, where getting every last bit of food energy out of the agricultural system is critical, any loss is keenly felt. Many of these nations, like China and India, also have heavy air pollution. Some pollutants have a positive effect on plant growth. Increased CO_2 seems to lessen ozone damage to some plants and it may promote growth. Unfortunately, CO_2 and other greenhouse gases cause other problems that harm the ecosystem and reduce growth of some plants.

Other air pollutants damage the environment (**Figure** 22.7). NO_2 is a toxic, orange-brown colored gas that gives air a distinctive orange color and an unpleasant odor. Nitrogen and sulfur-oxides in the atmosphere create acids that fall as acid rain. Human health suffers in locations with high levels of air pollution. Lead is the most common toxic material for humans and is responsible for lead poisoning. Carbon monoxide is a toxic gas and can kill people in poorly ventilated spaces, like tunnels. Nitrogen and sulfur-oxides cause lung disease and increase rates of asthma, emphysema, and viral infections like flu. Ozone also damages the human respiratory system, causing lung disease. High ozone levels are also associated with increased heart disease and cancer. Particulates enter the lungs and cause heart or lung disease. When particulate levels are high, asthma attacks are more common. By some estimates, 30,000 deaths a year in the United States are caused by fine particle pollution.

Although not all cases of asthma can be linked to air pollution, many can. During the 1996 Olympic Games, Atlanta, Georgia closed off their downtown to private vehicles. As a result, ozone levels decreased by 28%. At the same time, there were 40% fewer hospital visits for asthma.

Lung cancer among non-smokers is also increasing. One study showed that the risk of being afflicted with lung cancer increases directly with a person's exposure to air pollution. The

Figure 22.7: Smog in New York City. (12)

study concluded that no level of air pollution should be considered safe. Exposure to smog also increased the risk of dying from any cause, including heart disease.

Children are more vulnerable to problems from breathing dirty air than adults because their lungs are still growing and developing. Children take in 50% more air for their body weight than adults. Children spend more time outside in unfiltered air and are more likely to breathe hard from playing or exercising. One study found that in the United States, children develop asthma at more than twice the rate of two decades ago and at four times the rate in Canada. Adults also suffer from air pollution-related illnesses that include lung disease, heart disease, lung cancer, and weakened immune systems. The asthma rate worldwide is rising 20% to 50% every decade.

Especially dangerous are pollutants that remain in an organism throughout its life, called **bioaccumulation**. In this process, an organism accumulates the entire amount of a toxic compound that it consumes over its lifetime. Not all substances bioaccumulate. A person who takes a daily dose of aspirin only has that day's worth of aspirin in her system, because aspirin does not stay within her system. When a compound bioaccumulates, the person has all of that compound she's ever eaten in her system. Compounds that bioaccumulate are usually stored in the organism's fat.

Mercury is a good example of a substance that bioaccumulates. Bacteria and plankton store all of the mercury from all of the seawater they ingest. A small fish that eats bacteria and plankton accumulates all of the mercury from all of the tiny creatures it eats over its lifetime. A big fish accumulates all of the mercury from all of the small fish it eats over its lifetime. The organisms that accumulate the most mercury are the large predators that eat high on the food chain. Tuna pose a health hazard to anything that eats them because their bodies are so high in mercury. This is why the government recommends limits on the amount of tuna that people eat. These limits are especially important for children and pregnant women, since mercury particularly affects young people. If the mercury just stayed in fat, it would not be harmful, but that fat is used when a woman is pregnant or nursing a baby, or when she burns the fat while losing weight. Methyl mercury poisoning can cause nervous system or brain damage, especially in infants and children. Children may experience brain damage or developmental delays. Like mercury, other metals and VOCS can bioaccumulate, causing harm to animals and people high on the food chain.

Acid Rain

Acid rain is caused by sulfur and nitrogen oxides. These pollutants are emitted into the atmosphere from power plants or metal refineries. The oxides come out of smokestacks that have been built tall so that pollutants don't sit over cities. The high smokestacks allow the emissions to rise high into the atmosphere and travel up to 1000 km (600 miles) downwind. As they move, these pollutants combine with water vapor to form sulfuric and nitric acids. The acid droplets form acid fog, rain, snow, or they may be deposited dry. Most typical is **acid rain** (**Figure** 22.8).

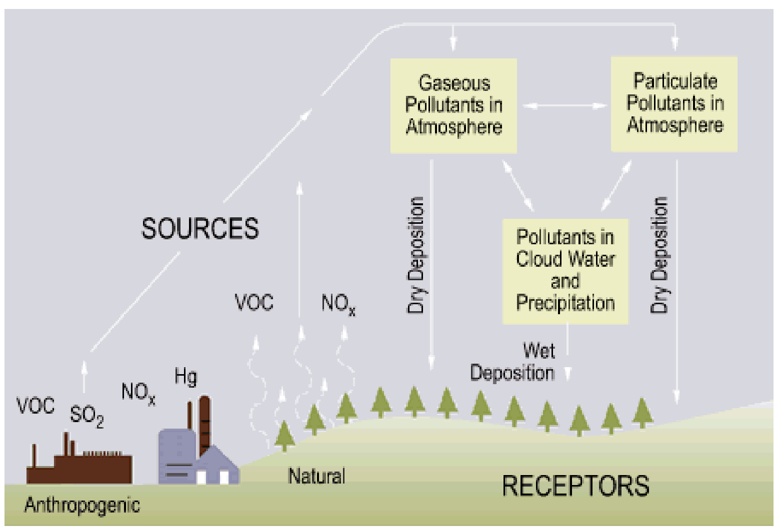

Figure 22.8: How acid rain is formed. Anthropogenic pollutants are those that are human-made. Deposition of a pollutant occurs when it is placed on a surface. Rain can bring wet deposition or a pollutant can be blown onto the ground for dry deposition. (4)

Acid rain water is more acidic than normal rain water. To be called acid rain, it must have a pH of less than 5.0. Acidity is measured on the **pH scale**, which goes from 1 to 14. A value of 7 is neutral. Lower numbers are more acidic and higher numbers are less acidic (also called more **alkaline**). The strongest acids are at the low end of the scale and the strongest bases are at the high end. Natural rain is somewhat acidic with a pH of 5.6. The acid comes from carbonic acid that forms when CO_2 combines with water in the atmosphere. A small change in pH represents a large change in acidity: rain with a pH of 4.6 is 10 times more acidic than normal rain (with a pH of 5.6). Rain with a pH of 3.6 is 100 times more acidic.

Regions that have a lot of coal-burning power plants have the most acidic rain. The acidity of average rainwater in the northeastern United States has fallen to between 4.0 and 4.6. Acid fog has even lower pH with an average of around 3.4. One fog in Southern California in 1986 had a pH of 1.7, equal to toilet bowl cleaner. In arid climates, like in Southern California, acids deposit on the ground dry. Acid precipitation ends up on the land surface and in water bodies. Some forest soils in the northeast are 5 to 10 times more acidic than they were two or three decades ago. Acid droplets move down through acidic soils to lower the pH of streams and lakes even more. Acids strip soil of metals and nutrients, which collect in streams and lakes. As a result, stripped soils may no longer provide the nutrients that native plants need.

Acid rain takes a toll on ecosystems (**Figure** 22.9). Plants that are exposed to acids become weak and are more likely to be damaged by bad weather, insect pests, or disease. Snails die in acid soils, so songbirds do not have as much food to eat. Young birds and mammals do not build bones as well and may not be as strong. Eggshells may also be weak and break more easily.

Figure 22.9: Acid rain has killed trees in this forest in the Czech Republic. (3)

The nitrates found in acid rain cause some plants to grow better. These nitrate-lovers can drive out other plants, which may cause the ecosystem to change. Nitrates also fertilize the oceans, which makes more algae grow. The algae use up all the oxygen in the water, which can bring about disastrous ecological changes, including the deaths of many fish. As lakes become acidic, organisms die off. If the pH drops below 4.5, all the fish die. Organic material cannot decay, and mosses take over the lake. Wildlife that depend on the lake for drinking water suffer population declines. Crops are damaged by acid rain. This is most noticeable in poor nations where people can't afford to fix the problems with fertilizers or other technology. Buildings and monuments are damaged by acid precipitation (**Figure** 22.10). These include the U.S. Capital and many buildings in Europe, such as Westminster Abbey.

Figure 22.10: Acid rain damages cultural monuments like buildings and statues. (6)

Carbonate rocks can neutralize acids and so some regions do not suffer the effects of acid rain nearly as much. The Midwestern United States is protected by the limestone rocks throughout the area, which are made up of calcium carbonate. One reason that the northeastern United States is so vulnerable to acid rain damage is that the rocks are not carbonates.

Because pollutants can travel so far, much of the acid rain that falls hurts states or nations other than ones where the pollutants were released. All the rain that falls in Sweden is acidic and fish in lakes all over the country are dying. The pollutants come from the United Kingdom and Western Europe, which are now working to decrease their emissions. Canada also suffers from acid rain that originates in the United States, a problem that is also improving. Southeast Asia is experiencing more acid rain between nations as the region industrializes.

Ozone Depletion

At this point you might be asking yourself, "Is ozone bad or is ozone good?" There is no simple answer to that question: It depends on where the ozone is located. In the troposphere, ozone is a pollutant. Higher up, in the stratosphere, ozone screens out high energy ultraviolet radiation and thus makes Earth habitable. This protective ozone is found in the ozone layer.

The ozone layer is being attacked by human-made chemicals that break ozone molecules apart in the stratosphere. The most common of these chemicals are chlorofluorocarbons (CFCs), but includes others such as halons, methyl bromide, carbon tetrachloride, and methyl chloroform. CFCs were once widely used because they are cheap, nontoxic, nonflammable, and non-reactive. They were used as spray-can propellants, refrigerants, and in many other products.

Once they are released into the air, CFCs float up to the stratosphere. Air currents move them toward the poles. In the winter, they freeze onto nitric acid molecules in polar stratospheric clouds (PSC). PSCs form only where the stratosphere is coldest, and are most common above Antarctica in the wintertime. In the spring, the sun's warmth starts the air moving, and ultraviolet light breaks the CFCs apart. The chlorine atom floats away and attaches to one of the oxygen atoms on an ozone molecule. The chlorine pulls the oxygen atom away, leaving behind an O_2 molecule, which provides no UV protection. The chlorine then releases the oxygen atom and moves on to destroy another ozone molecule. One CFC molecule can destroy as many as 100,000 ozone molecules.

Ozone destruction creates the **ozone hole** where the layer is dangerously thin (**Figure** 22.11). As air circulates over Antarctica in the spring, the ozone hole expands northward over the southern continents, including Australia, New Zealand, southern South America, and southern Africa. UV levels may rise as much as 20% beneath the ozone hole. The hole was first measured in 1981 when it was 2 million square km (900,000 square miles)). The 2006 hole was the largest ever observed at 28 million square km (11.4 million square miles). It had the lowest ozone levels ever recorded and also lasted the longest. The difference in the size of the ozone hole each year depends on many factors, including whether conditions are right for the formation of polar stratospheric clouds.

Ozone loss also occurs over the north polar region, but it is not enough for scientists to call it a hole. The region of low ozone levels is small because the atmosphere is not as cold and PSCs do not form as readily. Still, springtime ozone levels are relatively low. This low moves south over some of the world's most populated areas in Europe, North America, and Asia. At 40°N, the latitude of New York City, UV-B has increased about 4% per decade since 1978. At 55°N, the approximate latitude of Moscow and Copenhagen, the increase has been 6.8% per decade since 1978.

Ozone losses in population centers increase sunburns, cataracts (clouding of the lens of the eye), and skin cancers. A loss of ozone of only 1% is estimated to increase skin cancer cases by 5 to 6%. People may also suffer from decreases in their immune system's ability to fight off infectious diseases. Ozone loss may reduce crop yields, since many plants are sensitive to ultraviolet light. Excess UV appears to be decreasing the productivity of plankton in the oceans. A decrease of 6 to 12% has been measured around Antarctica, which may be at least partly related to the ozone hole. The effects of excess UV on other organisms is not known. When the problem with ozone depletion was recognized, world leaders took action. CFCs were banned in spray cans in some nations in 1978. The greatest production of CFCs was in 1986, but has declined since then. This will be discussed more in the next lesson.

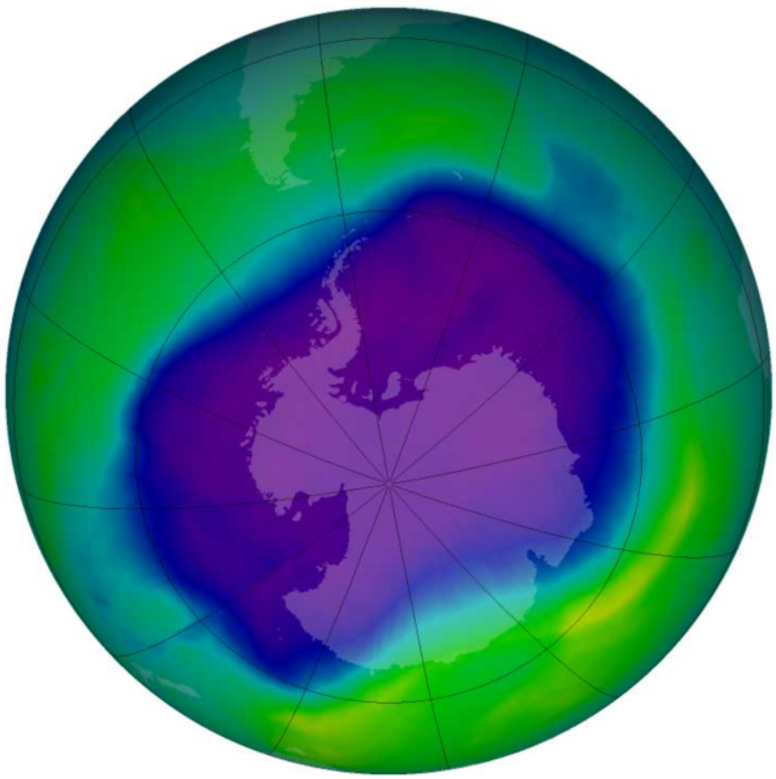

Figure 22.11: The September 2006 ozone hole, the largest ever observed. Blue and purple colors show particularly low levels of ozone. (13)

Lesson Summary

- Air pollutants damage human health and the environment. Particulates reduce visibility, alter the weather, and cause lung problems like asthma attacks.
- Ozone damages plants and can also cause lung disease. Acid rain damages forests, crops, buildings and statues.
- The ozone hole, caused by ozone-destroying chemicals, allows more UV radiation to strike the Earth.
- This can cause plankton populations to decline and skin cancers in humans to increase, along with other effects.

Review Questions

1. Why is visibility so reduced in the United States?
2. Why do health recommendations suggest that people limit the amount of tuna they eat?
3. Why might ozone pollution or acid rain change an entire ecosystem?
4. Why does air pollution cause problems in developing nations more than in developed ones?
5. Why are children more vulnerable to the effects of air pollutants than adults?
6. Describe bioaccumulation.
7. How does pollution indirectly kill or harm plants?
8. What do you think the effect is of jet airplanes on global warming?
9. Why is air pollution a local, regional and global problem?
10. How do CFCs deplete the ozone layer?

Vocabulary

acid rain Rain that has a pH of less than 5.0.

alkaline Also called basic. Substances that have a pH of greater than 7.0.

bioaccumulation The accumulation of toxic substances within organisms so that the concentrations increase up the food web.

ozone hole A region around Antarctica in which ozone levels are reduced in springtime, due to the action of ozone-destroying chemicals.

pH scale A scale that measures the acidity of a solution. A pH of 7 is neutral. Smaller numbers are more acidic and larger numbers are more alkaline.

polar stratospheric clouds (PSC) Clouds that form in the stratosphere when it is especially cold; PSCs are necessary for the breakup of CFCs.

Points to Consider

- Since mercury bioaccumulates and coal-fired power plants continue to emit mercury into the atmosphere, what will be the consequence for people who like to eat tuna and other large predatory fish?
- What are the possible causes of rising asthma rates in children?
- A ban has been imposed on CFCs and some other ozone-depleting substances. How will the ozone hole change in response to this ban?

22.3 Reducing Air Pollution

Lesson Objectives

- Describe the major ways that energy use can be reduced.
- Discuss new technologies that are being developed to reduce air pollutants, including greenhouse gases.
- Describe the difference between placing caps on emissions and reducing emissions.

Introduction

The Clean Air Act of 1970 and the amendments since then have done a great job in requiring people to clean up the air over the United States. Emissions of the six major pollutants regulated by the Clean Air Act, carbon monoxide, lead, nitrous oxides, ozone, sulfur dioxide, and particulates, have decreased by more than 50%. Cars, power plants, and factories individually release less pollution than they did in the mid-20th century. But there are many more cars, power plants and factories. Many pollutants are still being released and some substances have been found to be pollutants that were not known to be pollutants in the past. There is still much work to be done to continue to clean up the air.

Ways to Reduce Air Pollution

Air pollution can be reduced in a number of ways. Using less fossil fuel is one way to lessen pollution. People use less fuel by engaging in conservation, which means not using a resource or using less of it. For example, riding a bike or walking instead of driving doesn't use any fossil fuel. Taking a bus uses less than driving or riding by yourself in a car, as does carpooling. If you need to drive, buying a car that has greater fuel efficiency is important.

You can conserve electricity (and thus fossil fuels) at home by turning off light bulbs and appliances when they are not in use, using energy efficient light bulbs and appliances, and even buying less stuff. All these actions reduce the amount of energy that power plants need to produce.

There are many reasons for people in North America and Europe to try to reduce their use of fossil fuels. As you have already seen, air pollution has tremendous health and environmental costs. There are other reasons as well. Much of the oil we use comes from the Middle East, which is a politically unstable region of the world. Also, fossil fuels are running out, although some will run out sooner than others. The most easily accessible fossil fuels are mostly already gone and harder to use or recover fuels are now being used. There are other types of fossil fuels that can eventually replace coal and petroleum, such as tar sands and oil shale. But these have even more environmental problems than traditional fossil fuels have: mining them from the ground causes severe environmental damage and burning them releases pollutants, including greenhouse gases.

Alternative energy sources are important. They currently are not a large part of the energy supply, but they will increase rapidly over the coming years and decades. Several sources of alternative energy, including solar and wind are not currently being used much because the technologies are not well enough developed. Converting sunlight into usable solar power, for example, is still very expensive relative to using fossil fuels. For solar to be used more widely, technology will need to advance so that the price falls. Also, solar power is not practiced in all parts of the United States because some areas get low amounts of sunlight. These locations will need to develop different power sources. While the desert Southwest will need to develop solar, the Great Plains can use wind energy as its energy source. Perhaps some locations will rely on nuclear power plants, although current nuclear power plants have major problems like safety and waste disposal.

Some pollutants can be filtered out of the exhaust stream before they are released into the atmosphere. Other pollutants can be broken down into non-toxic compounds before they are released. Some of these technologies will be described in the following sections.

Reducing Air Pollution from Vehicles

Reducing air pollution from vehicles can be done in a number of ways. Pollutants can be broken down before they are released into the atmosphere. The vehicles can be more fuel efficient. New technologies can be developed so that they do not rely on fossil fuels at all.

Motor vehicles emit less pollution than they once did due to **catalytic converters** (**Figure** 22.12). Catalytic converters are placed on modern cars in the United States. These devices reduce emissions of nitrous oxides, carbon monoxide and VOCs. A **catalyst** speeds up chemical reactions without being used up in the reaction itself. For nitrous oxides, the catalyst breaks the nitrogen and oxygen atoms apart. The nitrogen then combines with another nitrogen ion to form nitrogen gas (N_2) and the oxygen forms O_2. VOCs and CO are similarly broken apart into the greenhouse gases H_2O and CO_2. Catalytic converters only work when they are hot, so a lot of exhaust escapes as the car is warming up.

Figure 22.12: A large catalytic converter on an SUV. (11)

There are several simple ways to make a vehicle more fuel efficient. Lighter vehicles need less energy to move. Streamlined vehicles experience less resistance from the wind. So, small, lightweight, streamlined cars get much better gas mileage than chunky, heavy SUVs. **Hybrid vehicles** are among the most efficient vehicles that are now widely available. Hybrids have a small internal combustion engine that works like an ordinary car. They also have an electric motor and a rechargeable battery. During braking, a normal car loses the energy it has because it is in motion. In a hybrid, that energy is instead funneled into charging the battery. When the car accelerates again, it uses the power stored in the battery. The internal combustion engine only takes over when power in the battery has run out. Hybrids get excellent gas mileage in cities where the vehicle frequently stops and starts. Hybrid vehicles also have catalytic converters: the battery preheats the converter so that it begins to work much sooner after the car is turned on. Hybrids can reduce auto emissions by 90% or more. Unfortunately, in many hybrid vehicles the hybrid technology is used to improve acceleration more than gas mileage.

A new technology that is in development is a plug-in hybrid. The vehicle is plugged into an electricity source when it is not in use, perhaps in a garage. The car uses the power stored in that battery when it is next used. Plug-in hybrids are less polluting than regular hybrids, since they can run for a longer time on electricity. Automakers expect that plug-in hybrids will become available around 2010.

Fuel cells are another technology that is in development (**Figure** 22.13). Hydrogen fuel cells harness the energy released when hydrogen and oxygen come together to create water. Fuel cells are extremely efficient and they produce no pollutants. But developing fuel cell technology has its problems. The oxygen the fuel cell uses comes from the atmosphere, but there is no easy source of hydrogen. Natural gas is a source, but converting it into usable hydrogen decreases the efficiency of the fuel cells and increases pollution, including greenhouse gases. Natural gas also has other important uses. A few fuel cell cars are now being produced as models. Right now these cars are extremely expensive and fueling stations are rare. Some automakers say that for fuel cell vehicles to become widespread the cost of production must decrease to 1% of its current price.

Figure 22.13: A hydrogen fuel cell car looks like a gasoline-powered car. (15)

Reducing Industrial Air Pollution

Pollutants are removed from the exhaust streams of power plants and industrial plants before they enter the atmosphere. Particulates can be filtered out, while sulfur and nitric oxides are broken down by catalysts. Removing these oxides reduces the pollutants that cause acid rain.

Particles are relatively easy to remove from emissions. Baghouses work like a giant vacuum cleaner bag, filtering dust as it streams past. Baghouses collect about 98% of dry particulates. Cyclones are air streams that rotate quickly through a container shaped like a cylinder or a cone. Large particles are forced toward the edges of the air stream. When they hit the outside wall of the container, they fall to the bottom and are swept up. Smaller particles can be picked up as the radius of the cyclone is reduced. Particles can also be collected and removed by static electricity. These electrostatic precipitators are useful for removing materials from very hot gases.

Scrubbers remove particles and waste gases from exhaust (**Figure** 22.14). Wet scrubbers use a liquid solution to scrub pollutants. Dry scrubbers use alkali or other materials to neutralize acid gas pollutants. Other techniques are used to eliminate other toxic gases. Nitrogen oxides, for example, can be broken down at very high temperatures.

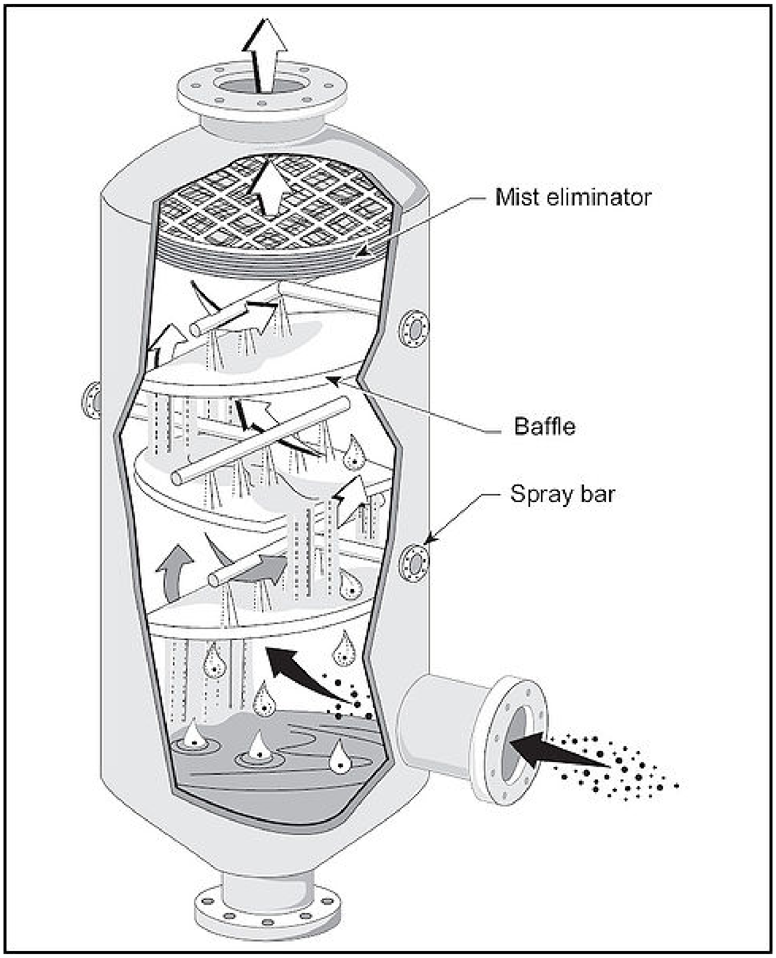

Figure 22.14: Diagram of one type of scrubber. (14)

Gasification is a developing technology. This method removes some of the toxins present in coal before they are released into the atmosphere. In gasification, coal is heated to extremely high temperatures. The gas that is produced is filtered and the energy goes on to drive a generator. About 80% less pollution is released over regular coal plants, and greenhouse gases are also lower. Clean coal plants do not need scrubbers or other pollution control devices. Although the technology is ready, clean coal plants are more expensive to construct and operate and so they are seldom built. Also, heating the coal to high enough temperatures uses a great deal of energy, so the technology not very energy efficient. In addition, large amounts of the greenhouse gas CO_2 are still released even with clean coal technology.

Reducing Ozone Destruction

One success story in reducing pollutants that harm the atmosphere concerns ozone-destroying chemicals. In 1973, scientists calculated that CFCs could reach the stratosphere and break apart. This would release chlorine atoms, which would then destroy ozone. Based only on their calculations, the United States and most Scandinavian countries banned CFCs in spray cans in 1978.

More confirmation that CFCs break down ozone was needed before more was done to reduce production of ozone-destroying chemicals. In 1985, members of the British Antarctic Survey reported that a 50% reduction in the ozone layer had been found over Antarctica in the previous three springs. Two years later, the 'Montreal Protocol on Substances that Deplete the Ozone Layer' was ratified by nations all over the world.

The Montreal Protocol controls the production and consumption of 96 chemicals that damage the ozone layer. Hazardous substances are phased out first by developed nations and one decade later by developing nations. More hazardous substances are phased out more quickly. CFCs have been mostly phased out since 1995, although some will be used in developing nations until 2010. The Protocol also requires that wealthier nations donate money to develop technologies that will replace these chemicals.

If CFCs were not being phased out, by 2050 they would have been probably been 10 times more abundant than they were in 1980. The result would have been about 20 million more cases of skin cancer in the United States and 130 million cases globally. Even though governments have acted to reduce CFC's, they take many years to reach the stratosphere and they can survive there a long time before they break down. So the ozone hole will probably continue to grow for some time before it begins to shrink. The ozone layer will reach the same levels it had before 1980 in around 2068 and 1950 levels in one or two centuries.

Reducing Greenhouse Gases

Reducing greenhouse gas emissions is related to air pollution control. Unlike many other air pollutants, climate change is a global problem. Climate scientists agree that all nations must come together to reduce greenhouse gas emissions. So far, this has not occurred.

The first attempt to cap greenhouse gas emissions was the Kyoto Protocol. The Kyoto Protocol limits greenhouse gas emissions for developed nations to below 1990 levels. Kyoto has not achieved the success of the Montreal Protocol for several reasons. The largest emitter of greenhouse gases, the United States, did not sign and was not bound by the agreement. Developing nations, most notably China, signed the treaty but are not obligated to make changes in their greenhouse gas emissions. Of the nations that agreed to reduce their emissions, few are on track to achieve their target. More importantly, several years have passed since this process was begun and climate scientists agree that the Protocol does not reduce emissions nearly enough. Some say that reductions 40 times those required by

Kyoto are needed to avoid dangerous climate change. Plans are now being made to replace the Kyoto Protocol with a more effective treaty in 2012.

The Kyoto Protocol set up a cap-and-trade system. Each participating nation was given a cap on greenhouse gas emissions that it should not go over. If a nation is likely to go over its cap, it can buy credits from a nation that will emit less greenhouses gases than allowed by the cap. Cap-and-trade provides a monetary incentive for nations to develop technologies that will reduce emissions and to conserve energy. Some states and cities within the United States have begun their own cap-and-trade systems, since they believe that the federal government is not doing enough to address the problem of climate change.

However it is done, climate scientists and many others agree that greenhouse gas emissions must be lowered. The easiest and quickest way is to increase energy efficiency. A carbon tax can be placed on CO_2 emissions to encourage conservation. The tax would be placed on gasoline, carbon dioxide emitted by factories, and home energy bills to encourage conservation. For example, when people make a purchase of a new car, they will be more likely to purchase an energy efficient model. The money from the carbon tax can then be used for research into alternative energy sources. All plans for a carbon tax allow a tax credit for people who cannot afford to pay more for energy, so that they do not suffer unfairly.

More energy efficient vehicles and appliances can be developed. Some, like hybrid cars are currently available. Agricultural practices that lessen the amount of methane produced can be used.

Beyond increasing efficiency, new technologies can be developed. Alternative energy sources, like solar and wind can be developed and expanded. **Biofuels** can replace gasoline in vehicles, but they must be developed sensibly (**Figure** 22.15). So far much of the biofuel is produced from crops like corn. But when food crops are used for fuel, the price of food goes up. Also modern agriculture is extremely reliant on fossil fuels for pesticides, fertilizers and the work of farming. This means that not much energy is gained from using a biofuel over using the fossil fuels directly. More promising crops for biofuels are now being researched. Surprisingly, algae is being investigated as a source of fuel! The algae can be grown in areas that are not useful for agriculture, and it also contains much more useable oil than crops like corn.

Greenhouse gases can also be removed from the atmosphere after they are emitted. **Carbon sequestration** occurs when carbon dioxide is removed from the atmosphere. Carbon is sequestered naturally in forests, but unfortunately, more forest land is currently being lost than gained. Another idea is to artificially sequester carbon. For example, carbon can be captured from the emissions from gasification plants. That carbon is then stored underground in salt layers or coal seams, which keeps it out of the atmosphere. While some small sequestration projects are underway, no large-scale sequestration has yet been attempted. While it is a promising new technology, carbon sequestration is also untested and may not prove to be significant in fighting global warming.

Just as individuals can diminish other types of air pollution, people can fight global warming by conserving energy. Also, people can become involved in local, regional and national efforts

Figure 22.15: A bus that runs on soybean oil shows the potential of biofuels. (1)

to make sound choices on energy policy.

Lesson Summary

- Air pollutants can be reduced in many ways. The best method is to not use the energy that produces the pollutants by conservation or increasing energy efficiency.
- Alternative energy sources are another good way to reduce pollution. Most of these alternate energy technologies are still being refined (solar, wind) and some have other problems associated with them (nuclear, biofuels).
- Pollutants can be removed from an exhaust stream by being filtered out or broken down. Some pollutants are best not released at all like CFCs.

Review Questions

1. Since the Clean Air Act was passed in 1970, why is the air still not clean?
2. What are some ways that you can conserve energy?
3. How does reducing air pollutants, as described in the Clean Air Act of 1970, affect greenhouse gas emissions?
4. What has to be done before alternative energy sources can replace fossil fuels?
5. What are catalytic converters?
6. Why are hybrid vehicles more energy efficient than regular vehicles powered by internal combustion engines?
7. Why aren't fuel cell vehicles widely available yet?

8. How does a cyclone reduce particulate pollution?
9. How can coal power be made so that it has nearly zero carbon contribution to the atmosphere?
10. Why is it that the ozone hole will not be healed for several decades?
11. Many people think that biofuels are the solution to a lot of the problem of climate change, but others disagree. What requirements would biofuels have to meet if they were to be really effective at replacing gasoline in motor vehicles?

Vocabulary

biofuel A fuel made from living materials, usually crop plants.

carbon sequestration Removal of carbon dioxide from the atmosphere, so that it does not act as a greenhouse gas in the atmosphere.

catalyst A substance that increases (or decreases) the rate of a chemical reaction but is not used up in the reaction.

catalytic converter Found on modern motor vehicles, these devices use a catalyst to break apart pollutants.

fuel cell An energy cell in which chemical energy is converted into electrical energy.

gasification A technology that cleans coal before it is burned, which increases efficiency and reduces emissions.

hybrid vehicle A very efficient vehicle that is powered by an internal combustion engine, an electric motor and a rechargeable battery.

Points to Consider

- Why is it important to reduce air pollution?
- What can you do in your own life to reduce your impact on the atmosphere?
- Why is a worldwide effort needed to reduce the threat of global climate change?

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Chapter 23

Observing and Exploring Space

23.1 Telescopes

Lesson Objectives

- Explain how astronomers use the whole electromagnetic spectrum to study the universe beyond Earth.
- Identify different types of telescopes.
- Describe historical and modern observations made with telescopes.

Introduction

Many scientists can interact directly with what they are studying. Biologists can collect cells, seeds, or sea urchins and put them in a controlled laboratory environment. Physicists can subject metals to stress or smash atoms into each other. Geologists can chip away at rocks to see what is inside. But astronomers, scientists who study the universe beyond Earth, rarely have a chance for direct contact with their subject. Instead, astronomers have to observe their subjects at a distance, usually a very large distance!

Electromagnetic Radiation

Earth is separated from the rest of the universe by very large expanses of space. Occasionally, matter from the outside reaches Earth, such as when a meteorite makes it through the atmosphere. But for the most part, astronomers have one main source for their data—light. Light can travel across empty space, and as it does so, it carries both energy and information. Light is one type of **electromagnetic (EM) radiation,** or energy transmitted through space as a wave.

The Speed of Light

Light travels faster than anything else in the universe. In the almost completely empty vacuum of space, light travels at a speed of approximately 300,000,000 meters per second (670,000,000 miles per hour). To give you an idea of how fast that is, a beam of light could travel from New York to Los Angeles and back again nearly 40 times in just one second. Even though light travels extremely fast, objects in space are so far away that it takes a significant amount of time for light from those objects to reach us. For example, light from the Sun takes about 8 minutes to reach Earth.

Light-Years

Because astronomical distances are so large, it helps to have a unit of measurement that is good for expressing those large distances. A **light-year** is a unit of distance that is defined as the distance that light travels in one year. One light-year is approximately equal to 9,500,000,000,000 (9.5 trillion) kilometers, or 5,900,000,000,000 (5.9 trillion) miles. That's a long way! By astronomical standards, it's actually a pretty short distance.

Proxima Centauri, the closest star to us after the Sun, is 4.22 light-years away. That means the light from Proxima Centauri takes 4.22 years to reach us. The galaxy we live in, the Milky Way Galaxy, is about 100,000 light-years across. So, how long does it take light to travel from one side of the galaxy to the other? 100,000 years! Even 100,000 light years is a short distance on the scale of the whole universe. The most distant galaxies we have detected so far are more than 13 billion light-years away. That's over a hundred-billion-trillion (100,000,000,000,000,000,000,000) kilometers!

Looking Back in Time

When we look at astronomical objects such as stars and galaxies, we are not just seeing over great distances—we are also seeing back in time. Because light takes time to travel, the image we see of a distant galaxy is an image of how the galaxy used to look. For example, the Andromeda Galaxy, shown in **Figure** 23.1, is about 2.5 million light years from Earth. If you look at the Andromeda Galaxy in a telescope, you will see the galaxy as it was 2.5 million years ago. If you want to see the galaxy as it is now, you will have to wait and look again 2.5 million years into the future!

Electromagnetic Waves

Earlier, we said that light is one type of electromagnetic (EM) radiation. That means light is energy that travels in the form of an *electromagnetic wave.* **Figure** 23.2 shows a diagram of an electromagnetic wave. An EM wave has two components: an electric field and a magnetic

Figure 23.1: This recent picture of the Andromeda Galaxy actually shows the galaxy as it was about 2.5 million years ago. (35)

field. Each of these components oscillates between positive and negative values, which is what makes the "wavy" shape in the diagram.

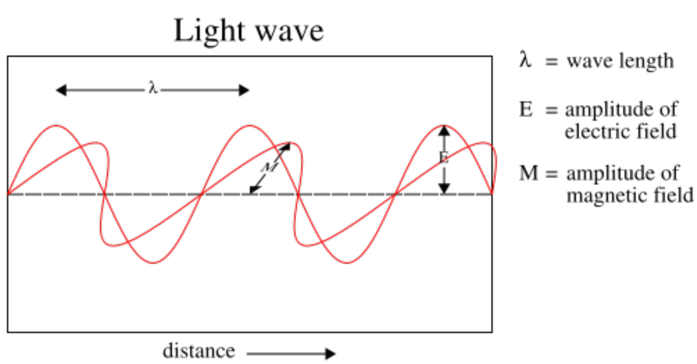

Figure 23.2: An electromagnetic wave consists of oscillating electric and magnetic fields. The distance between two adjacent oscillations is called wavelength. (33)

Notice the horizontal arrow at the top left of the diagram. This measurement corresponds to the **wavelength**, or the distance between two adjacent points on the wave. A related value is **frequency**, which measures the number of wavelengths that pass a given point every second. Wavelength and frequency are reciprocal, which means that as one increases, the other decreases.

The Electromagnetic Spectrum

Visible light—the light that human eyes can see—comes in a variety of colors. The color of visible light is determined by its wavelength. Visible light ranges from wavelengths of 400 nm to 700 nm, corresponding to the colors violet through red. But what about EM radiation with wavelengths shorter than 400 nm or longer than 700 nm? Such radiation exists all around you—you just can't see it! Visible light is part of a larger **electromagnetic spectrum,** as **Figure** 23.3 illustrates.

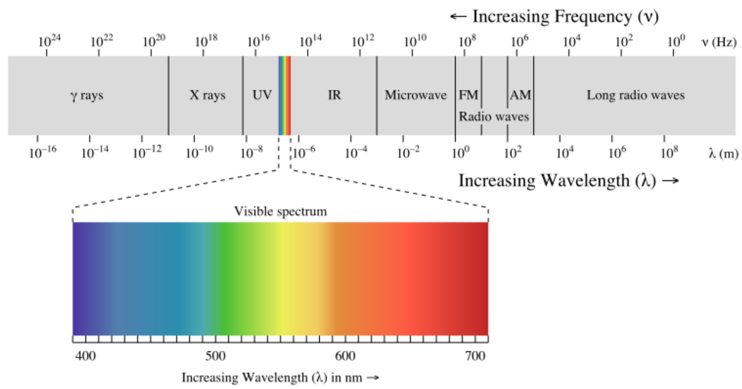

Figure 23.3: Visible light is part of a larger electromagnetic spectrum. The EM spectrum ranges from gamma rays with very short wavelengths, to radio waves with very long wavelengths. (19)

What does the electromagnetic spectrum have to do with astronomy? Every star, including our Sun, emits light at a wide range of wavelengths, all across the visible spectrum, and even outside the visible spectrum. Astronomers can learn a lot from studying the details of the spectrum of light from a star.

Some very hot stars emit light primarily at **ultraviolet** wavelengths, while some very cool stars emit mostly in the **infrared**. There are extremely hot objects that emit **X-rays** and even **gamma rays**. Light from some of the faintest, most distant objects is in the form of **radio waves**. In fact, a lot of the objects most interesting to astronomers today can't even be seen with the naked eye. Astronomers use telescopes to detect the faint light from distant objects and to see objects at wavelengths all across the electromagnetic spectrum.

Types of Telescopes

Optical Telescopes

Humans have been making and using lenses for magnification for thousands and thousands of years. However, the first true telescopes were made in Europe in the late 16th century. These telescopes used a combination of two lenses to make distant objects appear both nearer and larger. The term *telescope* was coined by the Italian scientist and mathematician Galileo Galilei (1564–1642). Galileo built his first telescope in 1608 and subsequently made many improvements to telescope design.

Telescopes that rely on the refraction, or bending, of light by lenses are called **refracting telescopes,** or simply *refractors.* The earliest telescopes, including Galileo's, were all refractors. Many of the small telescopes used by amateur astronomers today are refractors with a design similar to Galileo's. Refractors are particularly good for viewing details within our solar system, such as the surface of Earth's moon or the rings around Saturn. **Figure** 23.4 shows the biggest refracting telescope in the world.

Figure 23.4: The largest refracting telescope in the world is at the University of Chicago's Yerkes Observatory in Wisconsin. This telescope was built in 1897. Its largest lens has a diameter of 102 cm. (20)

Around 1670, another famous scientist and mathematician—Sir Isaac Newton (1643–1727)—built a different kind of telescope. **Figure** 23.5 shows a telescope similar in design to Newton's.

Figure 23.5: The telescope still looks much the same today. (22)

Newton's telescope used curved mirrors instead of lenses to focus light. Telescopes that use mirrors are called **reflecting telescopes,** or *reflectors* (**Figure** 23.6). The mirrors in a reflecting telescope are much lighter than the heavy glass lenses in a refractor. This is significant, because thick glass lenses in a telescope mean that the whole telescope must be much stronger to support the heavy glass. In addition, it's much easier to precisely make mirrors than to precisely make glass lenses. For that reason, reflectors can be made larger than refractors. Larger telescopes can collect more light, which means they can study dimmer or more distant objects. The largest optical telescopes in the world today are reflectors, like the one in **Figure** 23.7.

Figure 23.6: Reflecting telescopes used by amateur astronomers today are similar to the one designed by Isaac Newton in the 17th century. (13)

Many consumer telescopes today use a combination of mirrors and lenses to focus light. These telescopes are called **catadioptric telescopes**. By using both kinds of elements,

Figure 23.7: The South African Large Telescope (SALT) is one of the largest reflecting telescopes on Earth. SALT's primary mirror consists of 91 smaller hexagonal mirrors, each with sides 1 m long. (21)

catadioptric telescopes can be made with large diameters but shorter lengths so they are less awkward to move around. **Figure** 23.8 shows a typical catadioptric telescope.

Radio Telescopes

Notice it says above that the largest *optical* telescopes in the world are reflectors. Optical telescopes are designed to collect visible light. There are even larger telescopes that collect light at longer wavelengths—radio waves. These telescopes are called—can you guess?—**radio telescopes.** Radio telescopes look a lot like satellite dishes. In fact, both are designed to do the same thing—to collect and focus radio waves or microwaves from space.

The largest single telescope in the world is at the Arecibo Observatory in Puerto Rico (see **Figure** 23.9). This telescope is located in a naturally-occurring sinkhole that formed when water flowing underground dissolved the limestone rock. If this telescope were not supported by the ground, it would collapse under its own weight. The downside of this design is that the telescope cannot be aimed to different parts of the sky—it can only observe the part of the sky that happens to be overhead at a given time.

A group of radio telescopes, such as those shown in **Figure** 23.10, can be linked together with a computer so that they are all observing the same object. The computer can combine the data from each telescope, making the group function like one single telescope.

Figure 23.8: Many amateur astronomers today use catadioptric telescopes. These telescopes have large mirrors to collect a lot of light, but short tubes for portability. (34)

Figure 23.9: The radio telescope at the Arecibo Observatory in Puerto Rico has a diameter of 305 m. (1)

Figure 23.10: The Very Large Array in New Mexico has 27 radio dishes, each 25 meters in diameter. When all the dishes are spread out and pointed at the same object, they act like a single telescope with a diameter of 22.3 mi. (7)

Space Telescopes

Telescopes on Earth all have one significant limitation: the electromagnetic radiation they gather must pass through Earth's atmosphere. The atmosphere blocks some radiation in the infrared part of the spectrum and almost all radiation in the ultraviolet and higher frequency ranges. Furthermore, motion in the atmosphere distorts light. You see evidence of this distortion when you see stars twinkling in the night sky. To minimize these problems, many observatories are built on high mountains, where there is less atmosphere above the telescope. **Space telescopes** avoid such problems completely because they are outside Earth's atmosphere altogether—in space.

The Hubble Space Telescope (HST), shown in **Figure** 23.11, is perhaps the best known space telescope. The Hubble was put into orbit by the Space Shuttle Atlantis in 1990. Once it was in orbit, scientists discovered that there was a flaw in the shape of the mirror. A servicing mission to the Hubble by the Space Shuttle Endeavor in 1994 corrected the problem. Since that time, the Hubble has provided huge amounts of data that have helped to answer many of the biggest questions in astronomy.

Figure 23.11: The Hubble Space Telescope orbits Earth at an altitude of 589 km (366 mi). It collects data in visible, infrared, and ultraviolet wavelengths. (12)

In addition to the Hubble, the National Aeronautics and Space Administration (NASA) has placed three other major space telescopes in orbit: the Compton Gamma-Ray Observatory (CGRO), the Chandra X-Ray Observatory (CXO) , and the Spitzer Space Telescope (SST). Together, these four telescopes comprise what NASA calls the 'Great Observatories'. **Figure** 23.12 shows how each of these telescopes specializes in a different part of the electromagnetic spectrum. Of these, all but the Compton are still in orbit and active. NASA is planning for another telescope, the James Webb Space Telescope, to serve as a replacement for the aging Hubble. The James Webb is scheduled to launch no earlier than 2013.

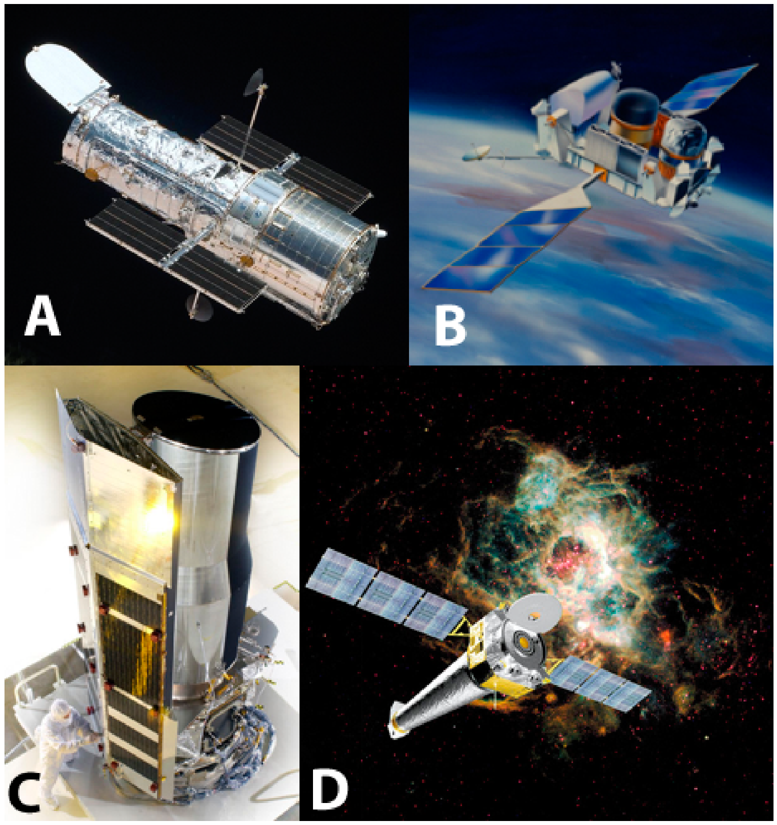

Figure 23.12: NASA's four space based Great Observatories were designed to view the universe in different ranges of the electromagnetic spectrum. A. Hubble Space Telescope: visible light, B. Compton Gamma Ray Observatory: gamma ray, C. Spitzer Space Telescope: infrared, D. Chandra X-ray Observatory: X-ray. (26)

Observations with Telescopes

Ancient Astronomers

Humans have been studying the night sky for thousands of years. Observing the patterns and motions in the sky helped ancient peoples keep track of time. This was important to them because it helped them know when to plant crops. They also timed many of their religious ceremonies to coincide with events in the heavens.

The ancient Greeks made careful observations of the locations of stars in the sky. They noticed that some of what they thought were 'stars' moved against the background of other stars. They called these bright spots in the sky **planets**, which in Greek means "wanderers." Today we know that the planets are not stars, but members of our solar system that orbit the Sun. The Greeks also identified **constellations**, patterns of stars in the sky. They associated the constellations with stories and myths from their culture. Constellations still help astronomers today; they are used to identify different regions of the night sky.

Galileo's Observations

Ancient astronomers knew a lot about the patterns of stars and the movement of objects in the sky, but they did not know much about what these objects actually were. All of that changed in the year 1610, when Galileo turned a telescope toward the heavens. Using a telescope, Galileo made the following discoveries (among others):

- There are more stars in the night sky than the naked eye can see.
- The band of stars called the Milky Way, consists of many stars.
- The Moon has craters (See **Figure** 23.13).
- Venus has phases like the Moon.
- Jupiter has moons orbiting around it.
- There are dark spots that move across the surface of the Sun.

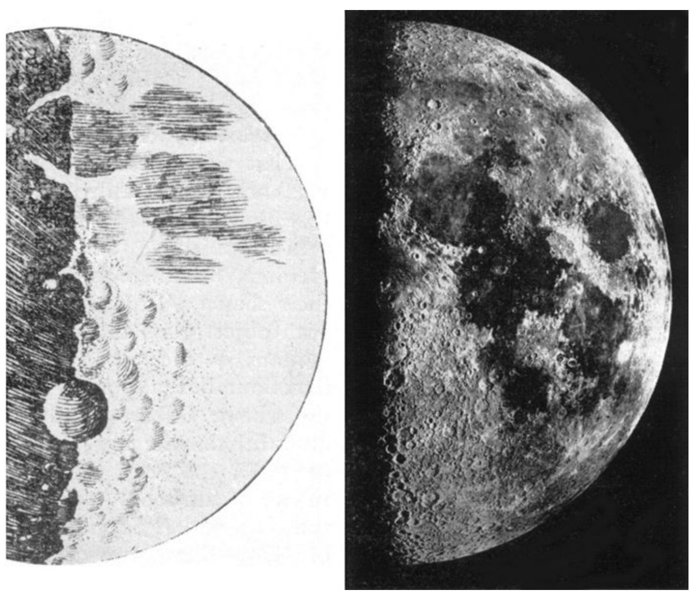

Figure 23.13: Galileo was the first person known to look at the Moon through a telescope. Galileo made the drawing on the left in 1610. The image on the right is a modern photograph of the Moon. (24)

Galileo's observations challenged people to think in new ways about the universe and Earth's place in it. About 100 years before Galileo, Nicolaus Copernicus had proposed a controversial new model of the universe. According to Copernicus's model, Earth and the other planets revolve around the Sun. In Galileo's time, most people believed that the Sun and planets revolved around Earth. Galileo's observations provided direct evidence to support Copernicus' model.

Observations with Modern Telescopes

Today, equipped with no more than a good pair of binoculars, you can see all of the things Galileo saw, and more. You can even see sunspots, but you need special filters on the lenses to protect your eyes. Never look directly at the Sun without using the proper filters! With a basic telescope like those used by many amateur astronomers, you can also see polar caps on Mars, the rings of Saturn, and bands in the atmosphere of Jupiter.

We now know that all of these objects are within our solar system. You can also see many times more stars with a telescope than without a telescope. However, stars seen in a telescope still look like single points of light. Because they are so far away, stars continue to appear as points of light in even the most powerful professional telescopes. **Figure** 23.14 shows one rare exception.

Today, very few professional astronomers look directly through the eyepiece of a telescope. Instead, they attach sophisticated instruments to telescopes. These instruments capture and process the light from a telescope, and astronomers then look at the images or data shown on these instruments. Most of the time, the instruments then pass the data on to a computer where the data can be stored for later use. It can take an astronomer weeks or months to analyze all the data collected from just a single night!

A **spectrometer** is a tool that astronomers commonly use to study the light from a telescope. A spectrometer uses a prism or other device to break light down into its component colors. This produces a spectrum like the one shown in **Figure** 23.15. The dark lines in the spectrum of light from a star are caused by gases in the outer atmosphere of the star absorbing light. This spectrum can be observed directly, captured on film, or stored digitally on a computer.

From a single spectrum of a star, an astronomer can tell:

- How hot the star is (by the relative brightness of different colors).
- What elements the star contains (by the pattern of dark lines).
- Whether and how fast the star is moving toward or away from Earth (by how far the dark lines are shifted from their normal positions).

Using telescopes, astronomers can also learn how stars evolve, what kind of matter is found throughout the universe, and how it is distributed, and even how the universe might have formed.

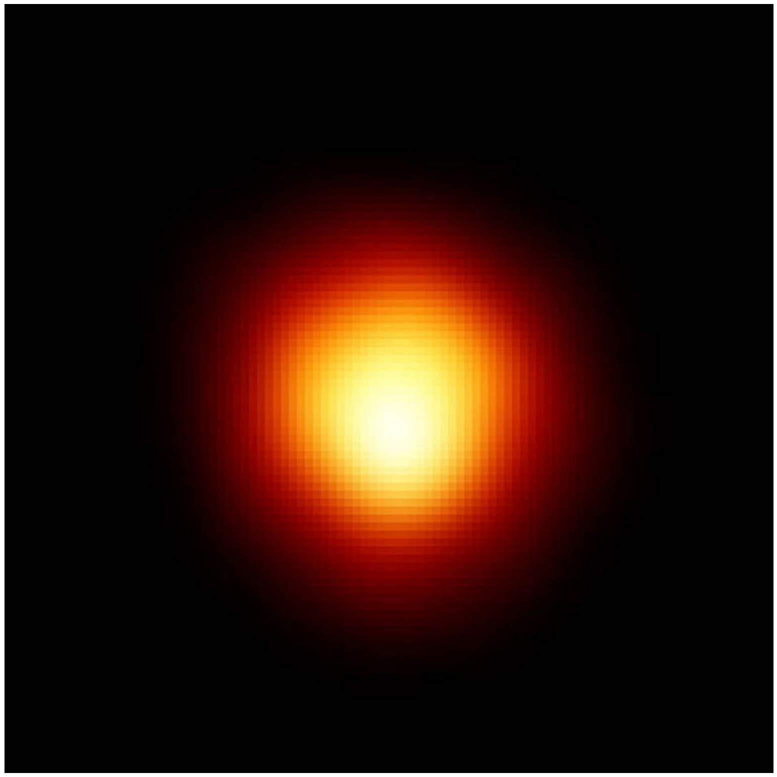

Figure 23.14: This is an ultraviolet image of the red supergiant star Betelgeuse taken with the Hubble Space Telescope in 1996. This was the first direct image taken of the disk of a star other than the Sun. (31)

Figure 23.15: This is a simplified example of what light from a star looks like after it passes through a spectrometer. (2)

Lesson Summary

- Astronomers study light from distant objects.
- Light travels at 300,000,000 meters per second—faster than anything else in the universe.
- A light-year is a unit of distance equal to the distance light travels in one year, 9.5 trillion kilometers.
- When we see distant objects, we see them as they were in the past, because their light has been traveling to us for many years.
- Light is energy that travels as a wave.
- Visible light is part of the electromagnetic spectrum.
- Telescopes make distant objects appear both nearer and larger. You can see many more stars through a telescope than with the unaided eye.
- Optical telescopes are designed to collect visible light. The three main types of optical telescopes are reflecting telescopes, refracting telescopes, and catadioptric telescopes.
- Radio telescopes collect and focus radio waves from distant objects.
- Space telescopes are telescopes orbiting Earth. They can collect wavelengths of light that are normally blocked by the atmosphere.
- Galileo was the first person known to use a telescope to study the sky. His discoveries helped change the way humans think about the universe.
- Modern telescopes collect data that can be stored on a computer.
- A spectrometer produces a spectrum from starlight. Astronomers can learn a lot about a star by studying its spectrum.

Review Questions

1. Proxima Centauri is 4.22 light-years from Earth. Light travels 9.5 trillion kilometers in one year. How far away is Proxima Centauri in kilometers?
2. Identify four regions of the electromagnetic spectrum that astronomers use when observing objects in space.
3. List the 3 main types of optical telescopes, and describe their differences.
4. Explain the advantages of putting a telescope into orbit around Earth.
5. Describe two observations that Galileo was the first to make with his telescope.
6. List 3 things that an astronomer can learn about a star by studying its spectrum.

Further Reading / Supplemental Links

- http://science.nasa.gov/headlines/y2002/08feb_gravlens.htm
- http://www.nasa.gov/audience/forstudents/postsecondary/features/F_NASA_Great_Observatories_PS.html
- http://www.stargazing.net/David/constel/howmanystars.html

- http://www.astronomics.com/main/category.asp/catalog_name/Astronomics/category_name/V1X41SU50GJB8NX88JQB360067/Page/1
- http://galileo.rice.edu/sci/instruments/telescope.html
- http://www.nrao.edu/whatisra/index.shtml
- http://www.astronomy.pomona.edu/archeo/
- http://www.colorado.edu/physics/PhysicsInitiative/Physics2000/quantumzone/
- http://en.wikipedia.org

Vocabulary

catadioptric telescope Telescopes that use a combination of mirrors and lenses to focus light.

constellations Patterns of stars as observed from Earth.

electromagnetic radiation Energy transmitted through space as a wave.

electromagnetic spectrum The full range of electromagnetic radiation.

frequency The number of wavelengths that pass a given point every second.

gamma rays A penetrating form of electromagnetic radiation.

infrared light Electromagnetic waves with frequencies between radio waves and red light; about 1 mm to 750 nanometers.

light-year The distance light can travel in one year; 9.5 trillion kilometers.

microwaves The shortest wavelength radio waves.

planets Around celestial object orbiting a star that has cleared its neighboring region of planetesimals.

radio telescope A radio antenna that collects radio waves.

radio waves The longest wavelengths of the electromagnetic spectrum; from 1 mm to more than thousands of kilometers.

reflecting telescope Telescopes that use mirrors to collect and focus light.

refracting telescope Telescopes that use convex lenses to collect and focus light.

space telescope Telescopes in orbit above Earth's atmosphere.

spectrometer A tool that uses a prism to break light into its component colors.

ultraviolet Electromagnetic radiation having wavelengths shorter than the violet.

wavelength Horizontal distance measured from wave crest to wave crest, or wave trough to wave trough.

visible light The portion of light in the electromagnetic spectrum that is visible to humans.

X rays A band of electromagnetic radiation between gamma and ultraviolet.

Points to Consider

- Radio waves are used for communicating with spacecraft. A round-trip communication from Earth to Mars takes anywhere from 6 to 42 minutes. What challenges might this present for sending unmanned spacecraft and probes to Mars?
- The Hubble Space Telescope is a very important source of data for astronomers. The fascinating and beautiful images from the Hubble also help to maintain public support for science. However, the Hubble is growing old. Missions to service and maintain the telescope are extremely expensive and put the lives of astronauts at risk.
- Do you think there should be another servicing mission to the Hubble?

23.2 Early Space Exploration

Lesson Objectives

- Explain how a rocket works.
- Describe different types of satellites.
- Outline major events in early space exploration, including the Space Race.

Introduction

Humans have long dreamed of traveling into space. Greek mythology tells of Daedelus and Icarus, a father and son who took flight using wings made of feathers and wax. Daedelus warned his son not to fly too close to the sun, but Icarus, thrilled with the feel of flying, drifted higher and higher. When he got too close to the Sun, the wax melted, and Icarus fell into the sea. This myth is often interpreted to be about foolishness or excessive pride, but we can also relate to the excitement Icarus would have felt. Much later, science fiction writers, such as Jules Verne (1828–1905) and H.G. Wells (1866–1946), wrote about technologies that might make the dream of traveling beyond Earth into space possible.

Rockets

Humans did not reach space until the second half of the 20th century. However, the main technology that makes space exploration possible, the **rocket** has been around for a long time. A rocket is a device propelled by particles flying out of it at high speed. We do not know exactly who built the first rocket, or when, but there are records of the Chinese using rockets in war against the Mongols as early as the 13th century. The Mongols, in turn, spread rocket technology in their attacks on Eastern Europe. Early rockets were also used to launch fireworks and for other ceremonial purposes.

How Rockets Work

Rockets were used for centuries before anyone could explain exactly how they work. The theory to explain this did not arrive until 1687, when Isaac Newton (1643–1727) described three basic laws of motion, now referred to as Newton's Laws of Motion:

1. An object in motion will remain in motion unless acted upon by a net force.
2. Force equals mass multiplied by acceleration.
3. To every action, there is an equal and opposite reaction.

Newton's third law of motion is particularly useful in explaining how a rocket works. To better understand this law, consider the ice skater in **Figure** 23.16. When the skater pushes the wall, the skater's force—the "action"—is matched by an equal force by the wall on the skater in the opposite direction—the reaction.

Once the skater is moving, however, she has nothing to push against. Imagine now that the skater is holding a fire extinguisher. When she pulls the trigger on the extinguisher, a fluid or powder flies out of the extinguisher, and she moves backward. In this case, the action force is the pressure pushing the material out of the extinguisher. The reaction force of the material against the extinguisher pushes the skater backward.

For a long time, many believed that a rocket wouldn't work in space because there would be nothing for the rocket to push against. However, a rocket in space moves like the skater holding the fire extinguisher. Fuel is ignited in a chamber, which causes an explosion of gases. The explosion creates pressure that forces the gases out of the rocket. As these gases

Figure 23.16: When the skater pushes against the wall, the wall exerts an equal force on the skater in the opposite direction. (27)

rush out the end, the rocket moves in the opposite direction, as predicted by Newton's Third Law of Motion. The reaction force of the gases on the rocket pushes the rocket forward, as shown in **Figure** 23.17. The force pushing the rocket is also called **thrust**.

Figure 23.17: Explosions in a chamber create pressure that pushes gases out of a rocket. This in turn produces thrust that pushes the rocket forward. The rocket shown here is a Saturn V rocket, used for the Apollo 11 mission—the first to carry humans to the Moon. (4)

A Rocket Revolution

For centuries, rockets were powered by gunpowder or other solid fuels. These rockets could travel only fairly short distances. At the end of the 19th century and the beginning of the 20th century, several breakthroughs in rocketry would lead to rockets that were powerful enough to carry rockets—and humans—beyond Earth. During this period, three people independently came up with similar ideas for improving rocket design.

The first person to establish many of the main ideas of modern rocketry was a Russian schoolteacher, named Konstantin Tsiolkovsky (1857–1935). Most of his work was done even before the first airplane flight, which took place in 1903. Tsiolkovsky realized that in order for rockets to have enough power to escape Earth's gravity, they would need liquid fuel instead of solid fuel. He also realized that it was important to find the right balance between the amount of fuel a rocket uses and how heavy the rocket is. He came up with the idea of using multiple stages when launching rockets, so that empty fuel containers would drop away to reduce mass. Tsiolkovsky had many great ideas and designed many rockets, but he never built one.

The second great rocket pioneer was an American, named Robert Goddard (1882–1945). He independently came up with some of the same ideas as Tsiolkovsky, such as using liquid fuel and using multiple stages. He also designed a system for cooling the gases escaping from a rocket, which made the rocket much more efficient. Goddard was more practical than Tsiolkovsky and built rockets to test his ideas. **Figure** 23.18 shows Goddard with the first rocket to use liquid fuel. This rocket was launched on March 16, 1926 in Massachusetts. Over a lifetime of research, Goddard came up with many innovations that are still used in rockets today.

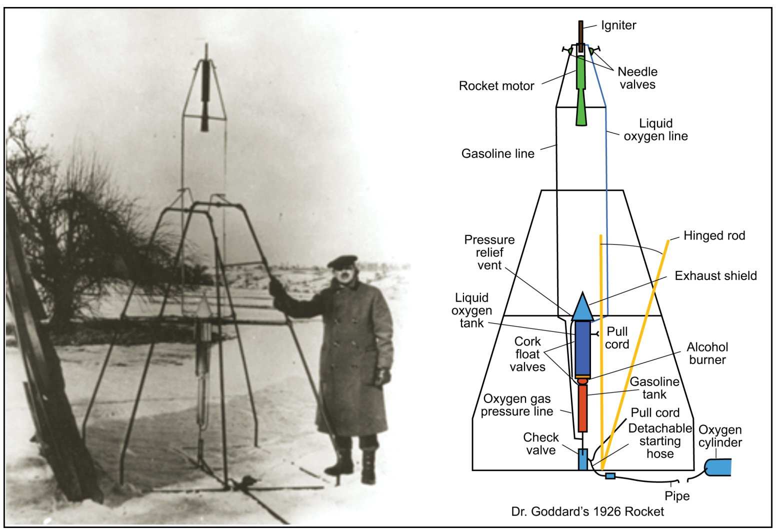

Figure 23.18: (Left) Robert Goddard launched the first liquid-fueled rocket on March 16, 1926; (Right) This schematic shows details of Goddard's rocket. (9)

The third great pioneer of rocket science was a Romanian-born German, named Hermann Oberth (1894–1989). In the early 1920's, Oberth came up with many of the same ideas as Tsiolkovsky and Goddard. His early work was not taken seriously by most scientists. Nonetheless, Oberth built a liquid-fueled rocket, which he launched in 1929. Later, he joined a team of scientists that designed the rocket shown in **Figure** 23.19 for the German military. This rocket, first called the A-4 and later the V-2, played a major role in World War II. The Germans used the V-2 as a missile to bomb numerous targets in Belgium, England,

and France. In 1942, the V-2 was launched to an altitude of 176 km (109 miles), making it the first human-made object to travel into space. An altitude of 100 km (62 miles) is generally considered to be the dividing line between Earth's atmosphere and space.

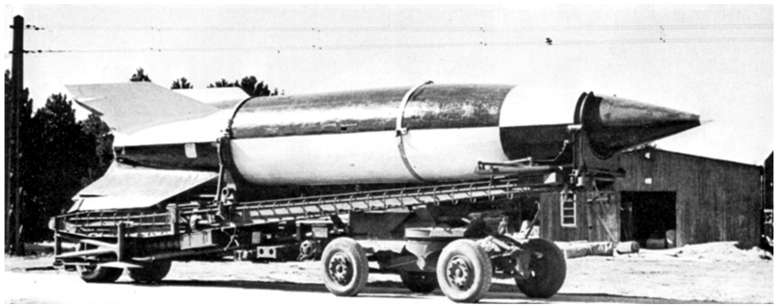

Figure 23.19: V-2 Rocket: Explosions in a chamber create pressure that pushes gases out of a rocket. This in turn produces thrust that pushes the rocket forward. (17)

The leader of the team that built the V-2 rocket was a German scientist, named Wernher von Braun. von Braun later fled Germany and came to the United States, where he helped the United States develop missile weapons and then joined the National Aeronautics and Space Administration (NASA) to design rockets for space travel. At NASA, von Braun designed the Saturn V rocket (**Figure** 23.17), which was eventually used to send the first humans to the Moon.

Satellites

One of the first uses of rockets in space was to launch **satellites.** A satellite is an object that orbits a larger object. To **orbit** something just means to travel in a circular or elliptical path around it. This path is also called an orbit. When you think of a satellite, you probably picture some kind of metallic spacecraft orbiting Earth, but the Moon is also a satellite. Human-made objects put into orbit are called *artificial satellites.* Natural objects in orbit, such as moons, are called *natural satellites.*

Newton's Law of Universal Gravitation

Isaac Newton, whose third law of motion explains how rockets work, also came up with the theory that explains why satellites stay in orbit. Newton's *law of universal gravitation* describes how every object in the universe is attracted to every other object. The same gravity that makes an apple fall to the ground, and keeps you from floating away into the sky, also holds the Moon in orbit around Earth, and Earth in orbit around the Sun.

Newton used the following example to explain how gravity makes orbits possible. Consider a cannonball launched from a high mountain, as shown in **Figure** 23.20. If the cannonball is launched at a slow speed, it will fall back to Earth, as in paths A and B in the figure. However, if it is launched at a fast enough speed, the Earth below will curve away at the same rate that the cannonball falls, and the cannonball will go into a circular orbit, as in path C. If the cannonball is launched even faster, it could go into an elliptical orbit (D) or leave Earth's gravity altogether (E).

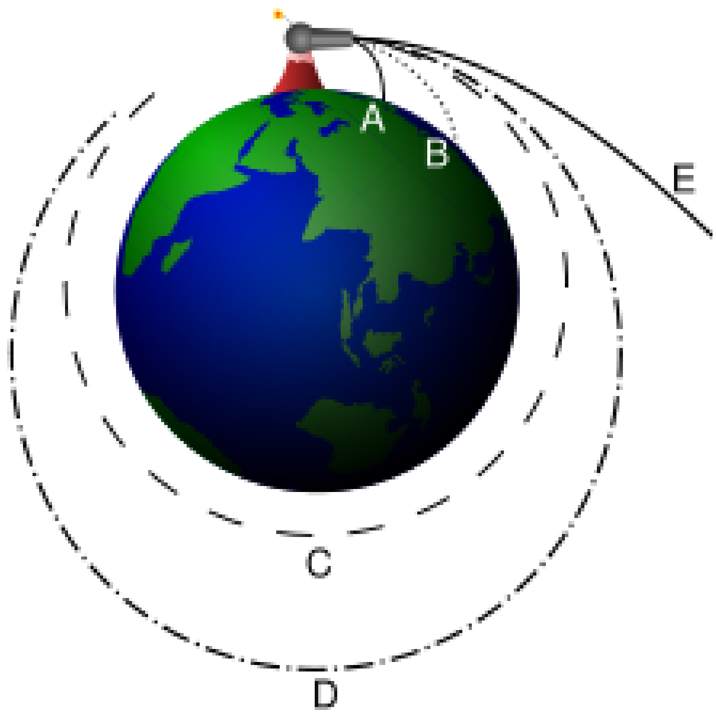

Figure 23.20: Isaac Newton explained how a cannonball fired from a high point with enough speed could orbit Earth. (25)

Note that Newton's idea would not actually work in real life; a cannonball launched from Mt. Everest, the highest mountain on Earth, would burn up in the atmosphere if launched at the speed required to put the cannonball into orbit. However, a rocket can launch straight up, then steer into an orbit. A rocket can also carry a satellite above the atmosphere and then release the satellite into orbit.

Types of Satellites

Since the launch of the first satellite over 50 years ago, thousands of artificial satellites have been put into orbit around Earth. We have even put satellites into orbit around the Moon, the Sun, Venus, Mars, Jupiter, and Saturn. Imaging satellites are designed for taking pictures of Earth's surface. The images can be used by the military, when taken by spy satellites or for scientific purposes, such as meteorology, if taken by weather satellites. Astronomers use imaging satellites to study and make maps of the Moon and other planets. Communications satellites, such as the one in **Figure** 23.21, are designed to receive and send signals for telephone, television, or other types of communications. Navigational satellites are used for navigation systems, such as the Global Positioning System (GPS). The largest artificial satellite is the International Space Station, designed for humans to live in space while conducting scientific research.

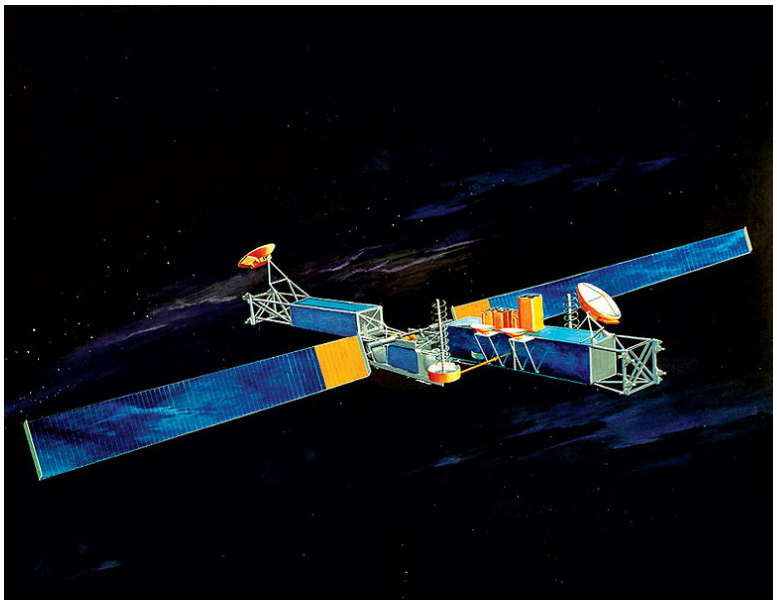

Figure 23.21: This is a Milstar communications satellite used by the U.S. military. The long, flat solar panels provide power for the satellite. Most of the other instruments you can see are antennas for sending or receiving signals. (3)

Types of Orbits

The speed of a satellite depends on how high it is above Earth or whatever object it is orbiting. Satellites that are relatively close to Earth are said to be in **low Earth orbit** (LEO). Satellites in LEO are also often in **polar orbit**, which means they orbit over the North and South Poles, perpendicular to Earth's spin. Because Earth rotates underneath the orbiting satellite, a satellite in polar orbit is over a different part of Earth's surface each time it circles. Imaging satellites and weather satellites are often put in low-Earth, polar orbits.

A satellite placed at just the right distance above Earth–35,786 km (22,240 miles)— orbits at the same rate that Earth spins. As a result, the satellite is always in the same position over Earth's surface. This type of orbit is called a **geostationary orbit** (GEO). Many communications satellites are put in geostationary orbits.

The Space Race

From the end of World War II in 1945 to the breakup of the Soviet Union (USSR) in 1991, the Soviet Union and the United States were in military, social, and political conflict. This period is known as the Cold War. While there were very few actual military confrontations, the two countries were in an arms race—continually developing new and more powerful weapons as each country tried to have more powerful weapons than the other. While this competition had many social and political consequences, it did also help to drive technology. The development of missiles for war significantly sped up the development of rocket technologies.

Sputnik

On October 4, 1957, the Soviet Union launched Sputnik 1, the first artificial satellite ever put into orbit. Sputnik 1, shown in **Figure** 23.22, was 58 cm in diameter and weighed 84 kg (184 lb). Antennas trailing behind the satellite sent out radio signals, which were detected by scientists and amateur radio operators around the world. Sputnik 1 orbited Earth in low Earth orbit on an elliptical path every 96 minutes. It stayed in orbit for about 3 months, until it slowed down enough to descend into Earth's atmosphere, where it burned up as a result of friction with Earth's atmosphere.

The launch of Sputnik 1 started the **Space Race** between the Soviet Union and the United States. Many people in the U.S. were shocked that the Soviets had the technology to put the satellite in orbit, and they worried that the Soviets might also be winning the arms race. On November 3, 1957, the Soviets launched Sputnik 2, which carried the first animal to go into orbit—a dog named Laika.

The Race Is On

In response to the Sputnik program, the U.S. launched their own satellite, Explorer I, on January 31, 1958. Shortly after that—March 17 1958—the U.S. launched another satellite, Vanguard 1. Later that year, the U.S. Congress and President Eisenhower established the National Aeronautics and Space Administration (NASA).

The Soviets still managed to stay ahead of the United States for many notable "firsts." On April 12, 1961, Soviet cosmonaut Yuri Gagarin became both the first human in space and the first human in orbit. Less than one month later—May 5, 1961—the U.S. sent their first astronaut into space: Alan Shepherd. The first American to orbit Earth was John Glenn, in February 1962. The first woman in space was a Soviet: Valentina Tereshkova, in June 1963. The timeline in **Table** 23.1 shows many other Space Race firsts.

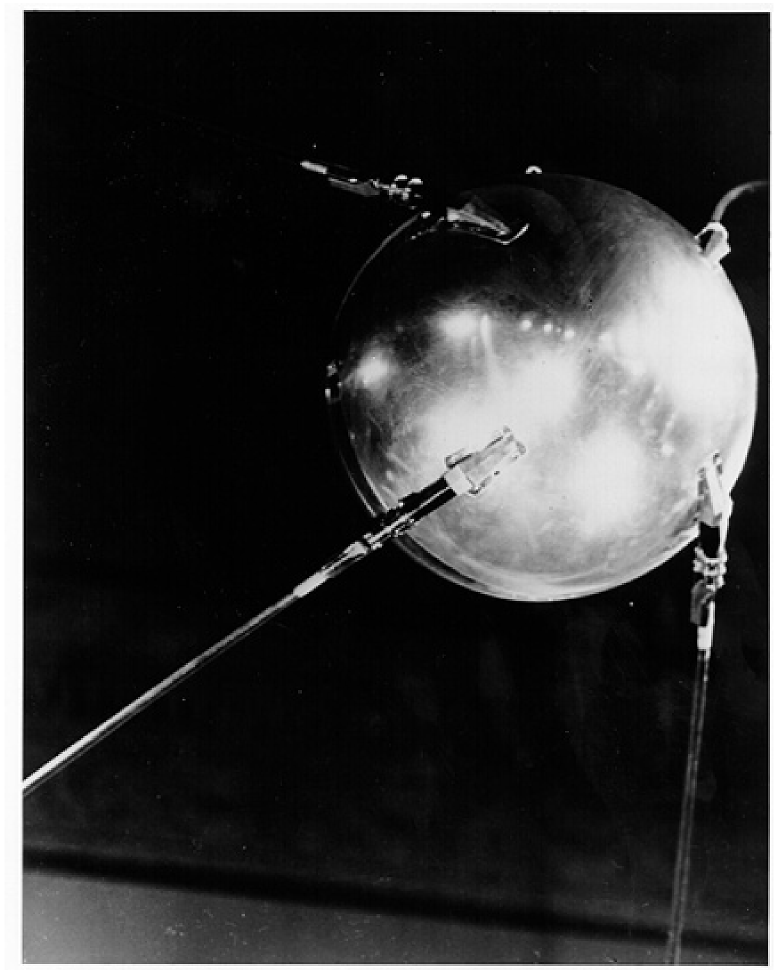

Figure 23.22: The Soviet Union launched Sputnik 1, the first artificial satellite,.on October 4, 1957. (16)

Table 23.1: **Space Race Timeline**

Date	Accomplished	Country	Name of Mission
October 4, 1957	First artificial satellite, first signals from space	USSR	Sputnik 1
November 3, 1957	First animal in orbit (the dog Laika)	USSR	Sputnik 2
January 31, 1958	USA's first artificial satellite	USA	Explorer I
January 4, 1959	First human-made object to orbit the Sun	USSR	Luna 1
September 13, 1959	First impact into another planet or moon (the Moon)	USSR	Luna 2
April 12, 1961	First manned spaceflight and first manned orbital flight (Yuri Gagarin)	USSR	Vostok 1
May 5, 1961	USA's first spaceflight with humans (Alan Shepherd)	USA	Mercury-Redstone 3 (Freedom 7)
February 20, 1962	USA's first orbital flight with humans (John Glenn)	USA	Mercury-Atlas 6 (Friendship 7)
December 14, 1962	First planetary flyby (Venus)	USA	Mariner 2
June 16, 1963	First woman in space, first woman in orbit (Valentina Tereshkova)	USSR	Vostok 6
March 18, 1965	First extra-vehicular activity ("spacewalk") (Aleksei Leonov)	USSR	Voskhod 2
February 3, 1966	First soft landing on another planet or moon (the Moon), first photos from another world	USSR	Luna 9

Table 23.1: (continued)

Date	Accomplished	Country	Name of Mission
March 1, 1966	First impact into another planet (Venus)	USSR	Venera 3
April 3, 1966	First artificial satellite around another world (the Moon)	USSR	Luna 10
June 2, 1966	USA's first soft landing on the Moon, USA's first photos from the Moon	USA	Surveyor 1
December 21, 1968	First humans to orbit another world (the Moon) (James Lovell, Frank Borman, Bill Anders)	USA	Apollo 8
July 21, 1969	First humans on the Moon (Neil Armstrong, Buzz Aldrin)	USA	Apollo 11

(*Source:* http://en.wikipedia.org/wiki/Timeline_of_space_exploration and David Bethel, License: GNU-FDL and CC-BY-SA)

The Space Race between the United States and the Soviet Union reached a peak in 1969 when the U.S. put the first humans on the Moon. However, the competition between the two countries' space programs continued for many more years.

Reaching the Moon

On May 25, 1961, shortly after the first American went into space, President John F. Kennedy presented the following challenge to the U.S. Congress:

> "I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him back safely to the Earth. No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish."

Eight years later, NASA's Apollo 11 mission achieved Kennedy's ambitious goal. On July 20, 1969, astronauts Neil Armstrong and Buzz Aldrin were the first humans to set foot on the moon, as shown in **Figure** 23.23.

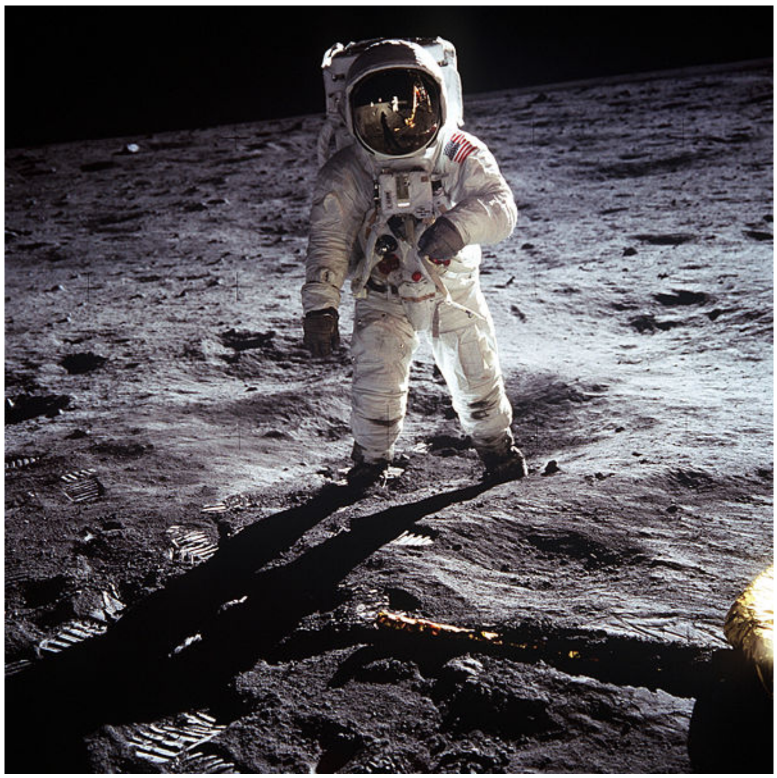

Figure 23.23: Neil Armstrong took this photo of Buzz Aldrin on the Moon during the Apollo 11 mission. Armstrong and the Lunar Module can be seen in the reflection in Aldrin's helmet. (28)

Following the Apollo 11 mission, four other American missions successfully put astronauts on the Moon. The last manned mission to the moon was Apollo 17, which landed on December 11, 1972. To date, no other country has put a person on the Moon.

In July 1975, the Soviet Union and the United States carried out a joint mission called the Apollo-Soyuz Test Project. During the mission, an American Apollo spacecraft docked with a Soviet Soyuz spacecraft, as shown in **Figure** 23.24. Many considered this to be the symbolic end of the Space Race.

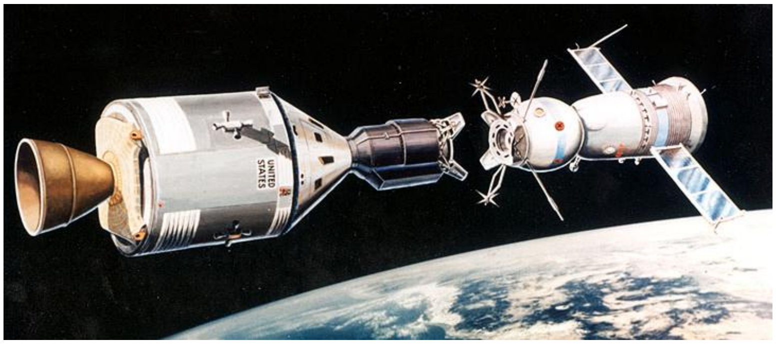

Figure 23.24: The docking of an Apollo spacecraft with a Soyuz spacecraft in 1975 was a symbolic end to the Space Race. (8)

Exploring Other Planets

Both the United States and the Soviet Union also sent probes to other planets during the Space Race. A **space probe** is a spacecraft that is sent without a crew to collect data by flying near or landing on an object in space, such as a planet, moon, asteroid, or comet. In the Venera missions, the USSR sent several probes to Venus, including some that landed on the surface. The U.S. sent probes to Mercury, Venus, and Mars in the Mariner missions, and landed two probes on Mars in the Viking missions.

In the Pioneer and Voyager missions, the U.S. also sent probes to the outer solar system, including flybys of Jupiter, Saturn, Uranus, and Neptune. The Pioneer and Voyager probes are still traveling, and are now beyond the edges of our solar system. We have lost contact with the two Pioneer probes, but expect to have contact with the two Voyager probes until at least 2020.

Lesson Summary

- Rockets have been used for warfare and ceremonies for many centuries.
- Newton's third law explains how a rocket works. The action force of the engine on the gases is accompanied by a reaction force of the gases on the rocket.

- Konstantin Tsiolkovsky, Robert Goddard, and Hermann Oberthall came up with similar ideas for improving rocket design. These included using liquid fuel and using multiple stages.
- A satellite is an object that orbits a larger object. Moons are natural satellites. Artificial satellites are made by humans.
- Newton's law of universal gravitation explains how the force of gravity works, both on Earth and across space. Gravity hold satellites in orbit.
- Artificial satellites are used for imaging Earth and other planets, for navigation, and for communication.
- The launch of the Sputnik 1 satellite started a Space Race between the United States and the Soviet Union.
- The United States' Apollo 11 mission put the first humans on the Moon.
- The U.S. and Soviet Union also sent several probes to other planets during the Space Race.

Review Questions

1. Use Newton's third law to explain how a rocket moves.
2. List the three great pioneers of rocket science.
3. What is the difference between a rocket and a satellite? How are they related?
4. What is the name of Earth's natural satellite?
5. Explain why a satellite in polar orbit will be able to take pictures of all parts of the Earth over time.
6. Describe three different types of orbits.
7. What event launched the Space Race?
8. What goal did John F. Kennedy set for the United States in the Space Race?
9. What are the advantages of a multi-stage rocket instead of a single-stage rocket?

Further Reading / Supplemental Links

- http://exploration.grc.nasa.gov/education/rocket/TRCRocket/history_of_rockets.html
- http://www.solarviews.com/eng/rocket.htm
- http://www.thespaceplace.com/history/rocket2.html
- Hermann_Oberth; Wernher_von_Braun; V-2_rocket; Satellites; Natural_satellite; Newton_cannonball; Sputnik_1; Sputnik_program; Space_Race; Cold_War; John_F._Kennedy; Apollo_program; List_of_planetary_probes.
- http://www.thespacesite.com/space_contents.html
- http://www.thespaceplace.com/history/space.html
- http://www.aero.org/education/primers/space/history.html
- http://science.howstuffworks.com/satellite.htm

- http://ctd.grc.nasa.gov/rleonard/index.html
- http://www.nasm.si.edu/exhibitions/gal114/gal114.htm
- http://nssdc.gsfc.nasa.gov/planetary/lunar/apollo_25th.html
- http://en.wikipedia.org/

Vocabulary

geostationary orbit A satellite place at just the right distance above Earth to orbit at the same rate that Earth spins.

low Earth orbit Satellites that orbit relatively close to Earth.

orbit To travel in a circular or elliptical path around another object.

polar orbit A path for a satellite that goes over the North and South Poles, perpendicular to Earth's spin.

rocket A device propelled by particles flying out of it at high speed.

satellite An object, either natural or human made, that orbits a larger object.

space probe A spacecraft that is sent without a crew to collect data by flying near or landing on an object in space.

Space Race A competition between the United States and the Soviet Union to have the best space technology.

thrust The forward force produced by gases escaping from a rocket engine.

Points to Consider

- The Space Race and the USA's desire to get to the Moon brought about many advances in science and technology.
- Can you think of any challenges we face today that are, could be, or should be a focus of science and technology?
- If you were in charge of NASA, what new goals would you set for space exploration?

23.3 Recent Space Exploration

Lesson Objectives

- Outline the history of space stations and space shuttles.
- Describe recent developments in space exploration.

Space Shuttles and Space Stations

While the United States continued missions to the Moon in the early 1970s, the Soviets had another goal: to build a **space station**. A space station is a large spacecraft on which humans can live for an extended period of time.

Early Space Stations

The Soviet Union put the first space station, Salyut 1, into orbit on April 19, 1971. At first, the station had no crew. Three cosmonauts boarded the station on June 7, 1971, and stayed for 22 days. Unfortunately, the cosmonauts died during their return to Earth, when the return capsule lost pressure while still in the airless vacuum of space. Salyut 1 left orbit on October 11, 1971, and burned up as a result of friction with the Earth's atmosphere.

Between 1971 and 1982, the Soviets put a total of seven Salyut space stations into orbit. **Figure** 23.25 shows the last of these, Salyut 7. These were all temporary stations that were launched and later inhabited by a human crew. Three of the Salyut stations were used for secret military purposes. The others were used to study the problems of living in space and for a variety of experiments in astronomy, biology, and Earth science. Salyut 6 and Salyut 7 each had two docking ports, so one crew could dock a spacecraft to one end, and later a replacement crew could dock to the other end.

The U.S. only launched one space station during this time—Skylab, shown in **Figure** 23.26. Skylab's design was based on a segment of the Saturn V rockets that were used in the Apollo missions to the Moon. Skylab was launched into low Earth orbit in May 1973. It was damaged as it passed out of Earth's atmosphere, but repairs were made when the first crew arrived.

Three crews visited Skylab, all within its first year in orbit. Skylab was used to study the effects of staying in space for long periods. It was also used for studying the Sun. Skylab reentered Earth's atmosphere in 1979, sooner than expected. It was so large that Skylab did not completely burn as it reentered the Earth's atmosphere. As a result, pieces of it fell across a large area, including some of western Australia. News headlines read, "The Skylab is Falling!"

Figure 23.25: The Soviet Salyut 7 space station was in orbit from 1982 to 1991. (14)

Figure 23.26: This image of Skylab was taken as the last crew left the station in January of 1974. (10)

Modular Space Stations

The first space station designed for very long-term use was the Mir space station (**Figure** 23.27). Mir was a *modular* space station, which means it was launched in several separate pieces and put together in space. The core of Mir was launched by the Soviet Union in 1986. Mir was put together in several phases between 1986 and 1996. Mir holds the current record for the longest continued presence in space. There were people living on Mir continuously for almost 10 years, falling short of the 10-year mark by just eight days. Mir was taken out of orbit in 2001; it fell into the Pacific Ocean, as the Russians had planned.

Mir was the first major space project in which the United States and Russia (after the fall of the USSR) worked together. In 1993, U.S. Vice President, Al Gore and Russian prime minister, Viktor Chernomyrdin announced plans for a new space station, which would later be called the International Space Station, or ISS. They also agreed that the U.S. would be involved in the Mir project in the years ahead. Space shuttles would take part in the transport of supplies and people to and from Mir. In addition, American astronauts would live on Mir for many months. This cooperation with Russia allowed the United States to learn from Russia's experience with long duration space flights. **Figure** 23.28 shows Mir with an American space shuttle attached.

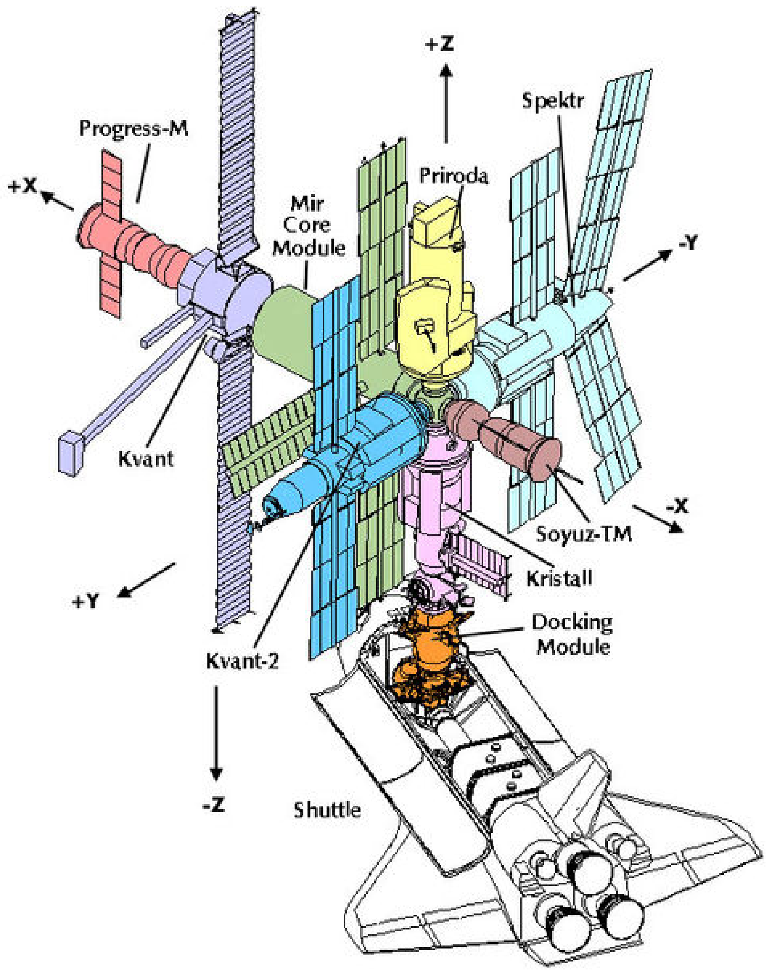

Figure 23.27: The Soviet/Russian space station Mir was designed to have several different parts attached to a core. (5)

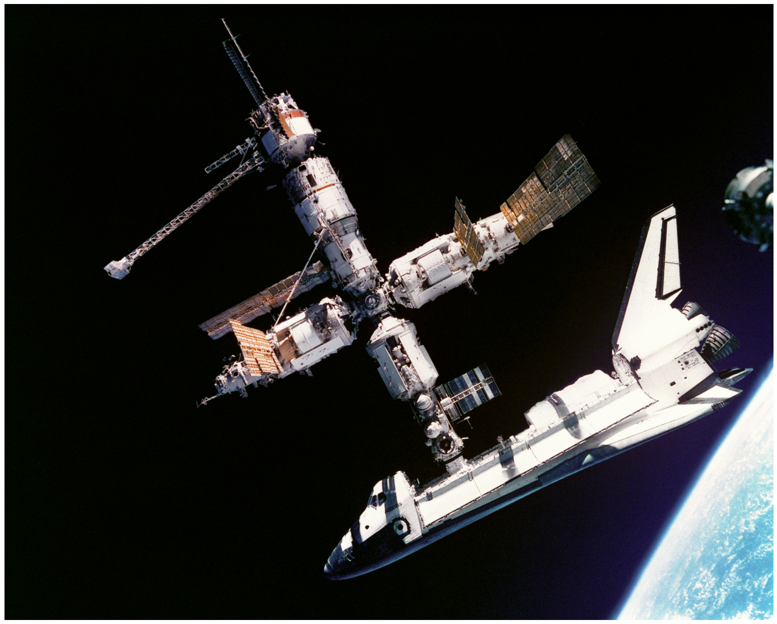

Figure 23.28: American space shuttles visited Mir several times during the 1990's. This picture was taken by Russian cosmonauts from their Soyuz spacecraft, as they flew around Mir and the Space Station to check on the space station. (32)

The International Space Station

Early space exploration was driven by competition between the United States and the Soviet Union. However, since the end of the Cold War, space technology and space exploration have benefited from a spirit of cooperation. The International Space Station, shown in **Figure** 23.29, is a joint project between the space agencies of the United States (NASA), Russia (RKA), Japan (JAXA), Canada (CSA) and several European countries (ESA). The Brazilian Space Agency also contributes.

The International Space Station is a very large station with many different sections. It is still being assembled. The first piece was launched in 1997. The first crew arrived in 2000, and the station has had people on board ever since. American space shuttles carry most of the supplies and equipment to the station, while Russian Soyuz spacecraft carry people. The primary purpose of the station is scientific research, especially in biology, medicine, and physics.

Space Shuttles

The spacecraft that NASA used for the Apollo missions were very successful, but they were very expensive, could not carry much cargo, and could be used only once. After the Apollo missions to the Moon, NASA wanted a new kind of space vehicle. They wanted this vehicle to

Figure 23.29: This photograph of the International Space Station was taken by the space shuttle Atlantis in June 2007. Construction of the station is scheduled to be finished in 2010. (18)

be reusable and able to carry large pieces of equipment, such as satellites, space telescopes, or sections of a space station. The resulting spacecraft was a **space shuttle**, shown in **Figure** 23.30. Although this vehicle is sometimes referred to as "the space shuttle," the U.S. has actually had five working space shuttles—Columbia, Challenger, Discovery, Atlantis, and Endeavor. The Soviet Union built a similar shuttle called Buran, but it never flew a mission with humans aboard.

Figure 23.30: Since 1981, the space shuttle has been the United States' primary vehicle for carrying people and large equipment into space. This photo shows the space shuttle Atlantis on the launch pad in 2006. (30)

A space shuttle has three main parts, although you are probably most familiar with the

orbiter, the part that has wings like an airplane. When a space shuttle launches, the orbiter is attached to a huge fuel tank that contains liquid fuel. On the sides of the fuel tank are two large *booster rockets*.

Figure 23.31 shows the stages of a normal space shuttle mission. The launch takes place at Cape Canaveral, in Florida. The booster rockets provide extra power to get the orbiter out of Earth's atmosphere. When they are done, they parachute down into the ocean so they can be recovered and used again. When the fuel tank is empty, it also falls away, but it burns up in the atmosphere. Once in space, the orbiter can be used to release equipment such as a satellite or supplies to the International Space Station, to repair existing equipment such as the Hubble Space Telescope, or to do experiments directly on board the orbiter.

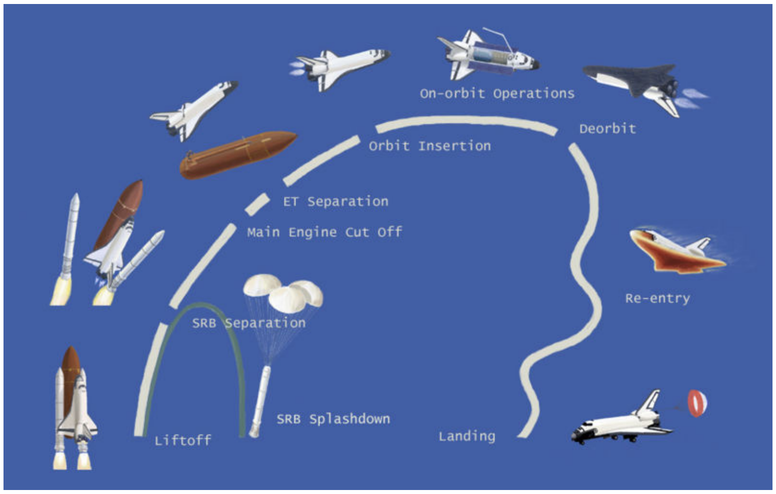

Figure 23.31: In a typical space shuttle mission, the orbiter takes off like a rocket and lands like an airplane. (15)

When the orbiter is done with its mission, it re-enters Earth's atmosphere. As it passes through the atmosphere, the outside of the orbiter heats up to over 1,500°C. The rockets do not fire during re-entry, so the shuttle is more like a glider than a regular airplane. Pilots have to steer the shuttle to the runway very precisely. Space shuttles usually land at Kennedy Space Center in Cape Canaveral, Florida, or at Edwards Air Force Base in California. However, if weather is bad at both these landing sites, a shuttle can land at one of many backup sites around the world. It can later be hauled back to Florida on the back of a jet airplane.

Space Shuttle Disasters

The space shuttle program has been very successful. Space shuttles have made possible many scientific discoveries and other great achievements in space. However, the program has also had some tragic disasters.

From the first flight in 1981 to the end of 1985, space shuttles flew over 20 successful missions, including many satellite launches and missions for scientific research. On January 28, 1986, the space shuttle Challenger launched carrying seven crew members, including Christa McAuliffe, who was to be the first teacher in space. Just 73 seconds after launch, the Challenger started to break apart, and most of it disintegrated in mid-air, as shown in **Figure** 23.32. All seven crew members on board died. Later study showed that the problem was due to an O-ring, a small part in one of the rocket boosters. Because of this disaster, space shuttle missions were put on hold while NASA studied the problem and improved the safety of the shuttles.

Figure 23.32: Plume of smoke from the Challenger disaster. The space shuttle Challenger broke apart 73 seconds after its launch on January 28, 1986. (11)

Shuttle missions started again in 1988, and there were over 87 consecutive missions without a major accident. However, during the takeoff of space shuttle Columbia on January 16, 2003, a small piece of insulating foam broke off the fuel tank. The foam smashed into one wing of the orbiter and damaged a tile on the front edge of the shuttle's wing. These tiles are heat shield tiles that protect the shuttle from extremely high temperatures. When Columbia returned to Earth on February 3, 2003, it could not withstand the high temperature, and broke apart. Pieces of the shuttle were found throughout the southern United States, especially in Texas. As in the Challenger disaster, all seven crew members died.

After the Columbia disaster, shuttle missions were stopped for over two years while NASA worked on the problem. One year after the disaster, President Bush announced that the space shuttle program was to end by the year 2010, and a new Crew Exploration Vehicle would take its place. The Crew Exploration Vehicle, now known as Orion is currently expected to be ready by 2014. All the remaining shuttle missions will be to the International Space Station, except for one repair mission to the Hubble Space Telescope.

Recent Space Missions

Since the 1986 Challenger disaster NASA has focused on missions without a crew, except for the International Space Station missions. These recent missions are less expensive and less dangerous than missions with a crew, yet still provide a great deal of valuable information.

Earth Science Satellites

In recent years, NASA and space agencies from other countries have launched dozens of satellites that collect data on the current state of Earth's systems. For example, NASA's Landsat satellites take detailed images of Earth's continents and coastal areas, such as those in **Figure** 23.33. Other satellites study the oceans, the atmosphere, the polar ice sheets, and other Earth systems. This data helps us to monitor climate change and understand how Earth's systems affect one another.

Figure 23.33: The two images above are from NASA's Landsat 7 satellite. The left shows New Orleans and Lake Pontchartrain on April 26, 2000. The right shows the same area on August 30, 2005, shortly after Hurricane Katrina flooded the city. Dark blue areas in the city are underwater. (6)

Space Telescopes

Some of the greatest astronomical discoveries—and greatest pictures, like the one in **Figure** 23.34, have come from the Hubble Space Telescope. The Hubble was the first telescope in space. It was put into orbit by the space shuttle Discovery in 1990. Since then, four shuttle missions have gone to the Hubble to make repairs and upgrades. A final repair mission to the Hubble is scheduled for 2008.

Figure 23.34: This image taken by the Hubble Space Telescope shows the Cat's Eye Nebula. Hubble has produced thousands of beautiful pictures that are also very valuable for scientific research. (23)

NASA has also put several other telescopes in space, including the Spitzer Space Telescope, the Chandra X-Ray Observatory, and the Compton Gamma Ray Observatory. The biggest and most advanced space telescope yet, the James Webb Telescope, is scheduled to be launched into orbit around 2013. The James Webb will replace the Hubble Space Telescope and will have an even greater ability to view distant objects. Other countries, including Russia, Japan, and several European countries have also put space telescopes in orbit.

Solar System Exploration

We have continued to explore the solar system in recent years. In 1997, the Mars Pathfinder **rover** landed on Mars. A rover is like a spacecraft on wheels (**Figure** 23.35). It can move around on the surface of a moon or planet and collect data from different locations. Two more rovers—Spirit and Opportunity—landed on Mars in 2004, and as of 2008 are still sending data back to Earth. Amazingly, both rovers were only designed to explore Mars for 90 days — they have now worked for more than 15 times their intended lifespan. Several spacecraft are currently in orbit around Mars, studying its surface and thin atmosphere.

Figure 23.35: This artists' painting of one of the two Mars rovers shows the six wheels, as well as a set of instruments being extended forward by a robotic arm. (29)

The Cassini mission has been studying Saturn, including its rings and moons, since 2004. The Huygens probe, built by the European Space Agency, is studying Saturn's moon Titan. Titan has some of the conditions that are needed to support life.

Some missions are studying the smaller objects in our solar system. The Deep Impact probe was sent to collide with a comet, collecting data all the way. When it hit the comet, the impact made a cloud of dust. Space telescopes and telescopes on Earth all collected data after the impact. The Stardust mission collected tiny dust particles from another comet. Missions are currently underway to study some of the larger asteroids and Pluto. Studies of smaller objects in the solar system may help us to understand how the solar system formed.

Future Missions

In 2004, President Bush proposed a "new vision for space exploration." He set the goal of putting humans on the Moon again by 2020. Unlike the Apollo missions, however, Bush proposed that reaching the Moon would only be the beginning. He also proposed building a permanent station on the Moon, which could serve as a base for missions taking humans to Mars and beyond. He announced that the space shuttle program would be retired after the International Space Station was complete (around 2010). A new kind of space vehicle, now called Orion, will be developed to take humans to space.

President Bush also explained we would meet these goals cooperatively, more like the International Space Station than the missions during the Space Race. He said, "We'll invite other nations to share the challenges and opportunities of this new era of discovery. The vision I outline today is a journey, not a race, and I call on other nations to join us on this journey, in a spirit of cooperation and friendship." Meanwhile, China, Russia, and Japan have all said they are planning to send humans to the Moon and establish Moon bases of their own.

Lesson Summary

- The Soviet Union put seven Salyut space stations into orbit between 1971 and 1982.
- The United States' first space station was Skylab. Skylab was in orbit from 1973 to 1979.
- The Soviet (later Russian) space station Mir was the first modular space station. Both Russian and American crews lived on Mir.
- The International Space Station is a huge project that involves many countries. It is still being assembled.
- Space shuttles are reusable vehicles for American astronauts to get into space. A space shuttle takes off like a rocket and lands like a glider plane.
- The space shuttle program has had two major disasters—the Challenger disaster in 1986 and the Columbia disaster in 2003. In each case, the spacecraft was destroyed and a crew of 7 people died.
- Recent space missions have mostly used small spacecraft, such as satellites and space probes, without crews.
- The United States plans to send humans to the Moon again by 2020, build a base on the Moon, then send humans to Mars.

Review Questions

1. Which space station was built and launched by the United States alone?
2. How many years was the Mir space station in orbit?
3. Which space station was the first to involve several countries working together?
4. Describe two ways in which space shuttles were an improvement over the spacecraft used for the Apollo missions?
5. Name the five fully functional space shuttles that the United States built. Which of these were destroyed?
6. Describe the space shuttle Columbia disaster, including its cause.
7. Describe two recent or ongoing space missions.
8. Is the Space Shuttle more like a rocket or a plane? Explain your answer.

Further Reading / Supplemental Links

- http://science.hq.nasa.gov/missions/earth.html
- http://landsat.gsfc.nasa.gov/images/archive/e0004.html
- http://www.whitehouse.gov/news/releases/2004/01/20040114-3.html
- http://www.nytimes.com/2007/09/25/science/space/25china.html?_r=1&ref=world&oref=slogin
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- http://starchild.gsfc.nasa.gov/docs/StarChild/space_level2/skylab.html
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- http://www.nasa.gov/missions/current/index.html; http://www.nasa.gov/mission_pages/exploration/main/index.html; http://en.wikipedia.org/wiki/Orion_%28spacecraft%29

Vocabulary

orbiter The main part of the space shuttle that has wings like an airplane.

space shuttle A reusable spacecraft capable of carrying large pieces of equipment or pieces of a space station.

space station A large spacecraft in space on which humans can live for an extended period of time.

Points to Consider

- To date, a total of 22 people have died on space missions. In the two space shuttle disasters alone, 14 people died. However, space exploration and research have led to many great discoveries and new technologies. Do you think sending people into space is worth the risk? Why or why not?
- In the past several years, private companies have been developing vehicles and launch systems that can take people into space.
- What applications can you think of for such vehicles? What advantages and disadvantages are there to private companies building and launching spacecraft?

Image Sources

(1) NASA. http://en.wikipedia.org/wiki/File:Arecibo_naic_big.gif. Public Domain.

(2) NASA. http://imagine.gsfc.nasa.gov/docs/science/how_l1/spectra.html. Public Domain.

(3) USAF. http://en.wikipedia.org/wiki/Image:Milstar.jpg. Public Domain.

(4) NASA. http://commons.wikimedia.org/wiki/File:Ksc-69pc-442.jpg. Public Domain.

(5) NASA. http://en.wikipedia.org/wiki/Image:Mir_module.jpg. Public Domain.

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(10) NASA. http://en.wikipedia.org/wiki/Image:Skylab_%28SL-4%29.jpg. Public Domain.

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(18) http://spaceflight.nasa.gov/gallery/images/station/assembly/html/s117e08045.html. Public Domain.

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(22) http://en.wikipedia.org/wiki/File:Yerkes_40_inch_Refractor_Telescope-2006.jpg. Public Domain.

(23) http://hubblesite.org/newscenter/archive/releases/2004/27/image/a. Public Domain.

(24) Public Domain. http://commons.wikimedia.org/wiki/Image:Galileos_Moon.jpg.

(25) http://en.wikipedia.org/wiki/Image:Newton_Cannon.svg. GNU-FDL.

(26) NASA. *http://en.wikipedia.org, http://en.wikipedia.org/wiki/File:Spitzer-_Telescopio.jpg/wiki/File:Cartoon_CGRO.jpg, http://commons.wikimedia.org/wiki/File:Chandra_X-ray_Observatory.jpg*. Public Domain.

(27) CK-12 Foundation. . CC-BY-SA.

(28) NASA. http://en.wikipedia.org/wiki/Image:Aldrin_Apollo_11.jpg. GNU-FD.

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Chapter 24

Earth, Moon, and Sun

24.1 Planet Earth

Lesson Objectives

- Recognize that Earth is a sphere, and describe the evidence for this conclusion.
- Describe what gravity is, and how it affects Earth in the solar system.
- Explain what causes Earth's magnetism, and the effects that magnetism has on the Earth.

Introduction

The Earth and Moon revolve around each other as they orbit the Sun. As planet Earth rotates and revolves, we experience cycles of day and night as well as seasons. Earth has a very large moon for an inner planet. We are the only inner planet that does, so how did the Moon form and what is the surface of the Moon like? We revolve around an average, ordinary star, the Sun. It does not look like any of the other stars we see in the sky. What can we discover about our amazing Sun?

Earth's Shape, Size, and Mass

Every day you walk across some part of Earth's surface, whether that surface is your yard or the sidewalks by your school. For most of us, a walk outside means walking on fairly flat ground. We don't usually stop and realize that the Earth is a **sphere**, an object similar in shape to a ball. How do we know that Earth is a sphere? How could you convince someone that even though the surfaces we walk on look flat, the Earth as a whole is round?

One of the most convincing pieces of evidence for a spherical Earth are the pictures we have of it from Space. Astronauts aboard the Apollo 17 shuttle took one of the most famous photographs in history, called "The Blue Marble" (**Figure** 24.1). This outstanding image shows Earth as it looks from about 29,000 kilometers (18,000 miles) away in Space. The picture shows us that Earth is spherical and looks like a giant blue and white ball. Hundreds of years before humans ever made it into space, we knew the Earth was round. What ways have you been able to see this for yourself?

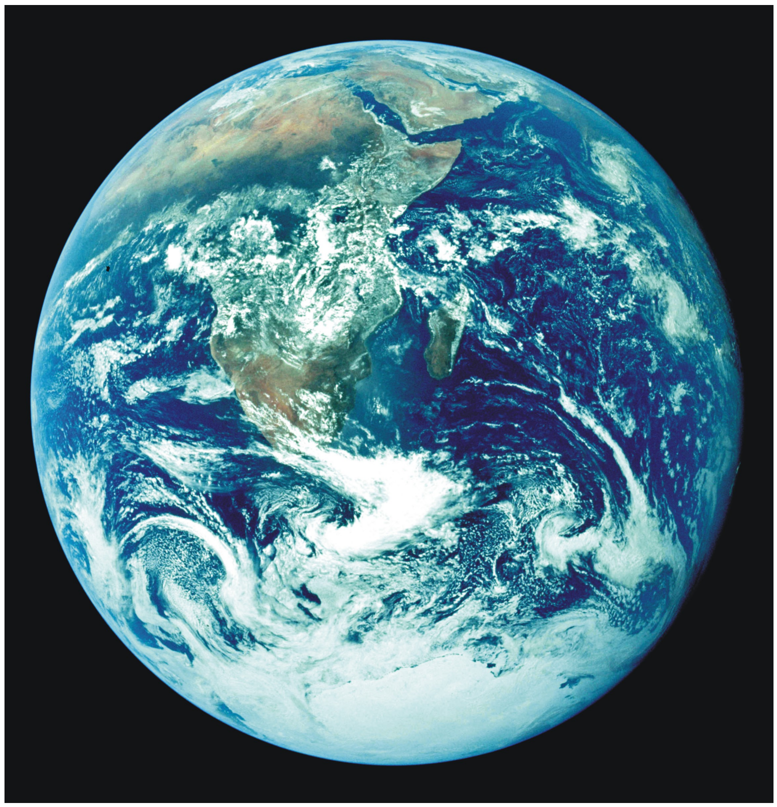

Figure 24.1: Photograph entitled "The Blue Marble" taken by Apollo 17 Crew. (15)

The Sun and the other planets of our Solar System are also spheres. The Sun is found in the center of the solar system, and the planets travel around the Sun in regular paths called **orbits**. Earth is the third planet from the Sun, and its mass is approximately 6.0 x 10^{24} kilograms. In contrast, the volume of planet Jupiter is about 1,000 times greater than Earth's volume, and the Sun's volume is about 1,000 times greater than Jupiter's (**Figure** 24.2).

While the outer planets in the Solar System are giant balls of swirling gas with very low densities, Earth is an inner planet. The inner planets are relatively small, denser, rockier planets than the outer planets. Three-fourths of Earth's rocky surface is covered with water. As far as we know, Earth is also the only planet that carries liquid water, another important requirement for life. The entire planet is also surrounded by a thin layer of air called the

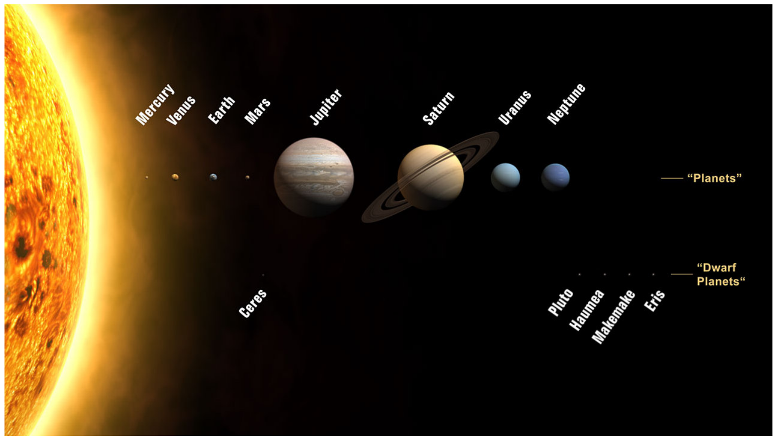

Figure 24.2: Planets and dwarf planets of the solar system. (2)

atmosphere. Earth's atmosphere is unique in the solar system in that it contains just the right amount of oxygen to support animal life. Therefore, Earth is the only planet in the solar system on which life is found. The 'Our Solar System' chapter will discuss the features of other planets in more detail.

When describing Earth, it's useful to name and define the many components of our planet. Since Earth is a sphere, the layers that make it up are also referred to as spheres (**Figure** 24.3).

They are:

- **Atmosphere**—the thin layer of air that surrounds the Earth.
- **Hydrosphere**–the part of Earth's surface that consists of water.
- **Biosphere**—the part of the Earth that supports life. The biosphere includes all the areas where life is found.
- **Lithosphere**–the solid part of Earth. The lithosphere consists of mountains, valleys, continents and all of the land beneath the oceans. Only one-fourth of Earth's surface is land, but solid rock makes up more than 99% of Earth's total mass.

Earth's layers all come into contact with each other and interact. Therefore, Earth's surface is constantly undergoing change.

Earth's Gravity

We know that the Earth orbits the Sun in a regular path (**Figure** 24.4). The Earth's Moon also orbits the Earth in a regular path. **Gravity** is the force of attraction between all objects. Gravity keeps the Earth and Moon in their orbits. Isaac Newton was one of the first scientists to explore the idea of gravity. He understood that the Moon can only circle the Earth because some force is pulling the Moon toward Earth's center. Otherwise, the Moon would continue moving in a straight line off into space. Newton also came to understand

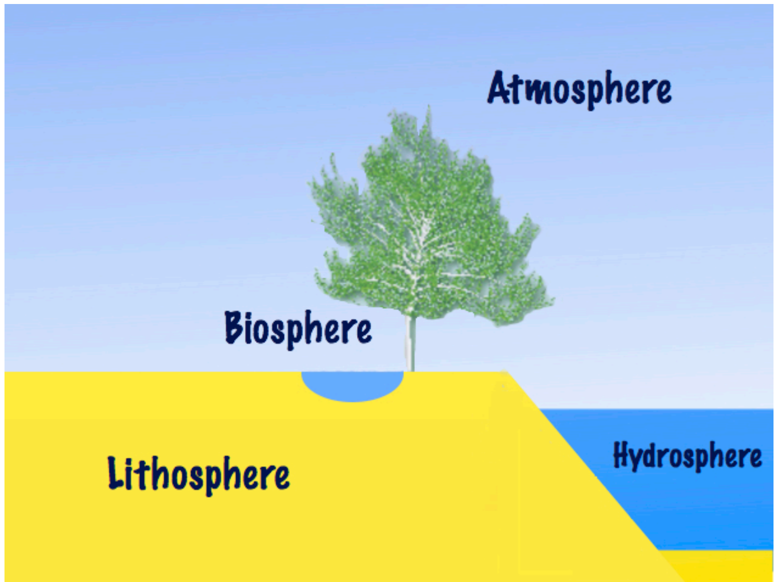

Figure 24.3: Earth has a hydrosphere, lithosphere, atmosphere, and biosphere. (6)

that the same force that keeps the Moon in its orbit is the same force that causes objects on Earth to fall to the ground.

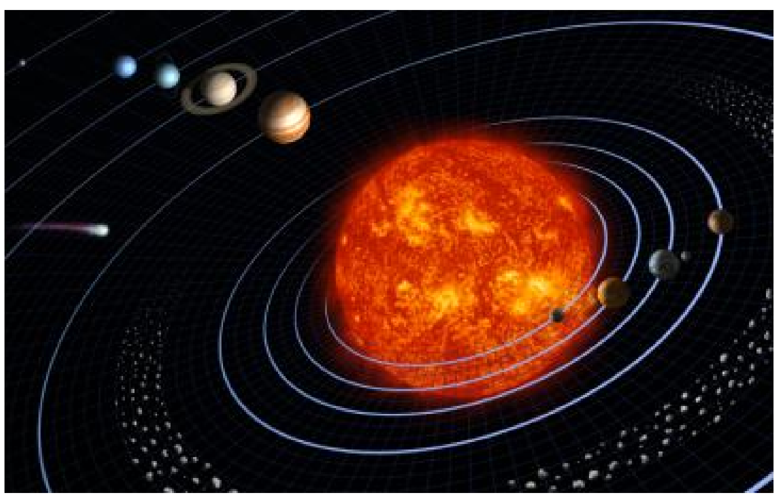

Figure 24.4: The planets orbit the Sun in regular paths. (21)

Newton defined the Universal Law of Gravitation, which states that a force of attraction, called gravity, exists between all objects in the universe (**Figure** 24.5). The strength of the gravitational force depends on how much mass the objects have and how far apart they are from each other. The greater the objects' mass, the greater the force of attraction; in addition, the greater the distance between the objects, the smaller the force of attraction.

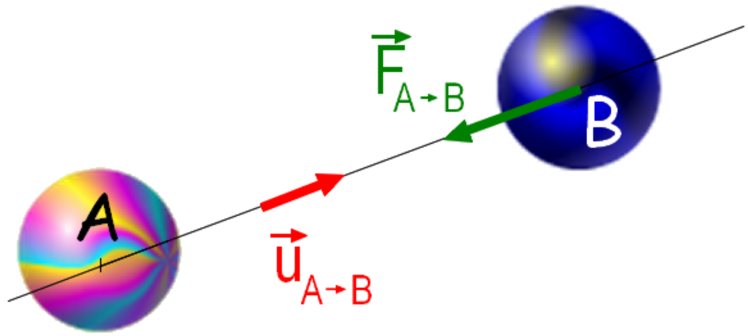

Figure 24.5: The force of gravity exists between all objects in the universe; the strength of the force depends on the mass of the objects and the distance between them. (20)

Earth's Magnetism

Earth has a **magnetic field** (**Figure** 24.6). It may be helpful to imagine that the Earth has a gigantic bar magnet inside of it. A bar magnet has a north and south pole and a magnetic field that extends around it. Earth's magnetic field also has a north and south pole and a magnetic field that surrounds it. Scientists believe Earth's magnetic field arises from the movements of molten metals deep inside Earth's outer liquid iron core. Iron and nickel flow within the Earth's core, and their movement generates Earth's magnetic field. Earth's magnetic field extends several thousand kilometers into space.

Earth's magnetic field serves an important role. It shields the planet from harmful types of radiation from the Sun (**Figure** 24.7). If you have a large bar magnet, you can tie a string to it, hang it from the string, and then watch as it aligns itself in a north-south direction, in response to Earth's magnetic field. This concept allows a compass to work, so that people can navigate by finding magnetic north (**Figure** 24.8).

Lesson Summary

- The Earth and other planets in our solar system are rotating spheres, that also revolve around the Sun in fixed paths called orbits.
- The inner four planets are small, dense rocky planets like Earth. The next four planets are large, gaseous planets like Jupiter.
- The balance between gravity and our motion around the Sun, keep the planets in orbit at fixed distances from the Sun.
- Earth has a magnetic field, created by motion within Earth's outer, liquid iron core that shields us from harmful radiation.

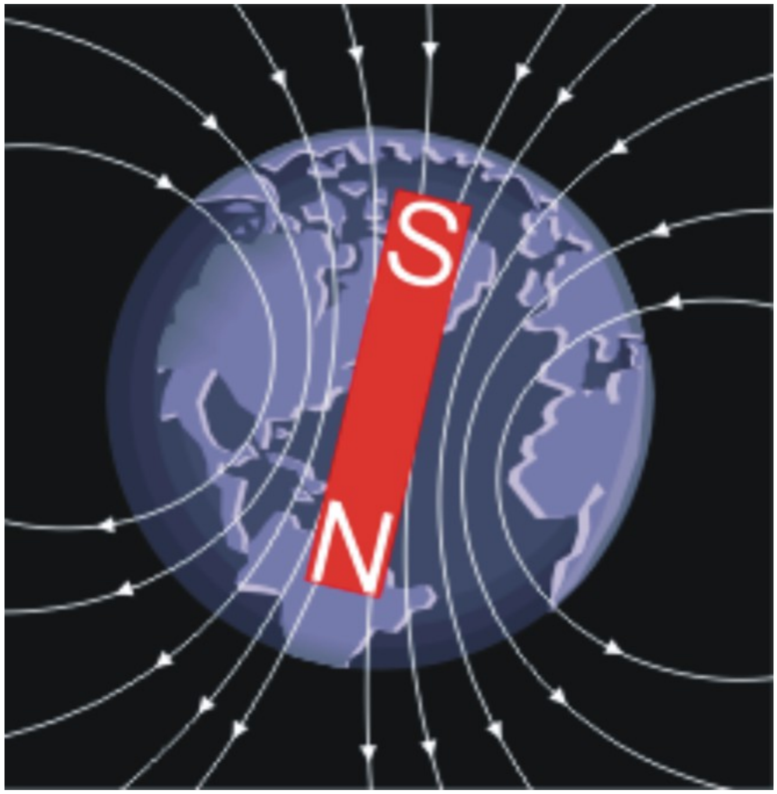

Figure 24.6: Earth's Magnetic Field (25)

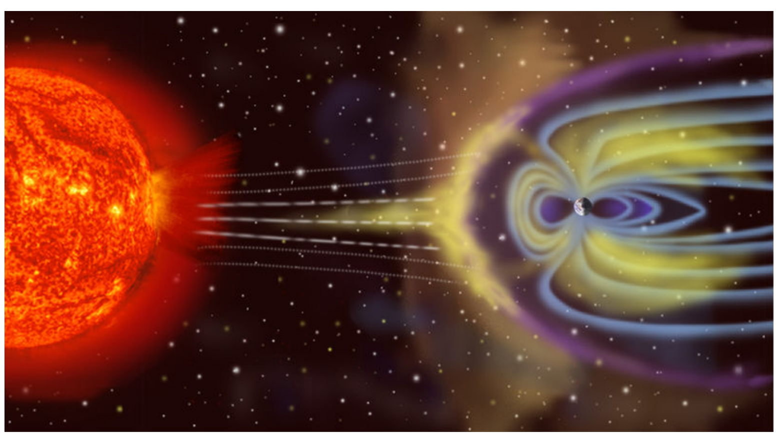

Figure 24.7: Earth's magnetic field protects the Earth from radiation from the sun; Earth, on the right, is tiny by comparison to the Sun. (16)

Figure 24.8: A compass; one end of the needle is pointing to the north. (11)

Review Questions

1. When you watch a tall ship sail over the horizon of the Earth, you see the bottom part of it disappear faster than the top part. With what you have learned about the shape of the Earth, describe why this happens.
2. What are two reasons that Earth is able to support life?
3. The planet Jupiter is gaseous and lacks a solid surface. How does this compare to Earth?
4. Give one example of how Earth's lithosphere and hydrosphere can interact, and can exchange material.
5. How do mass and distance influence the force of gravity?
6. Why are we able to use magnets to determine north-south directions on Earth?

Vocabulary

atmosphere The thin layer of air that surrounds the Earth.

biosphere All parts of the Earth that supports life.

gravity An attractive force that exists between all objects in the universe; gravity is responsible for planets orbiting the Sun, and for moons orbiting those planets.

hydrosphere The layer of Earth consisting of water.

lithosphere The solid layer of Earth, made of rock.

magnetic field A region of space surrounding an object, in which an attractive magnetic force can be detected.

orbit The path of an object, such as a planet or moon, around a larger object such as the Sun.

sphere An object similar in shape to a ball.

Points to Consider

- What would other planets need to have if they were able to support life?
- Would life on Earth be impacted if Earth lost its magnetic field?
- Could a large gas planet like Jupiter or Saturn support life?

24.2 Earth's Motions

Lesson Objectives

- Describe Earth's rotation on its axis.
- Describe Earth's revolution around the Sun.

Introduction

Imagine a line passing through the center of Earth that goes through both the North Pole and the South Pole. This imaginary line is called an *axis*. Earth spins around its axis, just as a top spins around its spindle. This spinning movement is called Earth's **rotation**. At the same time that the Earth spins on its axis, it also orbits, or revolves around the Sun. This movement is called **revolution**.

Earth's Rotation

In 1851, a French scientist named Léon Foucault took an iron sphere and swung it from a wire. He pulled the sphere to one side and then released it, letting it swing back and forth in a straight line. A ball swinging back and forth on a string is called a pendulum. A pendulum set in motion, will not change its motion, so it will not change the direction of the swinging. However, Foucault observed that his pendulum did seem to change direction. He knew that

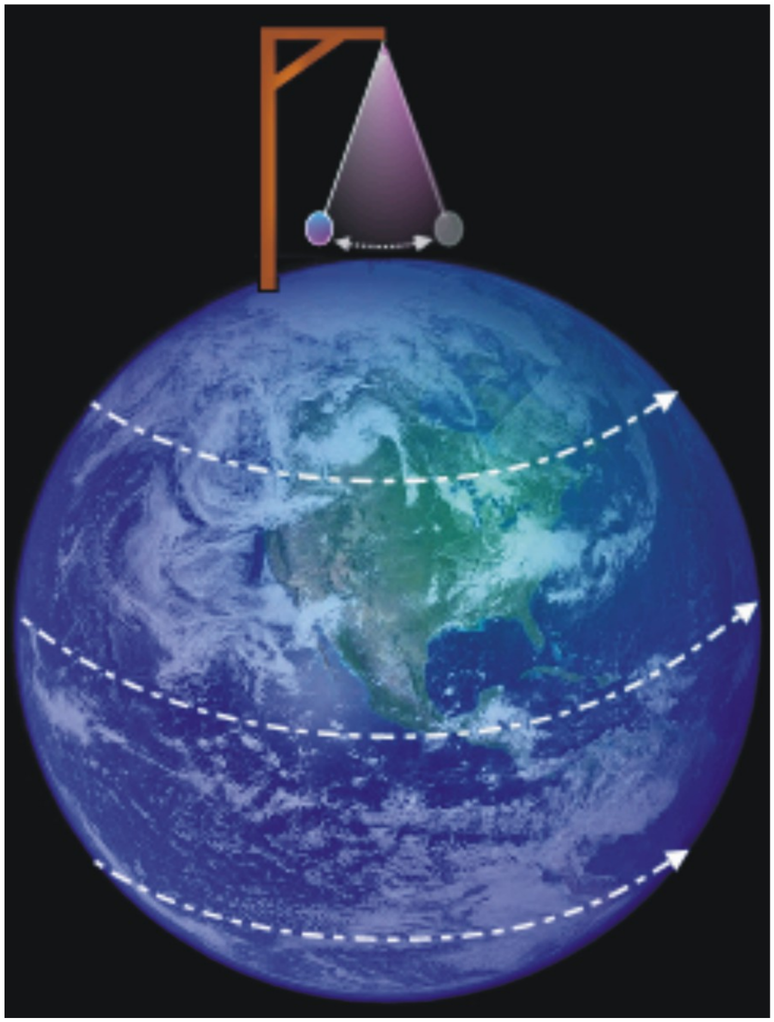

Figure 24.9: Imagine a pendulum at the North Pole. The pendulum always swings in the same direction but because of Earth's rotation; its direction will appear to change to observers on Earth. (14)

the pendulum itself could not change its motion, so he concluded that the Earth, underneath the pendulum was moving. **Figure** 24.9 shows how this might look.

It takes 23 hours, 59 minutes and 4 seconds for the Earth to make one complete rotation on its axis, if we watch Earth spin from out in space. Because Earth is moving around the Sun at the same time that it is rotating, Earth has to turn just a little bit more to reach the same place relative to the Sun, so we experience each day on Earth as 24 hours. At the equator, the Earth rotates at a speed of about 1,700 kilometers per hour. Thankfully, we do not notice this movement, because it would certainly make us dizzy.

Earth's Revolution

Earth's revolution around the Sun takes much longer than its rotation on its axis. One complete revolution takes 365.24 days, or one year. The Earth revolves around the Sun because gravity keeps it in a roughly circular orbit around the Sun. The Earth's orbital path is not a perfect circle, but rather an ellipse, which means that it is like a slight oval in shape (**Figure** 24.10). This creates areas where the Earth is sometimes farther away from the Sun than at other times. We are closer to the Sun at perihelion (147 million kilometers) on about January 3rd and a little further from the Sun (152 million kilometers) at aphelion on July 4th. Students sometimes think our elliptical orbit causes Earth's seasons, but this is not the case. If it were, then the Northern Hemisphere would experience summer in January!

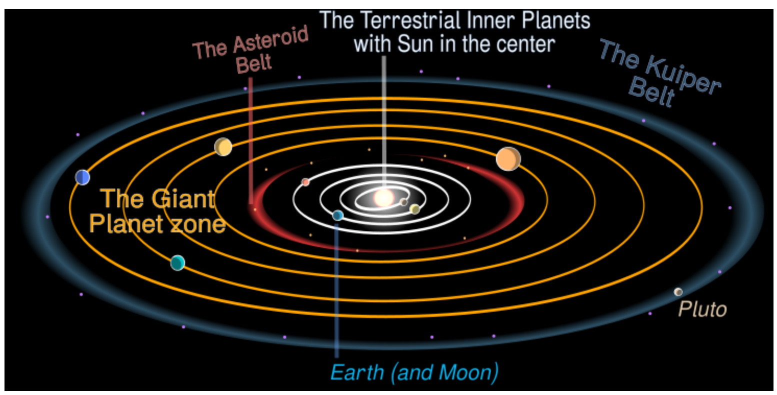

Figure 24.10: Earth and the other planets in the solar system make regular orbits around the Sun; the orbital path is an ellipse and is controlled by gravity. (8)

During one revolution around the Sun, the Earth travels at an average distance of about 150 million kilometers. Mercury and Venus take shorter times to orbit the Sun than the Earth, while all the other planets take progressively longer times depending on their distance from the Sun. Mercury only takes about 88 Earth days to make one trip around the Sun. While Saturn, for example, takes more than 29 Earth years to make one revolution around the Sun.

Earth revolves around the Sun at an average speed of about 27 kilometers (17 miles) per second. Our planet moves slower when it is farther away from the Sun and faster when it is closer to the Sun. The reason the Earth (or any planet) has seasons is that Earth is tilted

23 1/2 ° on its axis. This means that during the Northern **hemisphere** summer the North pole points toward the Sun, and in the Northern hemisphere winter the North Pole is tilted away from the Sun (**Figure** 24.11). The season we experience depends on where the Earth is in its revolutionary orbit around the Sun.

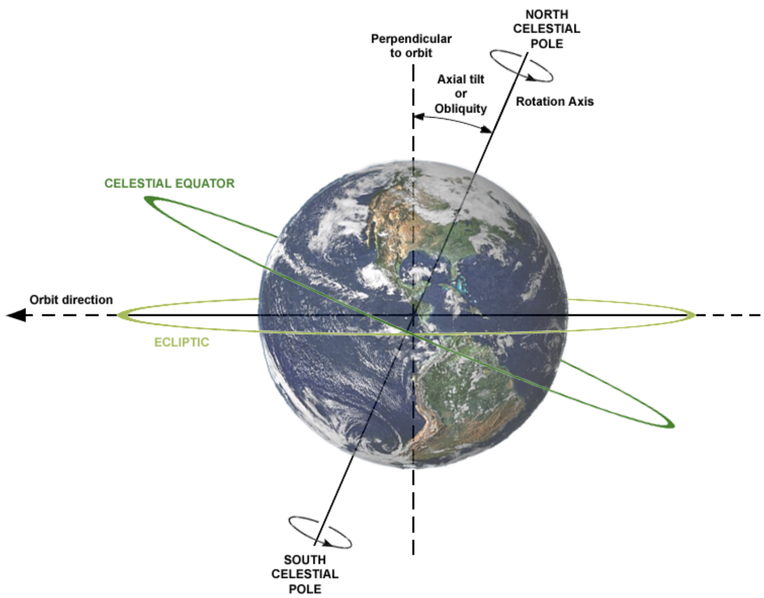

Figure 24.11: The Earth tilts on its axis. (4)

Lesson Summary

- Earth rotates or spins on its axis once each day and revolves around the Sun once every year.
- The tilt of Earth's axis produces seasons.

Review Questions

1. Describe the difference between Earth's rotation and its revolution.
2. What is the force that keeps the Earth and other planets in their orbital paths?
3. The planet Jupiter is about 778,570,000 kilometers from the Sun; Earth is about 150,000,000 kilometers from the Sun. Does Jupiter take more or less time to make one revolution around the sun? Explain your answer.
4. In its elliptical orbit around the Sun, the Earth is closest to the Sun in January. Even though Earth is closest to the Sun in January, people in the Northern hemisphere experience winter weather. Using your understanding of how the Earth is tilted on its axis, why do you think people in the Northern Hemisphere have winter in January?
5. Where on Earth would Foucault's pendulum appear to not be moving? Why?

Vocabulary

axis An imaginary line that runs from the North Pole to South Pole, and includes the center Earth.

ellipse A shape that looks like a slightly squashed circle.

hemisphere One half of a sphere.

revolution The Earth's movement around the Sun in an orbital path.

rotation The motion of the Earth spinning on its axis.

Points to Consider

- What type of experiment could you create to prove that the Earth is rotating on its axis?
- If you lived at the equator, would you experience any effects due to Earth's tilted axis?
- If Earth suddenly increased in mass, what might happen to its orbit around the Sun?

24.3 Earth's Moon

Lesson Objectives

- Explain how scientists believe the Moon formed.
- Describe the features of the Moon.

Introduction

On July 20, 1969 hundreds of millions of people all over the world excitedly sat in front of their televisions and witnessed something that had never happened before in the history of the world. On that day, two American astronauts named Neil Armstrong and Edwin "Buzz" Aldrin landed the *Eagle* on the surface of the Moon (**Figure** 24.12). Neil Armstrong was the commander of the mission, and he was the first human to ever step foot on the Moon. No other place in space, besides Earth, has been touched by humans. Even today, the Moon remains the only other body in space that humans have visited.

Between 1969 and 1972, six piloted spaceships were sent to land on the Moon. They are often referred to as **lunar** expeditions, the word lunar meaning "related to the Moon." On some missions, the astronauts brought back soil and rock samples from the Moon. Once back at Earth, the samples were studied to help scientists learn about the surface features of the Moon. No astronauts have visited the Moon since 1972, but in 2004 the United States President George W. Bush called for a return to Moon exploration by the year 2020. Maybe you can be one of the astronauts to return to the Moon!

This lesson focuses on how the Moon was formed and gives a description of the features and characteristics of the Moon—many of which were investigated and discovered during the major years of lunar exploration in the 1960s and 1970s.

Figure 24.12: Astronaut Buzz Aldrin walks on the Moon on July 20, 1969. (17)

How the Moon Formed

Astronomers have carried out computer simulations showing that the collision of a Mars-sized object with the Earth could have resulted in the formation of the Moon. Additional data shows that the surface of the Moon dates to about 4.5 billion years ago, suggesting that the collision occurred during the heavy bombardment period, about 70 million years after the Earth formed. The Moon also has a relatively small core and appears to be largely comprised of the same basalt material found in the Earth mantle. Such a collision would have been incredibly powerful, producing oceans of liquid magma over much of the surface of the Earth.

The explosive impact that likely led to the formation of the Moon would have produced a huge amount of energy, leaving the surface of the Moon in an initially **molten** state. This means that its surface would have been hot and fluid, like magma inside the Earth today. The magma eventually cooled and hardened so that the Moon now has a solid surface.

Lunar Characteristics

The Moon is Earth's only natural satellite. A **satellite** is a body that moves around a larger body in space. The Moon orbits Earth in the same way that the Earth orbits the Sun, and the Moon remains close to Earth because of the strength of Earth's gravity. The Moon is 3,476 kilometers in diameter, about one-fourth the size of Earth. Because the Moon is not as dense as the Earth, gravity on the Moon is only one-sixth as strong as it is on Earth. You could jump six times as high on the Moon as you can on Earth.

If you watch the Earth and the Moon from space, the Moon makes one complete orbit around the Earth every 27.3 days. The Moon also rotates on its axis once every 27.3 days. Thus, the same side of the Moon always faces Earth. This means from Earth we always see the same side of the Moon. The side of the Moon that faces Earth is called the near side (**Figure** 24.13). The side of the Moon that faces away from Earth is called the far side (**Figure** 24.14). The Moon makes no light of its own, but instead only reflects light from the Sun.

The Lunar Surface

The Moon has no atmosphere. The average surface temperature during the day is approximately 225°F and can reach temperatures as high as 253°F. At night the average temperature drops to -243°F and has been measured as low as -397°F. These extremely cold temperatures occur in craters in the permanently shaded south polar basin and are amongst the coldest temperatures recorded in our entire solar system.

There are no lakes, rivers, or even small puddles anywhere to be found on the Moon's surface. (However, it should be noted that in 2009, NASA scientists believe they discovered that in the top few millimeters of the Moon's surface, there is a large number of water molecules mixed in with dirt and rocks — you can stay up-to-date with their latest findings at `http://www.nasa.gov`). Yet, despite the possible presence of water, with a lack of atmosphere and extreme temperatures, it comes as no surprise to scientists that there has been zero evidence of life naturally occurring on the Moon.

Although there are no "naturally occurring" signs of life on the Moon, there are signs that life has encountered the Moon — that is, there are footprints of astronauts on the Moon's surface. It's likely that these footprints will remain unchanged for thousands of years, because

Figure 24.13: The near side of the Moon, the one that we see, has a thinner crust with many more maria. (1)

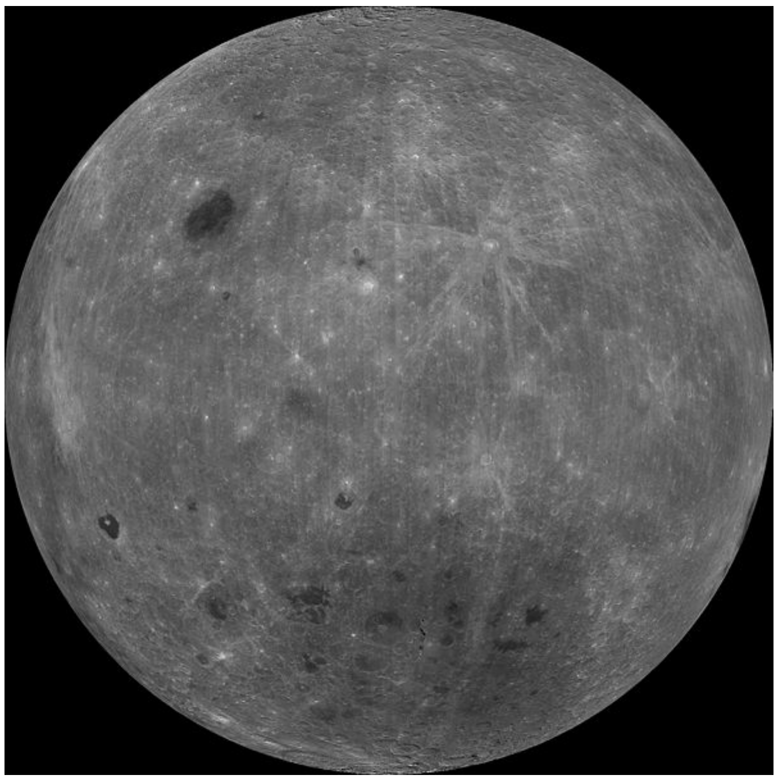

Figure 24.14: The far side of the Moon has a thicker crust and far fewer maria. (7)

there is no wind, rain, or living thing to disturb them. Only a falling **meteorite** or other matter from space could destroy them. A meteorite is a piece of rock that reaches the Moon from space. Meteorites also hit the Earth sometimes.

Earth has mountains, valleys, plains and hills. This combination of all of the surface features of an area of land is called a **landscape**. The landscape of the Moon is very different from that of Earth. The lunar landscape is covered by **craters** caused by the impacts of asteroids and meteorites that crashed into the Moon from space (**Figure** 24.15). The craters are bowl-shaped basins on the Moon's surface. Because the Moon has no water, wind, or weather the craters remain unchanged. If Earth did not have plate tectonics, which continually alters the planet's surface, or an atmosphere, which makes erosion possible, our planet's surface would be at least as covered with meteorite craters as the Moon's. The surfaces of many other moons orbiting other planets have been shaped by asteroid impacts.

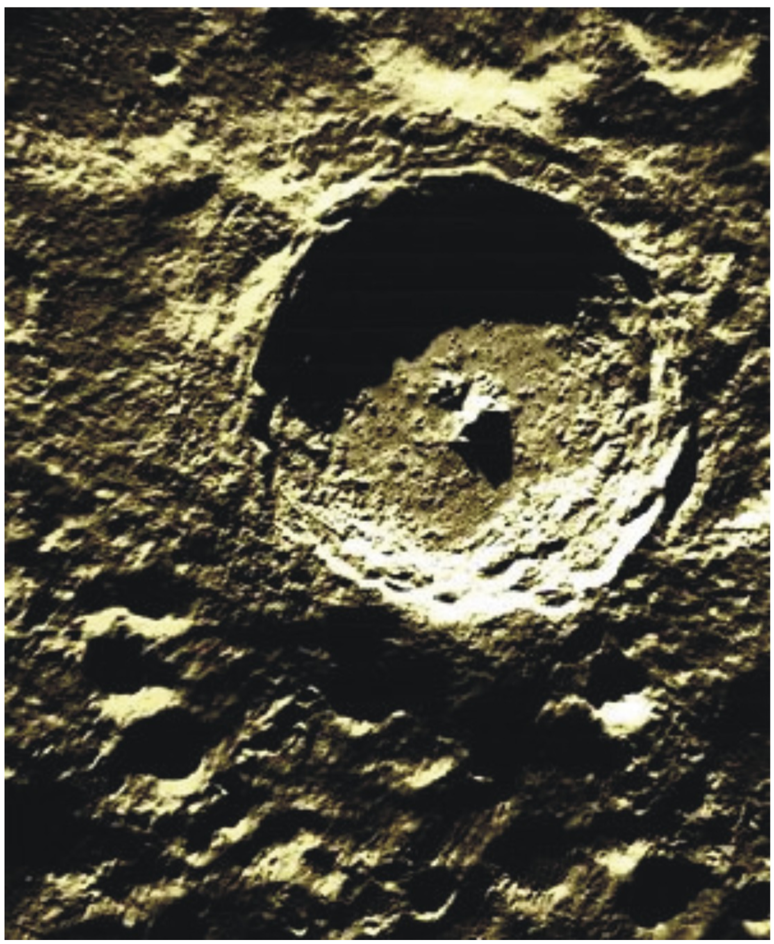

Figure 24.15: A crater on the surface of the Moon. (5)

When you look at the Moon from Earth you notice dark areas and light areas. The dark areas are called **maria**. They are solid, flat areas of basaltic lava. From about 3.0 to 3.5 billion years ago the Moon was continually bombarded by meteorites. Some of these meteorites were so large that they broke through the Moon's newly formed surface, then magma flowed out and filling the craters. Scientists estimate volcanic activity on the Moon ceased about 1.2 billion years ago.

The lighter parts are the Moon is called **terrae** or highlands (**Figure** 24.16). They are higher than the maria and include several high mountain ranges. They are believed to be the rims of ancient impact craters.

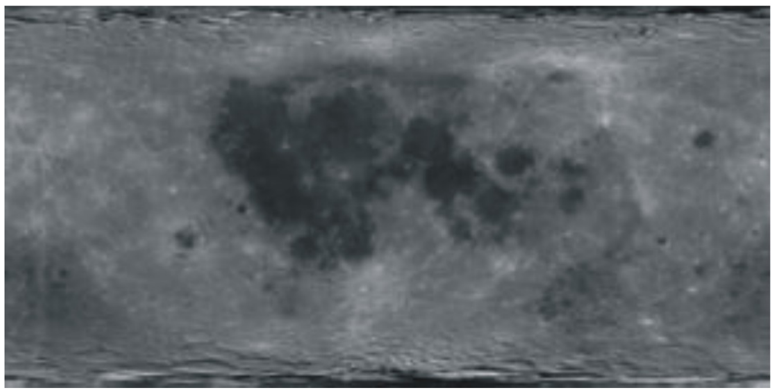

Figure 24.16: A close-up of the Moon, showing maria (the dark areas) and terrae (the light areas); maria covers around 16% of the Moon's surface, mostly on the side of the Moon we see. (12)

Interior of the Moon

Like the Earth, the Moon has a distinct crust, mantle, and core. The crust is composed of igneous rock rich in the elements oxygen, silicon, magnesium, and aluminum. The Moon's crust is about 60 kilometers thick on the near side of the Moon and about 100 kilometers thick on the far side. The mantle is composed of the minerals olivine and orthopyroxene. Analysis of Moon rocks indicates that there may also be high levels of iron and titanium in the lunar mantle. The Moon has a small core, perhaps 600 to 800 kilometers in diameter. The composition of the Moon's core is not known, but it is probably made mostly of iron with some sulfur and nickel. This information is gathered both from rock samples gathered by astronauts and from unpiloted spacecraft sent to the Moon.

Lesson Summary

- Many scientists believe the Moon formed when a Mars sized planet collided with Earth.
- The Moon makes one rotation on its axis in the same number of days it takes for it to orbit the Earth.

- The Moon has dark areas, called maria surrounded by lighter colored highland areas, called terrae.
- Because the Moon is geologically inactive and doesn't have an atmosphere, it has many thousands of craters on its surface.
- The Moon is made of many materials similar to Earth and has a crust, mantle and core, just like the Earth.

Review Questions

1. What is one piece of evidence that supports the idea that the Moon was formed by materials that were once part of the Earth?
2. Why is there no weather on the Moon?
3. Rusting is a process that happens when oxygen reacts chemically with iron, in the presence of water. Can rusting occur on the Moon? Explain your answer.
4. What is the difference between maria and terrea?
5. How much do landscape features on the Moon change over time compared to landscape features on Earth? Explain your answer.
6. Why is the force of gravity on your body weaker on the Moon than on the Earth?

Vocabulary

craters Bowl-shaped depressions on the surface of the Moon caused by impact from meteorites.

giant impact hypothesis The idea that the Moon was formed when a planet sized object from space collided with the Earth about 4.5 billion years ago and sent trillions of tons of material into Earth's orbit; the material eventually came together and formed the Moon.

landscape The surface features of an area.

lunar Related to the Moon.

maria The dark parts of the Moon's surface, made up of ancient basaltic eruptions.

meteorites Pieces of rock that hit the Moon, Earth, or another planet from space.

satellite A body that orbits a larger body in space.

terrae The light parts of the Moon's surface, composed of high crater rims.

Points to Consider

- What things would be different on Earth if Earth did not have a moon?
- If the Moon rotated on its axis once every 14 days, would we see anything different than we do now?
- How do we know that the Moon has been geologically inactive for billions of years?

24.4 The Sun

Lesson Objectives

- Describe the layers of the Sun.
- Describe the surface features of the Sun.

Introduction

Consider the Earth, the Moon, and all the other planets in our solar system. Think about the mass that all those objects must have when they are all added together. Added all together, however, they account for only 0.2% of the total mass of the solar system. The Sun makes up the remaining 99.8% of all the mass in the solar system (**Figure** 24.17)! The Sun is the center of the solar system and the largest object in the solar system. Our Sun is a star that provides light and heat and supports almost all life on Earth.

In this lesson you will learn about the features of the Sun. We will discuss the composition of the Sun, its atmosphere, and some of its surface features.

Layers of the Sun

The Sun is a sphere, but unlike the Earth and the Moon, is not solid. Most atoms in the Sun exist as **plasma**, or a fourth state of matter made up of superheated gas with an electrical charge. Our Sun consists almost entirely of the elements hydrogen and helium. Because the Sun is not solid, it does not have a defined outer boundary. It does, however, have a definite internal structure. There are several identifiable layers of the Sun:

The **core** is the innermost or central layer of the Sun. The core is plasma, but moves similarly to a gas. Its temperature is around 27 million degrees Celsius. In the core, nuclear reactions combine hydrogen atoms to form helium, releasing vast amounts of energy in the process. The energy released then begins to move outward, towards the outer layers of the Sun.

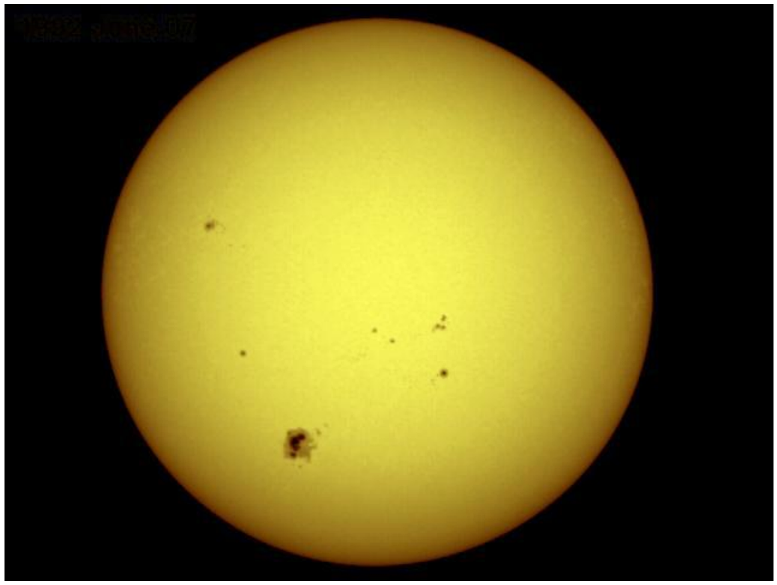

Figure 24.17: The Sun. (9)

The **radiative zone** is just outside the core, which has a temperature of about 7 million degrees Celsius.The energy released in the core travels extremely slowly through the radiative zone. Particles of light called photons can only travel a few millimeters before they hit another particle in the Sun, are absorbed and then released again. It can take a photon as long as 50 million years to travel all the way through the radiative zone.

The **convection zone** surrounds the radiative zone. In the convection zone, hot material from near the Sun's center rises, cools at the surface, and then plunges back downward to receive more heat from the radiative zone. This movement helps to create solar flares and sunspots, which we'll learn more about in a bit. These first three layers make up what we would actually call 'the Sun'. The next three layers make up the Sun's atmosphere. Of course, there are no solid layers to any part of the Sun, so these boundaries are fuzzy and indistinct.

The Sun's 'Atmosphere'

The **photosphere** is the visible surface of the Sun (**Figure** 24.18). This is the region of the Sun that emits sunlight. It's also one of the coolest layers of the Sun — only about 6700 °C. Looking at a photograph of the Sun's surface, you can see that it has several different colors; oranges, yellow and reds, giving it a grainy appearance. We cannot see this when we glance quickly at the Sun. Our eyes can't focus that quickly and the Sun is too bright for us to look at for more than a brief moment. Looking at the Sun for any length of time can cause blindness, so don't try it! Sunlight is emitted from the Sun's photosphere. A fraction of the light that travels from the Sun reaches Earth.

It travels as light in a range of wavelengths, including visible light, ultraviolet and infrared radiation. Visible light is all the light we can see with our eyes. We can't see ultraviolet and infrared radiation, but their effects can still be detected. For example, a sunburn is caused by ultraviolet radiation when you spend too much time in the Sun.

The **chromosphere** is the zone about 2,000 kilometers thick that lies directly above the photosphere. The chromosphere is a thin region of the Sun's atmosphere that glows red as it is heated by energy from the photosphere. Temperatures in the chromosphere range from about 4000°C to about 10,000°C. Jets of gas fire up through the chromosphere at speeds up to 72,000 kilometers per hour, reaching heights as high as 10,000 kilometers.

The **corona** is the outermost layer of the Sun and is the outermost part of its atmosphere. It is the Sun's halo or 'crown.' It has a temperature of 2 to 5 million degrees Celsius and is much hotter than the visible surface of the Sun, or photosphere. The corona extends millions of kilometers into space. If you ever have the chance to see a total solar eclipse, you will be able to see the Sun's corona, shining out into space.

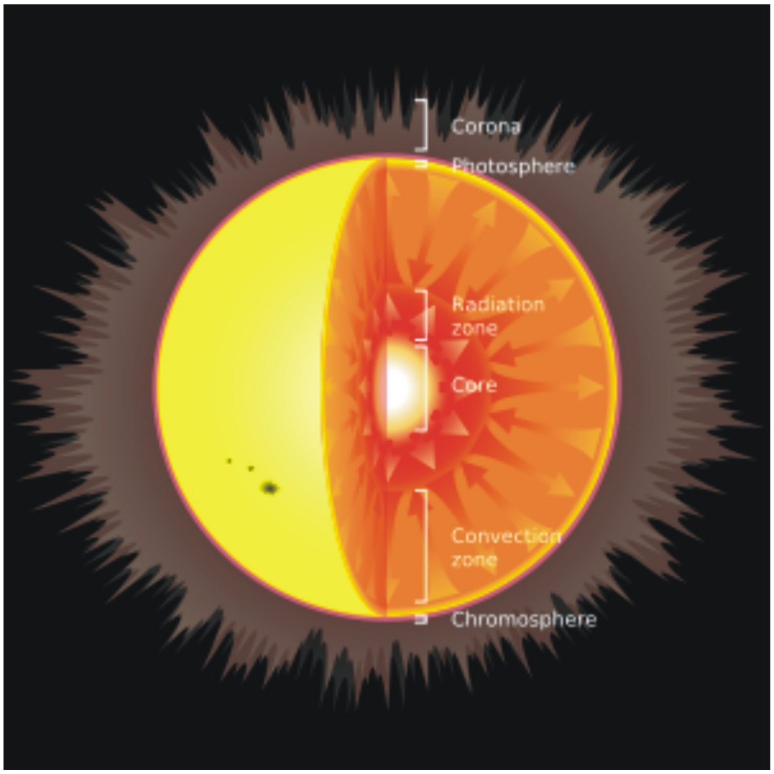

Figure 24.18: The layers of the Sun. (10)

In the Sun's core, **nuclear fusion** reactions generate energy by converting hydrogen to helium. Fusion is a process where the nuclei of atoms join together to form a heavier chemical element. Fusion reactions in the Sun's core produce energy, which we experience as heat and light. The rest of the Sun is heated by movement of heat energy outward from the core. Light energy from the Sun is emitted from the photosphere. It travels through space, and some of it reaches the Earth. The Sun is the source of almost all the energy on Earth and sunlight powers photosynthesis, as well as warming and illuminating our Earth.

Surface Features of the Sun

The most noticeable surface feature of the Sun is the presence of **sunspots**, which are cooler, darker areas on the Sun's surface (**Figure** 24.19). Sunspots are only visible with special light-filtering lenses. They exhibit intense magnetic activity. These areas are cooler and darker because loops of the Sun's magnetic field break through the surface and disrupt the smooth transfer of heat from lower layers. Sunspots usually occur in pairs. When a loop of the Sun's magnetic field breaks through the surface, it usually creates a sunspot both where it comes out and one where it goes back in again. Sunspots usually occur in 11 year cycles, beginning when the number of sunspots is at a minimum, increasing to a maximum number of sunspots and then gradually decreasing to a minimum number of sunspots again.

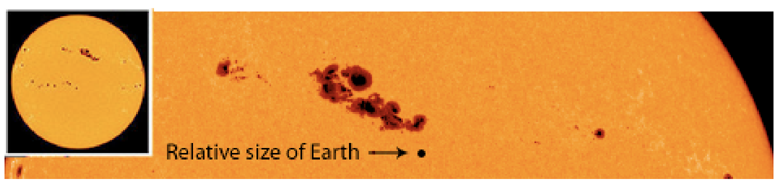

Figure 24.19: Sunspots. (18)

If a loop of the sun's magnetic field snaps and breaks, it creates **solar flares**, which are violent explosions that release huge amounts of energy (**Figure** 24.20). They release streams of highly energetic particles that make up the **solar wind**. The solar wind can be dangerous to spacecraft and astronauts. It sends out large amounts of radiation, which can harm the human body. Solar flares have knocked out entire power grids and can disturb radio, satellite and cell phone communications.

Another highly visible feature on the Sun are solar prominences. If plasma flows along a loop of the Sun's magnetic field from sunspot to sunspot, it forms a glowing arch that reaches thousands of kilometers into the Sun's atmosphere. Prominences can last for a day to several months. Prominences are also visible during a total solar eclipse.

A beautiful and mysterious effect of the Sun's electrically charged particles are auroras, which form around the polar regions high in Earth's atmosphere. Gases in Earth's atmosphere are excited by the electrically charged particles of the solar wind and glow producing curtains of light, which bend and change as you watch.

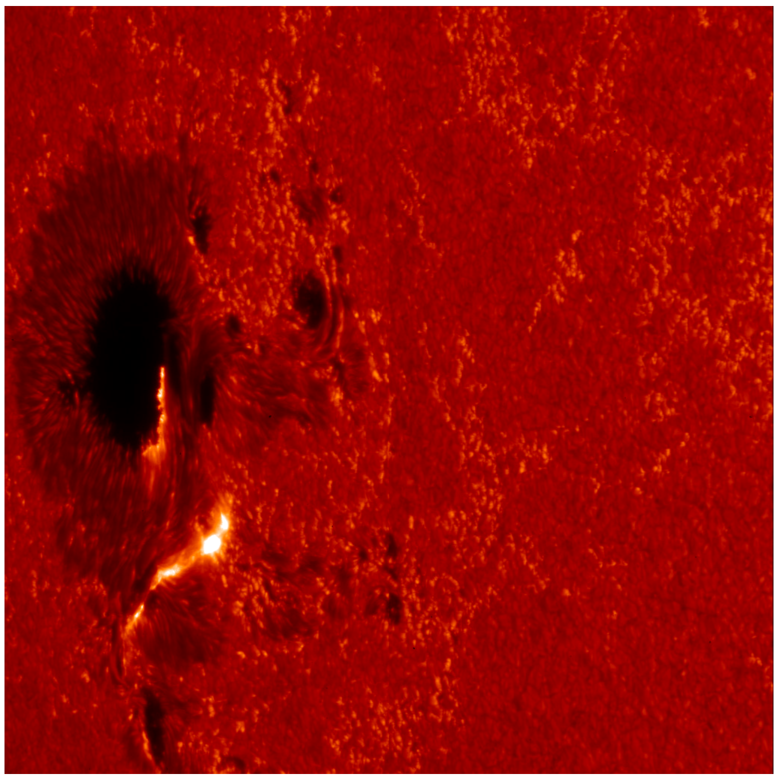

Figure 24.20: A Solar Flare. (22)

Lesson Summary

- The mass of the Sun is tremendous. It makes up 99.8% of the mass of our solar system.
- The Sun is mostly made of hydrogen with smaller amounts of helium in the form of plasma.
- The main part of the Sun has three layers: the core, the radiative zone and the convection zone.
- The Sun's atmosphere also has three layers: the photosphere, the chromosphere and the corona.
- Nuclear fusion of hydrogen in the core of the Sun produces tremendous amounts of energy that radiate out from the Sun.
- Some features of the Sun's surface include sunspots, solar flares, and prominences.

Review Questions

1. In what way does the Sun support all life on Earth?
2. Which two elements make up the Sun almost in entirety?
3. Which process is the source of heat in the Sun and where does it take place?
4. Some scientists would like to plan a trip to take humans to Mars. One of the things standing in the way of our ability to do this is solar wind. Why will we have to be concerned with solar wind?
5. Describe how movements in the convection zone contribute to solar flares.
6. Do you think fusion reactions in the Sun's core will continue forever and go on with no end? Explain your answer.

Vocabulary

chromosphere Thin layer of the Sun's atmosphere that lies directly above the Photosphere; glows red.

convection zone Layer of the Sun that surrounds the Radiative Zone; energy moves as flowing cells of gas.

core Innermost or central layer of the Sun.

corona Outermost layer of the Sun; a plasma that extends millions of kilometers into space.

nuclear fusion The merging together of the nuclei of atoms to form new, heavier chemical elements; huge amounts of nuclear energy are released in the process.

photosphere Layer of the Sun that we see; the visible surface of the Sun.

photosynthesis The process that green plants use to convert sunlight to energy.

plasma A high energy, high temperature form of matter. Electrons are removed from atoms, leaving each atom with an electrical charge.

radiation Electromagnetic energy; photons.

radiative zone Layer of the Sun immediately surrounding the core; energy moves atom to atom as electromagnetic waves.

solar flare A violent explosion on the Sun's surface.

solar wind A stream of radiation emitted by a solar flare. The solar wind extends millions of kilometers out into space and can even reach the Earth.

sunspots Cooler, darker areas on the Sun's surface that have lower temperatures than surrounding areas; sunspots usually occur in pairs.

Points to Consider

- If something were to suddenly cause nuclear fusion to stop in the Sun, how would we know?
- Are there any types of dangerous energy from the Sun? What might be affected by them?
- If the Sun is all made of gases like hydrogen and helium, how can it have layers?

Going Further - Applying Math

Have you ever wondered how to measure something that you cannot reach or touch? The answer is that you can use simple geometry. We can measure the diameter of the Sun, even though we cannot go to the Sun and even though the Sun is much too large for a human being to measure. We can do this using the rules of similar triangles. The sides of similar triangles are proportional to each other. By setting up one very small triangle that is proportional to another, very large triangle, we can find an unknown distance or measurement as long as we know three out of four of the parts of the equation. If you make a pinhole in an index card and project an image of the Sun onto a clipboard held 1 meter from the index card, the diameter of our projected image of the Sun will be proportional to the true diameter of the Sun. Here's the equation: $s / d = S / D$ where s = diameter of the projected image of the Sun, S = true diameter of the Sun. We also need to know the true distance between the Earth and the Sun, $D = 1.496 \times 10^{8}$ km and the distance (d

= 1 meter) between the clipboard and the index card. Before you can correctly solve this equation, you will need to change all of your measurements to the same unit - in this case, change all your measurements to km. Try this out and see how accurately you can measure the true diameter of the Sun.

24.5 The Sun and the Earth-Moon System

Lesson Objectives

- Describe how Earth's movements affect seasons and cause day and night.
- Explain solar and lunar eclipses.
- Describe the phases of the Moon and explain why they occur.
- Explain how movements of the Earth and Moon affect Earth's tides.

Introduction

The solar system is made up of the Sun, the planets that orbit the Sun, their satellites, dwarf planets and many, many small objects, like asteroids and comets. All of these objects move and we can see these movements. We notice the Sun rises in the eastern sky in the morning and sets in the western sky in the evening. We observe different stars in the sky at different times of the year. When ancient people made these observations, they imagined that the sky was actually moving while the Earth stood still. In 1543, Nicolaus Copernicus (**Figure** 24.21) proposed a radically different idea: the Earth and the other planets make regular revolutions around the Sun. He also suggested that the Earth rotates once a day on its axis. Copernicus' idea slowly gained acceptance and today we base our view of motions in the solar system on his work. We also now know that everything in the universe is moving.

In this lesson you will learn about how the movements of the Earth, Moon, and Sun affect different phenomena on Earth, including day and night, the seasons, tides, and phases of the Moon.

Positions and Movements

Earlier we discussed Earth's rotation and revolution. The Earth rotates once on its axis about every 24 hours. If you were to look at Earth from the North Pole, it would be spinning counterclockwise. As the Earth rotates, observers on Earth see the Sun moving across the sky from east to west with the beginning of each new day. We often say that the Sun is "rising" or "setting," but actually it is the Earth's rotation that gives us the perception of the Sun rising up or setting over the horizon. When we look at the Moon or the stars at night, they also seem to rise in the east and set in the west. Earth's rotation is

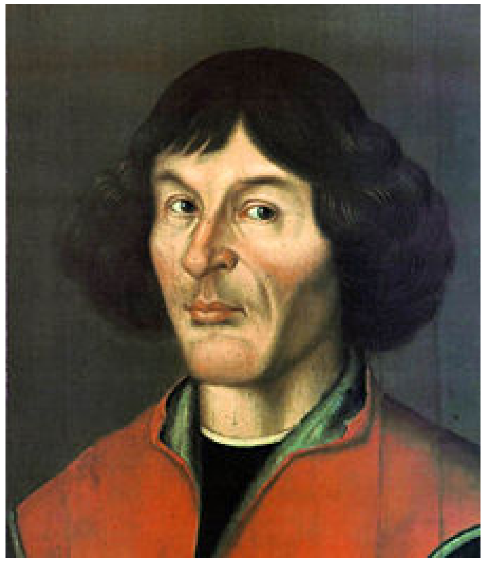

Figure 24.21: Nicholas Copernicus. (13)

also responsible for this. As Earth turns, the Moon and stars change position in our sky.

Earth's Day and Night

Another effect of Earth's rotation is that we have a cycle of daylight and darkness approximately every 24 hours. This is called a day. As Earth rotates, the side of Earth facing the Sun experiences daylight, and the opposite side (facing away from the Sun) experiences darkness or nighttime. Since the Earth completes one rotation in about 24 hours, this is the time it takes to complete one day-night cycle. As the Earth rotates, different places on Earth experience sunset and sunrise at a different time. As you move towards the poles, summer and winter days have different amounts of daylight hours in a day. For example, in the Northern hemisphere, we begin summer on June 21. At this point, the Earth's North Pole is pointed directly toward the Sun. Therefore, areas north of the equator experience longer days and shorter nights because the northern half of the Earth is pointed toward the Sun. Since the southern half of the Earth is pointed away from the Sun at that point, they have the opposite effect—longer nights and shorter days.

For people in the Northern hemisphere, winter begins on December 21. At this point, it is Earth's South Pole that is tilted toward the Sun, and so there are shorter days and longer nights for those who are north of the equator.

Earth's Seasons

It is a common *misconception* that summer is warm and winter and cold because the Sun is closer to Earth in the summer and farther away from it during the winter. Remember that seasons are caused by the 23 1/2 ° tilt of Earth's axis of rotation and Earth's yearly revolution around the Sun (**Figure** 24.22). This results in one part of the Earth being more directly exposed to rays from the Sun than the other part. The part tilted away from the Sun experiences a cool season, while the part tilted toward the Sun experiences a warm season. Seasons change as the Earth continues its revolution, causing the hemisphere tilted away from or towards the Sun to change accordingly. When it is winter in the Northern hemisphere, it is summer in the Southern hemisphere, and vice versa.

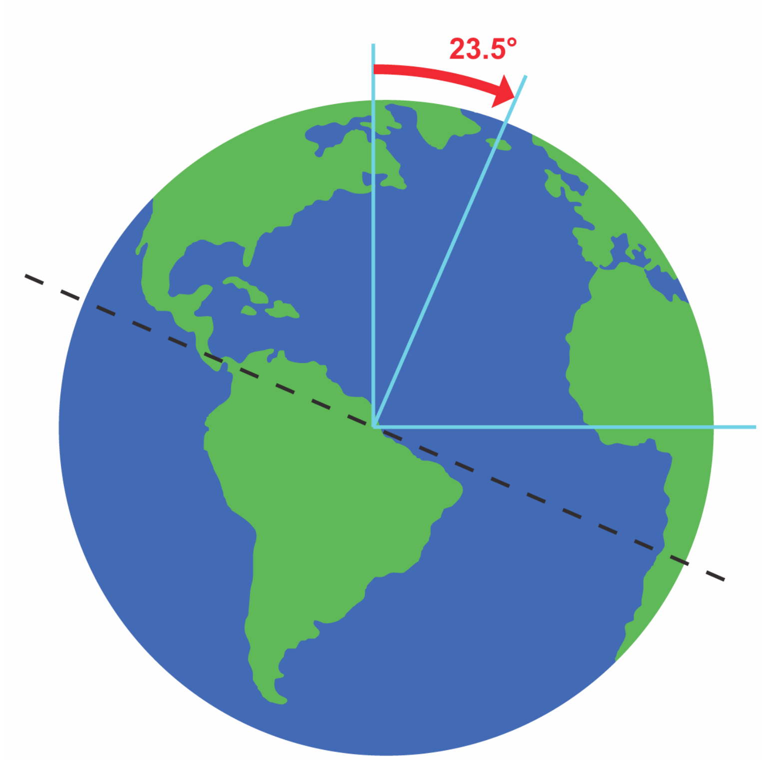

Figure 24.22: The Earth's tilt on its axis leads to one hemisphere facing the Sun more than the other hemisphere and gives rise to seasons. (19)

Solar Eclipses

A **solar eclipse** occurs when the new moon passes directly between the Earth and the Sun (**Figure** 24.23). This casts a shadow on the Earth and blocks our view of the Sun. A total solar eclipse occurs when the Moon's shadow completely blocks the Sun (**Figure** 24.24). When only a portion of the Sun is out of view, it is called a partial solar eclipse. Solar eclipses are rare events that usually only last a few minutes. That is because the Moon's shadow only covers a very small area on Earth and Earth is turning very rapidly. As the Sun is covered by the moon's shadow, it will actually get cooler outside. Birds may begin to sing, and stars will become visible in the sky. During a solar eclipse, the corona and solar prominences can be seen.

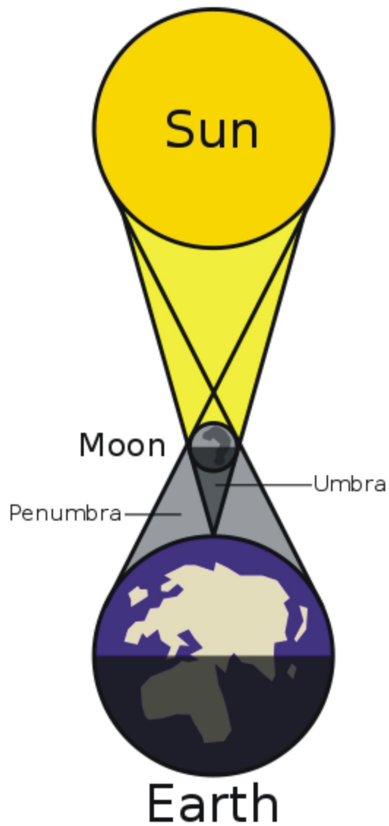

Figure 24.23: A Solar Eclipse. (26)

A Lunar Eclipse

A **lunar eclipse** occurs when the full moon moves through the shadow of the Earth (**Figure** 24.25). This can only happen when the Earth is between the Moon and the Sun and all three are lined up in the same plane, called the ecliptic. The ecliptic is the plane of Earth's orbit around the Sun. The Earth's shadow has two distinct parts: the umbra and the penumbra. The **umbra** is the inner, cone shaped part of the shadow, in which all of the light has been blocked. The outer part of Earth's shadow is the **penumbra** where only part of the light is blocked. In the penumbra, the light is dimmed but not totally absent. A total lunar eclipse occurs when the Moon travels completely in Earth's umbra. During a partial lunar

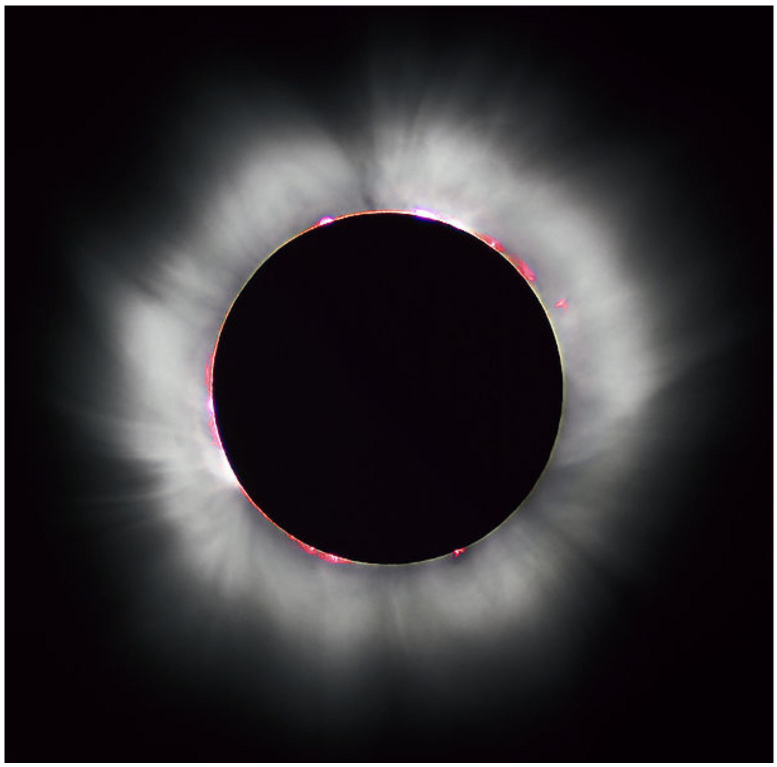

Figure 24.24: Photo of a Total Solar Eclipse. (28)

eclipse, only a portion of the Moon enters Earth's umbra. A penumbral eclipse happens when the Moon passes through Earth's penumbra. The Earth's shadow is quite large, so a lunar eclipse lasts for hours and can be seen by anyone with a view of the Moon at the time of the eclipse.

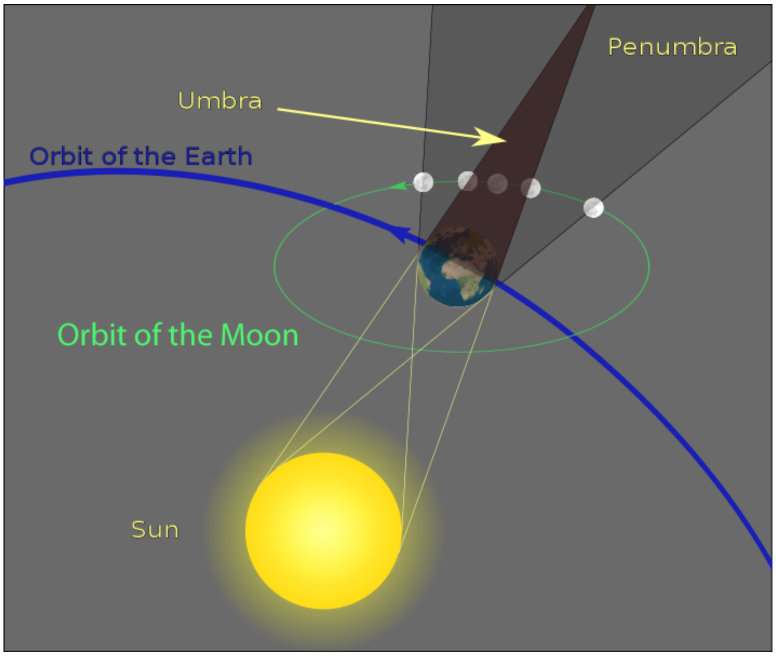

Figure 24.25: The Formation of a Lunar Eclipse. (3)

Partial lunar eclipses occur at least twice a year, but total lunar eclipses are less common. The next total lunar eclipse will occur December 21, 2010. The moon glows with a dull red coloring during a total lunar eclipse.

The Phases of the Moon

The Moon does not produce any light of its own — it only reflects light from the Sun. As the Moon moves around the Earth, we see different parts of the near side of the Moon illuminated by the Sun. This causes the changes in the shape of the Moon that we notice on a regular basis, called the phases of the Moon. As the Moon revolves around Earth, the illuminated portion of the near side of the Moon will change from fully lit to completely dark and back again.

A full moon is the lunar phase seen when the whole of the Moon's lit side is facing Earth. This phase happens when Earth is between the Moon and the Sun. About one week later, the Moon enters the quarter-moon phase. At this point, the Moon appears as a half-circle, since only half of the Moon's lit surface is visible from Earth. When the Moon moves between Earth and the Sun, the side facing Earth is completely dark. This is called the new moon phase, and we do not usually see the Moon at this point. Sometimes you can just barely make out the outline of the new moon in the sky. This is because some sunlight reflects off the Earth and hits the moon. Before and after the quarter-moon phases are the gibbous and crescent phases. During the gibbous moon phase, the moon is more than half lit but not full. During the crescent moon phase, the moon is less than half lit and is seen as only a sliver or crescent shape. It takes about 29.5 days for the Moon to revolve around Earth and go through all the phases (**Figure** 24.26).

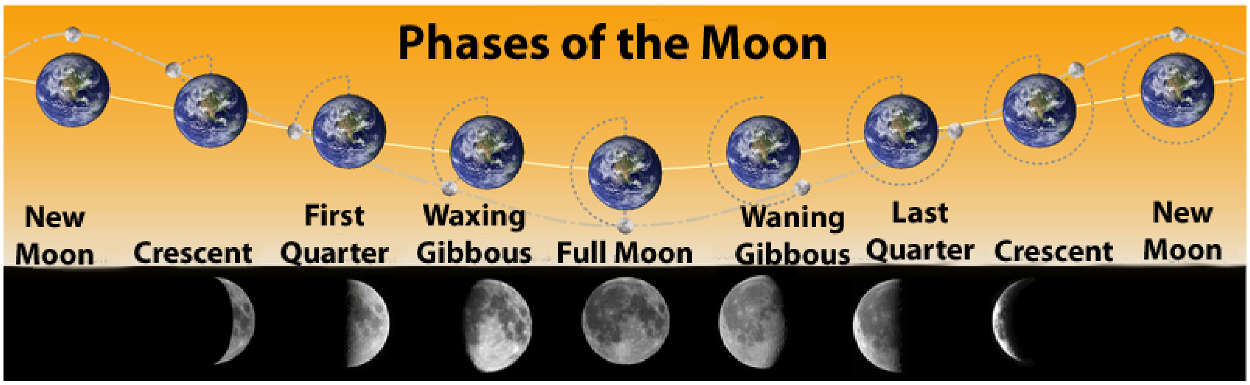

Figure 24.26: The Phases of the Moon. Note that the Sun would be above the top of this picture, and thus, the Sun's rays would be directed downward. (27)

The Tides

Tides are the regular rising and falling of Earth's surface water in response to gravitational attraction from the Moon and Sun. The Moon's gravity causes the oceans to bulge out in the direction of the Moon. In other words, the Moon's gravity is pulling upwards on Earth's water, producing a high tide. On the other side of the Earth, there is another high tide area, produced where the Moon's pull is weakest. As the Earth rotates on its axis, the areas directly in line with the Moon will experience high tides. Each place on Earth experiences changes in the height of the water throughout the day as it changes from high tide to low tide. There are two high tides and two low tides each tidal day. **Figure** 24.27 and **Figure** 24.28 will help you better understand how tides work.

The first picture shows what is called a **spring tide**. Confusingly, this tide has nothing to do with the season 'Spring', but means that the tide waters seem to spring forth. During a spring tide, the Sun and Moon are in line. This happens at both the new moon and the full moon. The Sun's gravity pulls on Earth's water, while the Moon's gravity pulls on the water in the same places. The high tide produced by Sun adds to the high tide produced by the Moon. So spring tides have higher than normal high tides. This water is shown on the picture as the gray bulges on opposite sides of the Earth. Notice that perpendicular to the gray areas, the water is at a relatively low level. The places where the water is being pulled

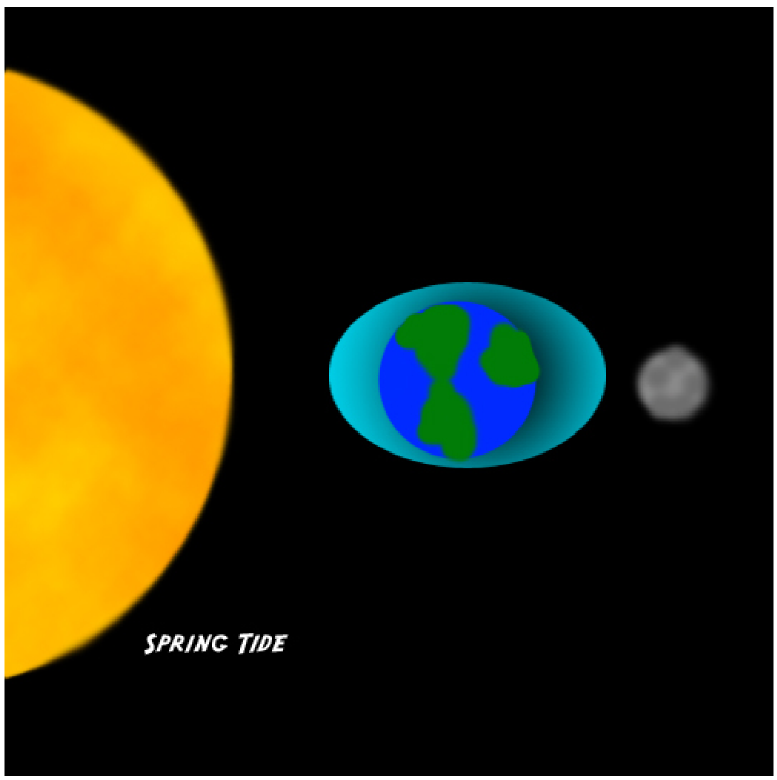

Figure 24.27: A Spring Tide. (23)

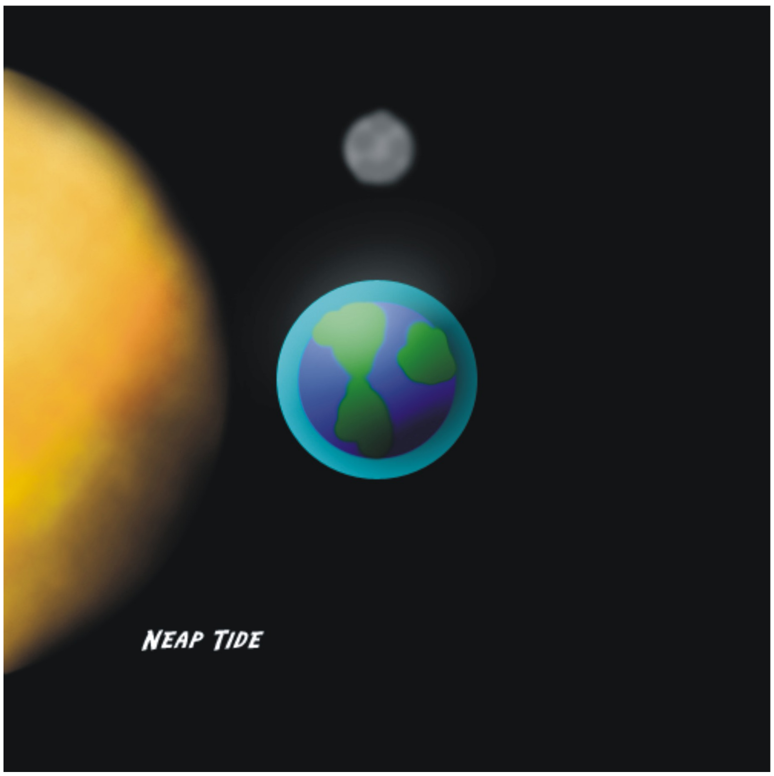

Figure 24.28: A Neap Tide. (24)

out experience high tides, while the areas perpendicular to them experience low tides. Since the Earth is rotating on its axis, the high-low tide cycle moves around the globe in a 24-hour period.

The second picture shows a **neap tide**. A neap tide occurs when the Earth and Sun are in line but the Moon is perpendicular to the Earth. This happens when the moon is at first or last quarter moon phase. In this case, the pull of gravity from the Sun partially cancels out the pull of gravity from the Moon, and the tides are less pronounced. Neap tides produce less extreme tides than the normal tides. This is because the high tide produced by the Sun adds to the low tide area of the Moon and vice versa. So high tide is not as high and low tide is not as low as it usually might be.

Lesson Summary

- As the Earth rotates on its axis and revolves around the Sun, several different effects are produced.
- When the new moon comes between the Earth and the Sun along the ecliptic, a solar eclipse is produced.
- When the Earth comes between the full moon and the Sun along the ecliptic, a lunar eclipse occurs.
- Observing the Moon from Earth, we see a sequence of phases as the side facing us goes from completely darkened to completely illuminated and back again once every 29.5 days.
- Also as the Moon orbits Earth, it produces tides aligned with the gravitational pull of the Moon.
- The Sun also produces a smaller solar tide. When the solar and lunar tide align, at new and full moons, we experience higher than normal tidal ranges, called spring tides.
- At first and last quarter moons, the solar tide and lunar tide interfere with each other, producing lower than normal tidal ranges called neap tides.

Review Questions

1. The globe is divided into time zones, so that any given hour of the day in one time zone occurs at a different time in other time zones. For example, New York City is in one time zone and Los Angeles is in another time zone. When it is 8 am in New York City, it is only 5 am in Los Angeles. Explain how Earth's motions cause this difference in times.
2. Explain how Earth's tilt on its axis accounts for seasons on Earth.
3. Explain how the positions of the Earth, Moon, and Sun vary during a solar eclipse and a lunar eclipse.
4. Draw a picture that shows how the Earth, Moon, and Sun are lined up during the new moon phase.

5. Why are neap tides less extreme than spring tides?

Further Reading / Supplemental Links

- Demonstration of Why Earth has Seasons http://www.youtube.com/watch?v=DuiQvPLWziQ&feature=related
- Solar and Lunar Eclipses hhttp://www.youtube.com/watch?v=tIE1MTGz4eI&feature=related

Vocabulary

crescent Phase of the moon when it is less than half full but still slightly lit.

gibbous Phase of the moon when it is more than half lit but not completely full.

lunar eclipse An eclipse that occurs when the Moon moves through the shadow of the Earth and is blocked from view.

neap tide Type of tide event when the Sun and Earth are in line and the Moon is perpendicular to the Earth.

penumbra Outer part of shadow that remains partially lit during an eclipse.

solar eclipse Occurs when moon passes directly between the Earth and Sun; the Moon's shadow blocks the Sun from view.

spring tide An extreme tide event that happens when the Earth, Moon, and the Sun are aligned; happens at full and new moon phases.

tide The regular rising and falling of Earth's surface waters twice a tidal day as a result of the Moon's and Sun's gravitational attraction.

umbra Inner cone shaped part of a shadow when all light is blocked during an eclipse.

Points to Consider

- Why don't eclipses occur every single month at the full and new moons?
- The planet Mars has a tilt that is very similar to Earth's. What does this produce on Mars?
- Venus comes between the Earth and the Sun. Why don't we see an eclipse when this happens?

Image Sources

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(27) http://en.wikipedia.org/wiki/Image:Phases_of_the_Moon.png. GNU-FDL.

(28) *Photo of a Total Solar Eclipse.*. GNU-FDL.

Chapter 25

The Solar System

25.1 Introduction to the Solar System

Lesson Objectives

- Describe historical views of the solar system.
- Name the planets, and describe their motion around the sun.
- Explain how the solar system formed.

Changing Views of the Solar System

People have not always known about all the objects in our solar system. The ancient Greeks were aware of five of the planets. They did not know what these objects were; they just noticed that they moved differently than the stars did. They seemed to wander around in the sky, changing their position against the background of stars. In fact, the word "planet" comes from a Greek word meaning "wanderer." They named these objects after gods from their mythology. The names we use now for the planets are the Roman equivalents of these Greek names: Mercury, Venus, Mars, Jupiter, and Saturn.

The Geocentric Universe

The ancient Greeks believed that Earth was at the center of the universe, as shown in **Figure** 25.1. This view is called the **geocentric model** of the universe. *Geocentric* means "Earth-centered." The geocentric model also described the sky, or *heavens,* as having a set of spheres layered on top of one another. Each object in the sky was attached to one of these spheres, and moved around Earth as that sphere rotated. From Earth outward, these spheres contained the Moon, Mercury, Venus, the Sun, Mars, Jupiter, Saturn, and an outer sphere which contained all the stars. The planets appear to move much faster than the stars and so the Greeks placed them closer to Earth.

Today, powerful telescopes can actually see the surfaces of planets in our solar system. Even though the closest stars have diameters that are hundreds of times larger than the Earth, the distant stars appear as tiny dots that cannot be resolved.

Figure 25.1: Model of a geocentric universe. This diagram of the universe from the Middle Ages shows Earth at the center, with the Moon, the Sun, and the planets orbiting Earth. (34)

The geocentric model may seem strange to us now, but at the time, it worked quite well. It explained why all the stars appear to rotate around Earth once per day. It also explained why the planets move differently from the stars, and from each other. One problem with the geocentric model was resolved around 150 A.D. by the astronomer Ptolemy. At times, some planets seemed to move backwards (in retrograde) instead of in their usual forward motion around the Earth. Ptolemy resolved this problem by using a system of circles to describe the motion of planets (**Figure** 25.2). In Ptolemy's system, a planet moved in a small circle, called an *epicycle.* This circle in turn moved around Earth in a larger circle, called a *deferent.* Ptolemy's version of the geocentric model worked so well that it remained the accepted model of the universe for more than a thousand years.

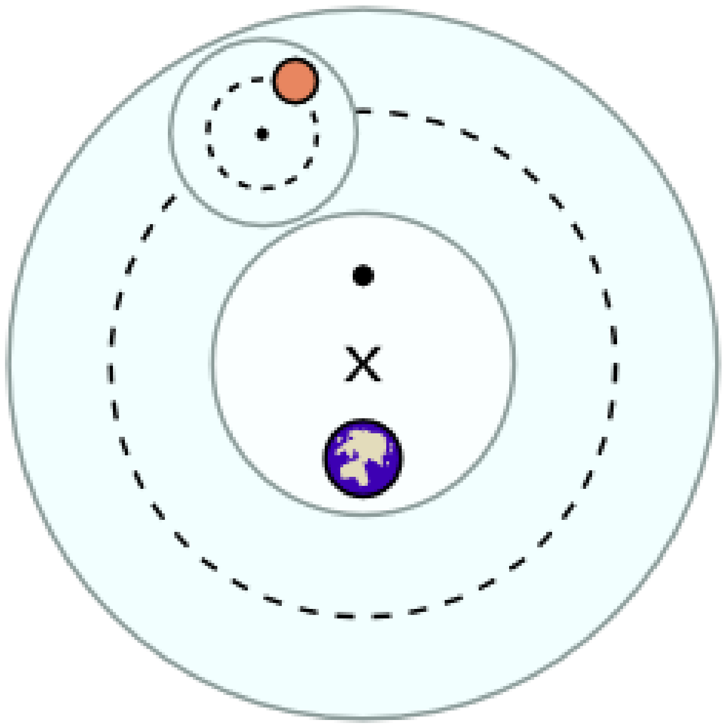

Figure 25.2: Diagram of an epicycle and deferent. According to Ptolemy, a planet moves on a small circle that in turn moves on a larger circle around Earth. (26)

The Heliocentric Universe

Ptolemy's geocentric model worked pretty well, but it was complicated and occasionally made errors in predicting the movement of planets. At the beginning of the 16th century A.D., Nicolaus Copernicus proposed a different model in which Earth and all the other planets orbited the Sun. Because this model put the Sun at the center, it is called the **heliocentric model** of the universe. *Heliocentric* means "sun-centered." **Figure** 25.3 shows the heliocentric model compared to the geocentric model. Copernicus' model explained the motion of the planets about as well as Ptolemy's model, but it did not require complicated additions like epicycles and deferents.

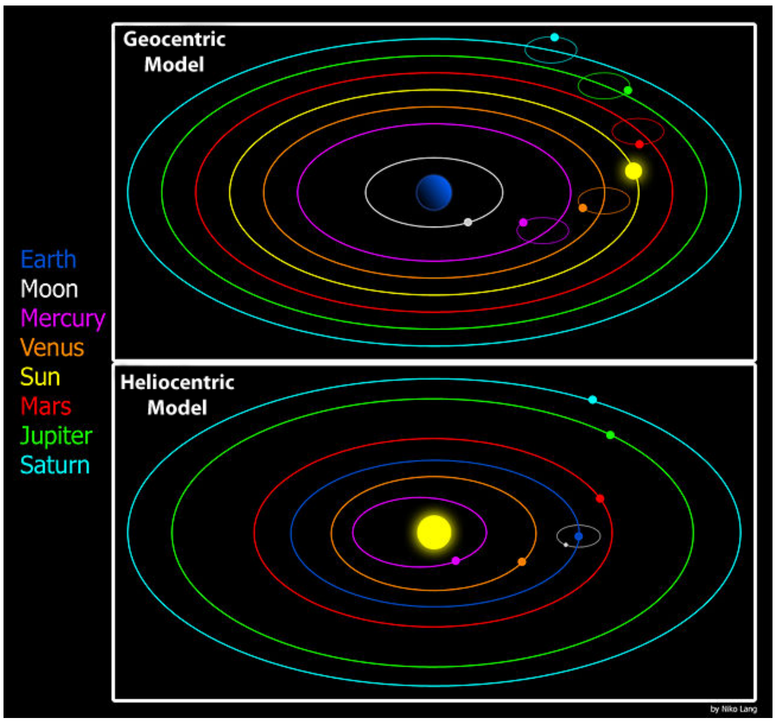

Figure 25.3: Unlike the geocentric model (top image), the heliocentric model (lower image), had the Sun at the center, and did not require epicycles. (5)

Although Copernicus' model worked more simply than Ptolemy's, it still did not perfectly describe the motion of the planets. The problem was that, like Ptolemy, Copernicus still thought planets moved in perfect circles. Not long after Copernicus, Johannes Kepler refined the heliocentric model. He proposed that planets move around the Sun in ellipses (ovals), not circles. This model matched observations perfectly.

Because people were so used to thinking of Earth at the center of the universe, the heliocentric model was not widely accepted at first. However, when Galileo Galilei first turned a telescope to the heavens in 1610, he made several striking discoveries. He found that the planet Jupiter has moons orbiting around it. This was the first evidence that objects could orbit something besides Earth. He also discovered that Venus has phases like our moon does. The phases of Venus provided direct evidence that Venus orbits the Sun. Galileo's discoveries caused many more people to accept the heliocentric model of the universe. The shift from an Earth-centered view to a Sun-centered view of the universe is referred to as the *Copernican Revolution.*

The Modern Solar System

Today, we know that our solar system is just one tiny part of the universe as a whole. Neither Earth nor the Sun are at the center of the universe —in fact, the universe has no true center. However, the heliocentric model does accurately describe our solar system. In our modern view of the solar system, the Sun is at the center, and planets move in elliptical orbits around the Sun. The planets do not emit their own light, but instead reflect light from the Sun.

Extrasolar Planets or Exoplanets

Since the early 1990s, astronomers have discovered other solar systems, with planets orbiting stars other than our own Sun (called "extrasolar planets" or simply "exoplanets"). Although a handful of exoplanets have now been directly imaged, the vast majority have been discovered by indirect methods. One technique involves detecting the very slight motion of a star periodically moving toward and away from us along our line-of-sight (also known as a star's "radial velocity"). This periodic motion can be attributed to the gravitational pull of a planet (or, sometimes, another star) orbiting the star. Another technique involves measuring a star's brightness over time. A temporary, periodic decrease in light emitted from a star can occur when a planet crosses in front of (or "transits") the star it is orbiting, momentarily blocking out some of the starlight. As of February 2010, over 420 exoplanets have been confirmed with more being discovered at an ever-increasing rate.

Planets and Their Motions

Since the time of Copernicus, Kepler, and Galileo, we have learned a lot more about our solar system. We have discovered two more planets (Uranus and Neptune), four dwarf planets (Ceres, Makemake, Pluto and Eris), over 150 moons, and many, many asteroids and other small objects.

Figure 4 shows the Sun and the major objects that orbit the Sun. There are eight planets. From the Sun outward, they are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. The Sun is just an average star compared to other stars, but it is by far the largest object in the solar system. The Sun is more than 500 times the mass of everything else in the solar system combined! **Table** 25.1 gives more exact data on the sizes of the sun and planets relative to Earth.

Table 25.1:

Object	Mass (Relative to Earth)	Diameter of Planet (Relative to Earth)
Sun	333,000 Earth masses	109.2 Earth diameters
Mercury	0.06 Earth's mass	0.39 Earth's diameter
Venus	0.82 Earth's mass	0.95 Earth's diameter
Earth	1.00 Earth mass	1.00 Earth diameter
Mars	0.11 Earth's mass	0.53 Earth's diameter
Jupiter	317.8 Earth masses	11.21 Earth diameters
Saturn	95.2 Earth masses	9.41 Earth diameters
Uranus	14.6 Earth masses	3.98 Earth diameters
Neptune	17.2 Earth masses	3.81 Earth diameters

(*Sources:* http://en.wikipedia.org/wiki/Planets, http://en.wikipedia.org/wiki/Sun, *License:* GNU-FDL)

What Is (and Isn't) a Planet?

So what exactly is a planet? Simply put, a **planet** is a massive, round body orbiting a star. For our solar system, this star is the Sun. A **moon** is an object that orbits a planet.

"Isn't Pluto a planet?" you may wonder. When it was discovered in 1930, Pluto was considered a ninth planet. When we first saw Pluto, our telescopes actually saw Pluto and its moon, Charon as one much larger object. With better telescopes, we realized that Pluto had a moon and Pluto was much smaller than we thought! With the discovery of many objects like Pluto, and one of them, Eris, even larger than Pluto, in 2006, astronomers refined the definition of a planet. According to the new definition, a planet must:

- orbit a star
- be big enough that its own gravity causes it to be shaped like a sphere
- be small enough that it isn't a star itself
- have cleared the area of its orbit of smaller objects

Objects that meet the first three criteria but not the fourth are called **dwarf planets**. Most astronomers now consider Pluto to be a dwarf planet, along with the objects Ceres and Eris. Even before astronomers decided to change the definition of a planet, there were many aspects of Pluto that did not fit with the other planets in our solar system.

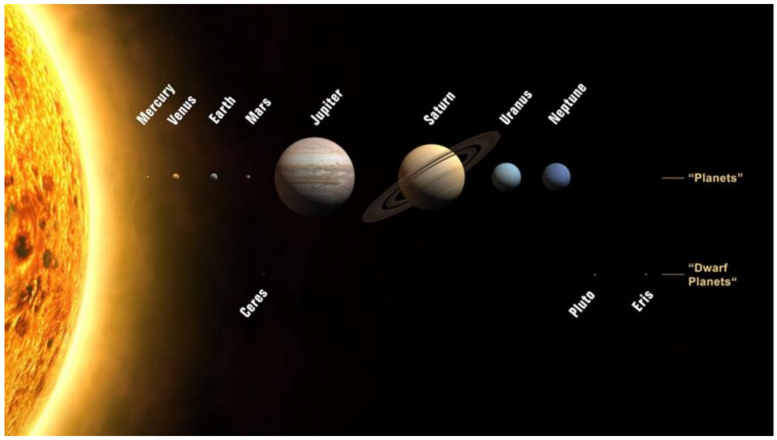

Figure 25.4: Relative sizes of the Sun, planets & dwarf planets. The largest objects in the solar system are the Sun, the eight planets, and the three known dwarf planets. In this figure, the relative sizes are correct but the relative distances are not correct. (30)

The Size and Shape of Orbits

Figure 25.4 shows the Sun and planets in the correct relative sizes. However, the relative distances are not correct. **Figure** 25.5 shows the relative sizes of the orbits. The image in the upper left shows the orbits of the inner planets. The upper left image also shows the *asteroid belt*, a collection of many small objects between the orbits of Mars and Jupiter. The image in the upper right shows the orbits of the outer planets. This upper right image also shows the *Kuiper belt*, another group of objects beyond the orbit of Neptune. In general, the farther away from the Sun, the greater the distance from one planet's orbit to the next.

In **Figure 5**, you can see that the orbits of the planets are nearly circular. In fact, the orbits are not quite circular, but are slightly elliptical. The orbit of Pluto is a much longer ellipse. Some astronomers think Pluto was dragged into its current orbit by Neptune.

Something else Kepler discovered was a relationship between the time it takes a planet to make one complete orbit around the Sun (this is also called an "orbital period") and the distance from the Sun to the planet. So, if the orbital period of a planet is known, then it is possible to determine how far away from the Sun the planet orbits. This is how we can measure the distances to other planets within our own solar system.

Distances in the solar system are often measured in **astronomical units** (AU). One astronomical unit is defined as the distance from Earth to the Sun. 1 AU equals about 150 million km, or 93 million miles. **Table** 25.2 shows the distances to the planets (the average radius of orbits) in AU. The table also shows how long it takes each planet to spin on its axis (the length of a day) and how long it takes each planet to complete an orbit (the length of a year); in particular, notice how slowly Venus rotates relative to Earth.

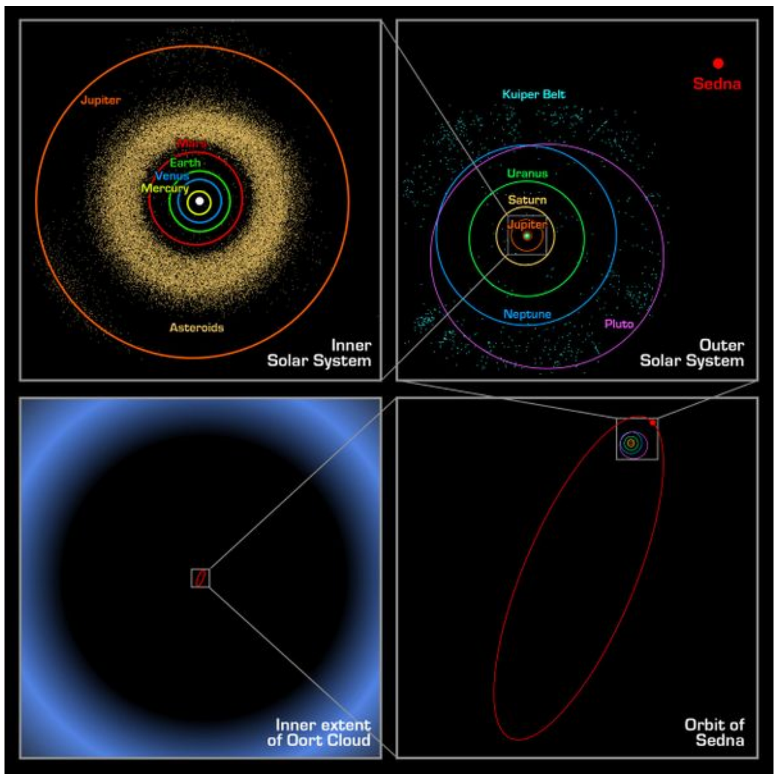

Figure 25.5: This figure shows the relative sizes of the orbits of planets in the solar system. The inner solar system is on the upper left. The upper right shows the outer planets of our solar system. (28)

Table 25.2: **Distances to the Planets and Properties of Orbits Relative to Earth's Orbit**

Planet	Average Distance from Sun (AU)	Length of Day (In Earth Days)	Length of Year (In Earth Years)
Mercury	0.39 AU	56.84 days	0.24 years
Venus	0.72	243.02	0.62
Earth	1.00	1.00	1.00
Mars	1.52	1.03	1.88
Jupiter	5.20	0.41	11.86
Saturn	9.54	0.43	29.46
Uranus	19.22	0.72	84.01
Neptune	30.06	0.67	164.8

(*Source:* http://en.wikipedia.org/wiki/Planets, *License:* GNU-FDL)

The Role of Gravity

Planets are held in their orbits by the force of gravity. Imagine swinging a ball on a string in a circular motion. If you were to let go of the string, the ball would go flying out in a straight line. But the force of the string pulling on the ball keeps the ball moving in a circle. The motion of a planet is very similar, except the force pulling the planet is the attractive force of gravity between the planet and the Sun.

Every object is attracted to every other object by gravity. The force of gravity between two objects depends on how much mass the objects have and on how far apart they are. When you are sitting next to a friend, there is a gravitational force between you and your friend, but it is far too weak for you to detect. In order for the force of gravity to be strong enough to detect, at least one of the objects has to have a lot of mass. You can feel the force of gravity between you and Earth because Earth has a lot of mass. This force of gravity is what keeps you from floating off the ground. The distances from the Sun to the planets are very large. But the force of gravity between the Sun and each planet is very large because the Sun and the planets are very large objects. The force of gravity also holds moons in orbit around planets.

The moon orbits the Earth, and the Earth-moon system orbits the Sun. But Earth and its moon are not the only things that orbit the Sun. There are also other planets and smaller objects, such as asteroids, meteoroids, and comets that also orbit the Sun. The **solar system** consists of the Sun and all the objects that revolve around the sun as a result of gravity.

Formation of the Solar System

There are two key features of the solar system we haven't mentioned yet. First, all the planets lie in nearly the same plane, or flat disk like region. Second, all the planets orbit in the same direction around the Sun. These two features are clues to how the solar system formed.

A Giant Nebula

The most widely accepted explanation of how the solar system formed is called the **nebular hypothesis**. According to this hypothesis, the solar system formed about 4.6 billion years ago from the collapse of a giant cloud of gas and dust, called a **nebula**. The nebula was made mostly of hydrogen and helium, but there were heavier elements as well.

The nebula was drawn together by gravity. As the nebula collapsed, it started to spin. As it collapsed further, the spinning got faster, much as an ice skater spins faster when he pulls his arms to his sides during a spin move. This effect, called "conservation of angular momentum," along with complex effects of gravity, pressure, and radiation, caused the nebula to form into a disk shape, as shown in **Figure** 25.6. This is why all the planets are found in the same plane.

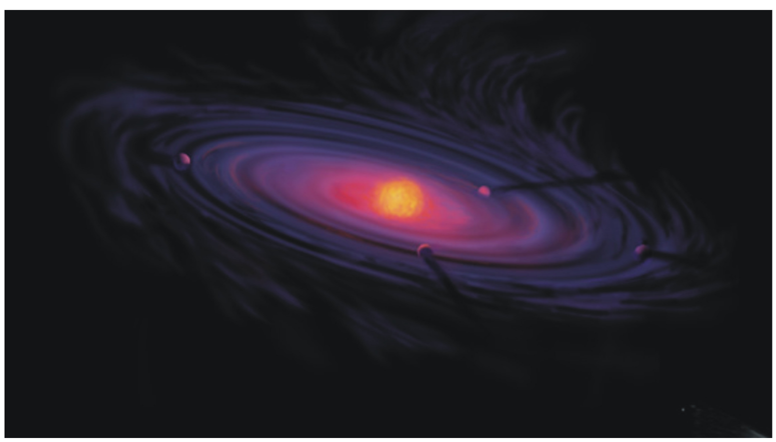

Figure 25.6: The nebular hypothesis describes how the solar system formed from a cloud of gas and dust into a disk with the Sun at the center. This painting was made by an artist; it's not an actual photograph of a protoplanetary disk. (9)

Formation of the Sun and Planets

As gravity pulled matter into the center of the disk, the density and pressure increased at the center. When the pressure in the center was high enough that nuclear fusion reactions started in the center, a star was born—the Sun.

Meanwhile, the outer parts of the disk were cooling off. Small pieces of dust in the disk started clumping together. These clumps collided and combined with other clumps. Larger clumps, called *planetesimals*, attracted smaller clumps with their gravity. Eventually, the planetesimals formed the planets and moons that we find in our solar system today.

The outer planets—Jupiter, Saturn, Uranus and Neptune—condensed farther from the Sun from lighter materials such as hydrogen, helium, water, ammonia, and methane. Out by Jupiter and beyond, where it's very cold, these materials can form solid particles. But in closer to the Sun, these same materials are gases. As a result, the inner planets—Mercury, Venus, Earth, and Mars—formed from dense rock, which is solid even when close to the Sun.

Lesson Summary

- The **solar system** consists of the Sun and all the objects that are bound to the Sun by gravity.
- There are eight planets in the solar system: Mercury, Venus, Earth, Mars, Jupiter, Saturn, and Neptune. Ceres, Makemake, Pluto and Eris are considered dwarf planets.
- The ancient Greeks believed in a geocentric model of the universe, with Earth at the center and everything else orbiting Earth.
- Copernicus, Kepler, and Galileo promoted a heliocentric model of the universe, with the sun at the center and Earth and the other planets orbiting the Sun.
- Planets are held by the force of gravity in elliptical orbits around the Sun.
- The nebular hypothesis describes how the solar system formed from a giant cloud of gas and dust about 4.6 billion years ago.
- The nebular hypothesis explains why the planets all lie in one plane and orbit in the same direction around the Sun.

Review Questions

1. What does *geocentric* mean?
2. Describe the geocentric model and heliocentric model of the universe.
3. How was Kepler's version of the heliocentric model different from Copernicus'?
4. Name the eight planets in order from the Sun outward.
5. What object used to be considered a planet, but is now considered a dwarf planet?
6. What keeps planets and moons in their orbits?
7. How old is the solar system?
8. Use the nebular hypothesis to explain why the planets all orbit the Sun in the same direction.

Further Reading / Supplemental Links

- http://www.youtube.com/watch?v=FHSWVLwbbNw&NR=1
- http://sse.jpl.nasa.gov/planets/index.cfm
- http://www.iau.org/iau0602.423.0.html
- http://starchild.gsfc.nasa.gov/docs/StarChild/solar_system_level2/solar_system.html; http://sse.jpl.nasa.gov/planets/index.cfm
- http://www.solarviews.com/eng/homepage.htm
- http://www.nineplanets.org/
- http://www.teachingideas.co.uk/science/orderingplanets.htm
- http://www.classzone.com/books/earth_science/terc/content/visualizations/es2701/es2701page01.cfm?chapter_no=27
- http://www.windows.ucar.edu/tour/link=/our_solar_system/formation.html
- http://www.solarviews.com/cap/misc/ssanim.htm
- http://en.wikipedia.org/

Vocabulary

geocentric model Model used by the ancient Greeks that puts the Earth at the center of the universe.

heliocentric model Model proposed by Copernicus that put the Sun at the center of the universe.

moon A celestial object that orbits a larger celestial object.

nebula An interstellar cloud of gas and dust.

nebular hypothesis The hypothesis that our solar system developed from a spinning cloud of gas and dust, or a nebula.

planet Around, celestial object that orbits a star and has cleared its orbit of smaller objects.

solar system The Sun and all the objects that revolve around the Sun as a result of gravity.

Points to Consider

- Would you expect all the planets in the solar system to be made of similar materials? Why or why not?

- The planets are often divided into two groups: the inner planets and the outer planets. Which planets do you think are in each of these two groups? What do members of each group have in common?

25.2 Inner Planets

Lesson Objectives

- Describe key features of each of the inner planets.
- Compare each of the inner planets to Earth and to one another.

The Inner Planets

The four planets closest to the sun - Mercury, Venus, Earth and Mars are the inner planets, also called the terrestrial planets because they are similar to Earth. **Figure** 25.7 shows the relative sizes of these four planets. All of the inner planets are small, relative to the outer planets. All of the inner planets are solid, dense, rocky planets. The inner planets either do not have moons or have just one (Earth) or two (Mars). None of the inner planets has rings. Compared to the outer planets, the inner planets have shorter orbits around the Sun, but all the inner planets spin more slowly. Venus spins the slowest of all the planets. At one time, all the inner planets have been geologically active. They are all made of cooled igneous rock with inner iron cores.

Mercury

Mercury, shown in **Figure** 25.7, is the planet closest to the Sun. Mercury is the smallest planet, and it has no moon. As **Figure** 25.7 shows, the surface of Mercury is covered with craters, like Earth's moon. The presence of impact craters that are so old means that Mercury hasn't changed much geologically for billions of years and, with only a trace of an atmosphere, has no weather to wear down the ancient craters.

Because Mercury is so close to the Sun, it is difficult to observe from Earth, even with a telescope. However, the Mariner 10 spacecraft, shown in **Figure** 25.8, visited Mercury in 1974–1975. In January 2008, the Messenger mission returned to Mercury and took much more detailed pictures. One of these images can be seen in **Figure** 25.9.

Short Year, Long Days

Mercury is named for the Roman messenger god, who could run extremely fast. Likewise, Mercury moves very fast in its orbit around the Sun. A **year** on Mercury—the length of

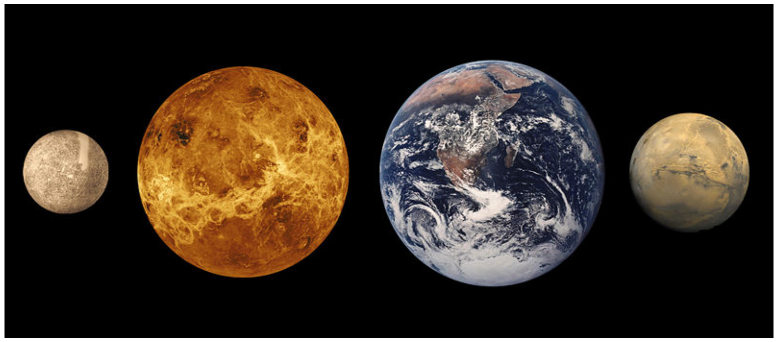

Figure 25.7: This composite shows the relative sizes of the four inner planets. From left to right, they are Mercury, Venus, Earth, and Mars. (35)

Figure 25.8: Mariner 10 made three flybys of Mercury in 1974 and 1975. (32)

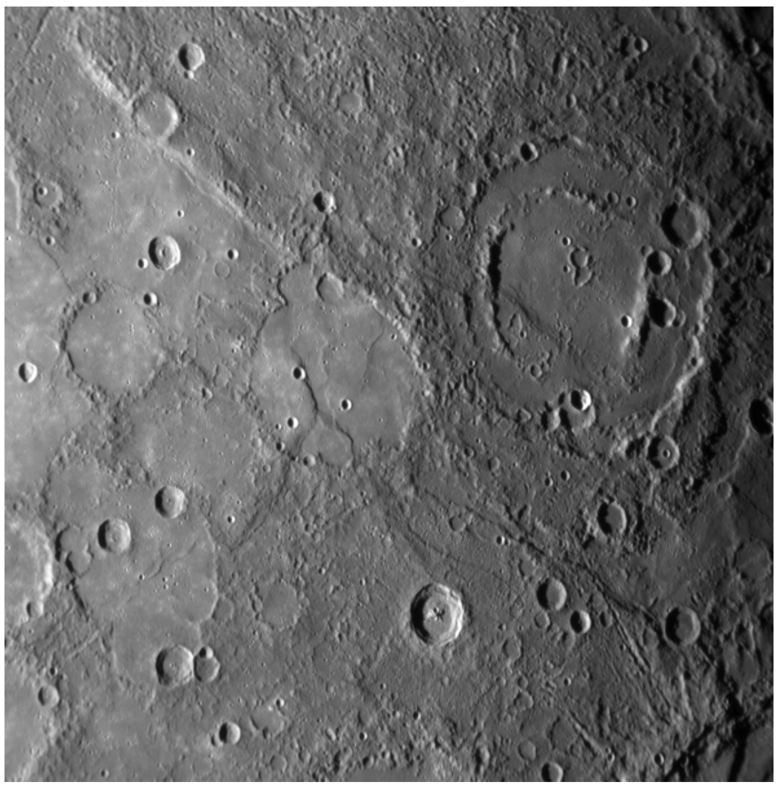

Figure 25.9: Mercury is covered with craters, like Earth's moon. (4)

time it takes to orbit the Sun—is just 88 Earth days.

Mercury has a very short year, but very long days. A **day** is defined as the time it takes a planet to turn on its axis. Mercury rotates slowly on its axis, turning exactly three times for every two times it orbits the Sun. Therefore, each day on Mercury is 58 Earth days long. In other words, on Mercury, a year is only a Mercury day and a half long!

Extreme Temperatures

Mercury is very close to the Sun, so it can get very hot. However, Mercury has virtually no atmosphere and it rotates very slowly. Because there is no atmosphere and no water to insulate the surface, temperatures on the surface of Mercury vary widely. In direct sunlight, the surface can be as hot as 427 °C (801 °F). On the dark side, or in the shadows inside craters, the surface can be as cold as –183 °C (–297 °F)! Although most of Mercury is extremely dry, scientists believe there may be a small amount of water in the form of ice at the poles of Mercury, in areas which never receive direct sunlight.

A Liquid Metal Core

Figure 25.10 shows a diagram of Mercury's interior. Mercury is one of the densest planets. Scientists believe the interior contains a relatively large, liquid core made mostly of melted iron. Mercury's core takes up about 42% of the planet's volume. Mercury's highly cratered surface is evidence that Mercury is not geologically active.

Venus

The second planet out from the Sun, Venus, is our nearest neighbor. Not only is it closer to Earth than any other planet, but it also is the most similar to Earth in size. Named after the Roman goddess of love, it is the only planet named after a female. Venus is sometimes called Earth's "sister planet." But just how similar is Venus to Earth?

A Harsh Environment

Viewed through a telescope, Venus looks smooth and featureless. That's because Venus is covered by a thick layer of clouds, as shown in pictures of Venus taken at ultraviolet wavelengths, such as **Figure** 25.11. Because of the thick, cloudy atmosphere, we cannot take ordinary photos of the surface of Venus, even from spacecraft orbiting the planet. However, we can make maps of the surface using radar. **Figure** 25.12 shows a topographical map of Venus produced by the Magellan probe using radar.

Unlike clouds on Earth, Venus's clouds are not made of water vapor. They are made of

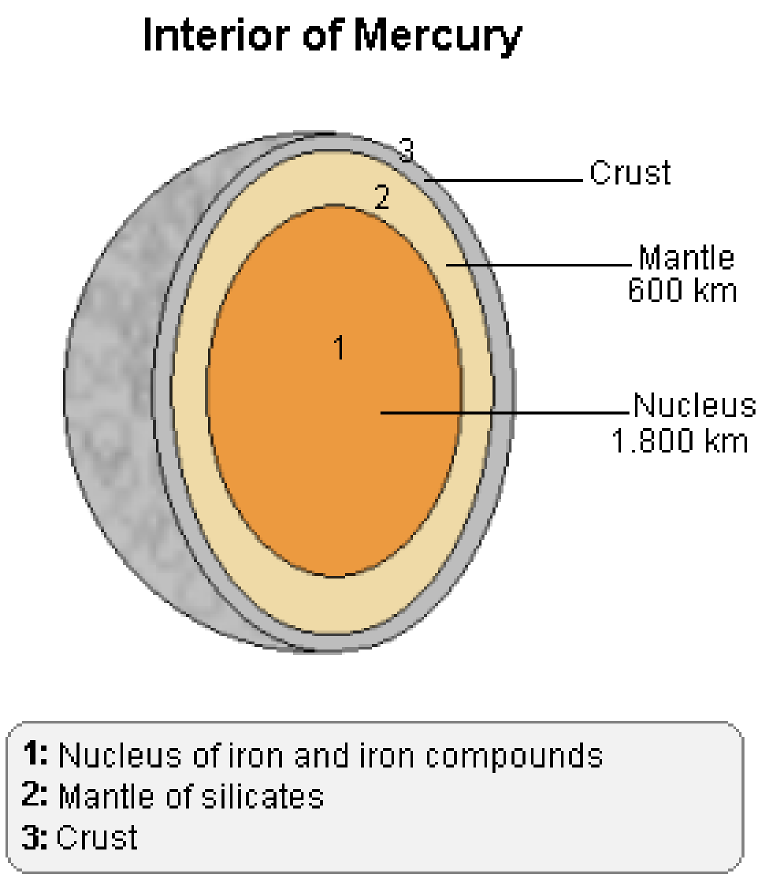

Figure 25.10: Mercury contains a thin crust, a mantle, and a large, liquid core that is rich in iron. (17)

carbon dioxide and sulfur dioxide—and they also contain large amounts of corrosive sulfuric acid!

Figure 25.11: This ultraviolet image from the Pioneer Venus Orbiter shows thick layers of clouds in the atmosphere of Venus. (2)

The atmosphere of Venus is so thick that the atmospheric pressure on the surface of Venus is 90 times greater than the atmospheric pressure on Earth's surface. The thick atmosphere also causes a strong greenhouse effect, which traps heat from the Sun. As a result, Venus is the hottest planet, even hotter than Mercury. Temperatures at the surface reach 465°C (860 °F). That's hot enough to melt lead!

Volcanoes

Venus has more volcanoes than any other planet. Planetary scientists have estimated that Venus has up to 100,000 or even a million volcanoes. Although these volcanoes contributed carbon dioxide in the past, most of the volcanoes are now dead. Venus doesn't seem to have tectonic plates like the Earth's. It's surface is covered with dead volcanoes and ancient craters.

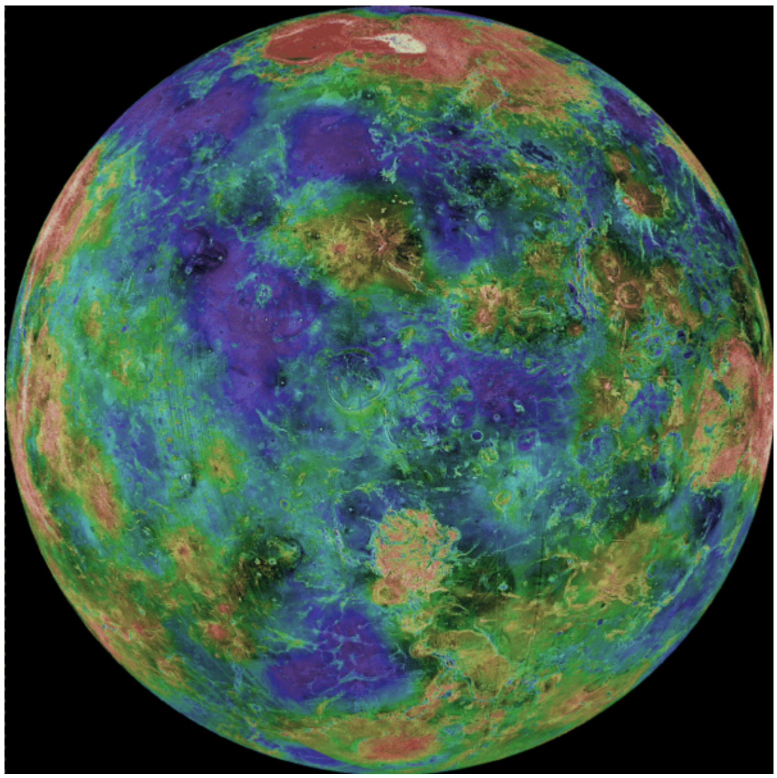

Figure 25.12: This topographic map of Venus was made from radar data collected by the Magellan probe between 1990 and 1994. (1)

Orbiting spacecraft have used radar to reveal mountains, valleys, and canyons on Venus. Most of the surface, however, has large areas of volcanoes surrounded by plains of lava. **Figure** 25.13 is an image made by a computer using radar data. It shows a volcano called Maat Mons, with lava beds in the foreground. The reddish-orange color is close to what scientists think the color of sunlight would look like on the surface of Venus.

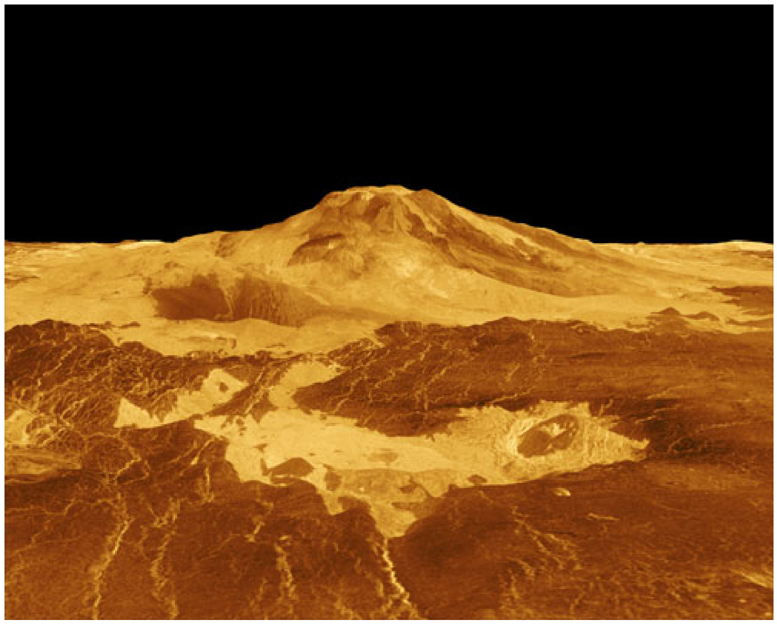

Figure 25.13: This image of Maat Mons was generated from radar data. The surface of Venus has many mountains, volcanoes, and plains of lava. (10)

Motion and Appearance

Venus is the only planet that rotates clockwise as viewed from its North pole, in a direction opposite to the direction it orbits the Sun. It turns slowly in the reverse direction, making one turn every 243 days. This is longer than a year on Venus—it takes Venus only 224 days to orbit the Sun.

Because the orbit of Venus is inside Earth's orbit, Venus always appears close to the Sun. When Venus rises early in the morning, just before the Sun rises, it is sometimes called "the morning star." When it sets in the evening, just after the Sun sets, it may be called "the evening star." Venus' clouds reflect sunlight very well. As a result, Venus is very bright. When it is visible, Venus is the brightest object in the sky besides the sun and the Moon.

Like Mercury, Venus has no moon.

Earth

The third planet out from the Sun is shown in **Figure** 25.14. Does it look familiar? It's Earth! Because it is our home planet, we know a lot more about Earth than we do about any other planet. But what are key features of Earth when viewed as a member of our solar system?

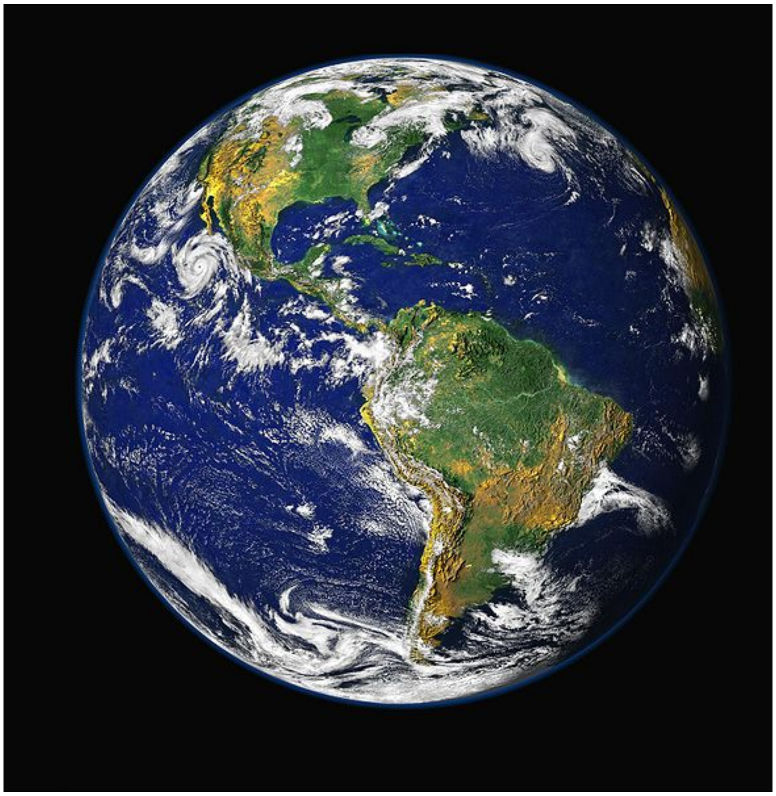

Figure 25.14: This famous image of Earth was taken during the Apollo 17 mission to the moon. (21)

Oceans and Atmosphere

As you can see in **Figure** 25.14, Earth has vast oceans of liquid water, large masses of land, ice covering the poles, and a dynamic atmosphere with clouds of water vapor. Earth's average surface temperature is 14°C (57°F). As you know, water is a liquid at this temperature. The oceans and the atmosphere help keep Earth's surface temperatures fairly steady.

Earth is the only planet known to have life. The conditions on Earth, especially the presence of liquid water, are ideal for life as we know it. The atmosphere filters out radiation that would be harmful to life, such as ultraviolet radiation and X rays. The presence of life has changed Earth's atmosphere, so it has much more oxygen than the atmospheres of other planets.

Plate Tectonics

The top layer of Earth's interior—the crust—contains numerous plates, known as tectonic plates. These plates move on the convecting mantle below, so they slowly move around on the surface. Movement of the plates causes other geological activity, such as earthquakes, volcanoes, and the formation of mountains. Earth is the only planet known to have plate tectonics.

Earth's Motions and Moon

Earth rotates on its axis once per day. In fact, the time of this rotation is how people have defined a day. Earth orbits the Sun once every 365.24 days, which is also how we have defined a year. Earth has one large moon, which orbits Earth once every 29.5 days, a period known as a month.

Earth's moon is the only large moon around a terrestrial planet in the solar system. The Moon is covered with craters, and also has large plains of lava. There is evidence that the Moon formed when a very large object—perhaps as large as the planet Mars—struck Earth in the distant past.

Mars

Mars, shown in **Figure** 25.15, is the fourth planet from the Sun, and the first planet beyond Earth's orbit. The Martian atmosphere is thin relative to Earth's and with much lower atmospheric pressure. Unlike Earth's neighbor on the side nearer the sun, Mars has only a weak greenhouse effect, which raises its temperature only slightly above what it would be if the planet did not have an atmosphere.

Although Mars is not the closest planet to Earth, it is the easiest to observe. Therefore, Mars has been studied more thoroughly than any other planet besides Earth. Humans have sent many space probes to Mars. Currently, there are three scientific satellites in orbit around Mars, and two functioning rovers on the surface. No humans have ever set foot on Mars. However, both NASA and the European Space Agency have set goals of sending people to Mars sometime between 2030 and 2040.

Figure 25.15: This image of Mars, taken by the Hubble Space Telescope in August, 2003, shows the planets reddish color and a prominent polar ice cap. (33)

A Red Planet

Viewed from Earth, Mars is reddish in color. The ancient Greeks and Romans named the planet after the god of war. They may have associated the planet with war because its red color reminded them of blood. Mars appears red because the surface of the planet really is a reddish-orange rust color, due to large amounts of iron in the soil. Mars has only a very thin atmosphere, made up mostly of carbon dioxide.

Surface Features

Mars is home to the largest mountain in the solar system—Olympus Mons, shown in **Figure** 25.16. Olympus Mons is a shield volcano, similar to the volcanoes that make up the Hawaiian islands on Earth. Olympus Mons is about 27 km (16.7 miles/88,580 ft) above the normal Martian surface level. That makes it more than three times taller than Mount Everest. At its base, Olympus Mons is about the size of the entire state of Arizona!

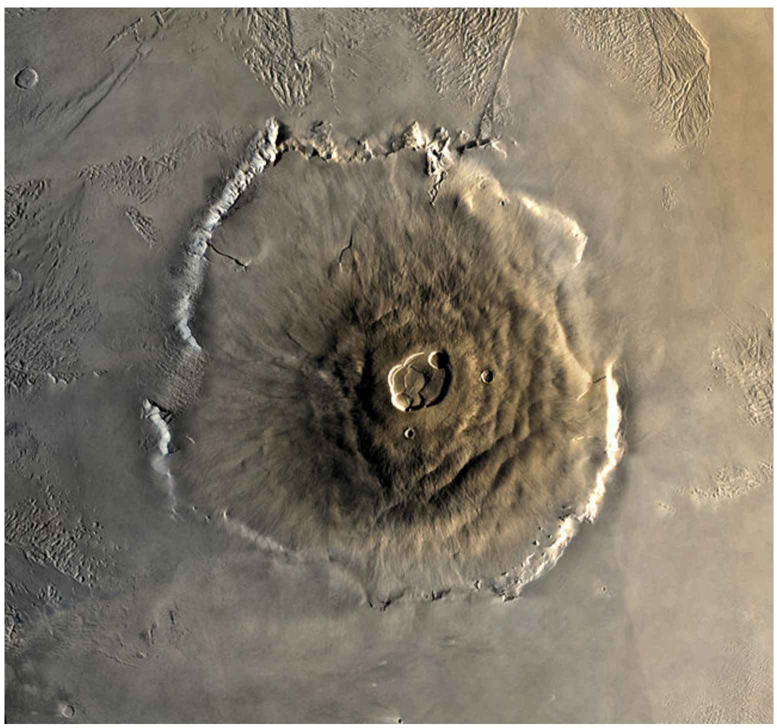

Figure 25.16: The Martian volcano Olympus Mons is the largest mountain in the solar system. (29)

Mars also has the largest canyon in the solar system, Valles Marineris (**Figure** 25.17). This canyon is 4,000 km (2,500 miles) long, as long as Europe is wide, and one-fifth the circumference of Mars. The canyon is 7 km (4.3 miles) deep. By comparison, the Grand Canyon on Earth is only 446 km (277 miles) long and about 2 km (1.2 miles) deep.

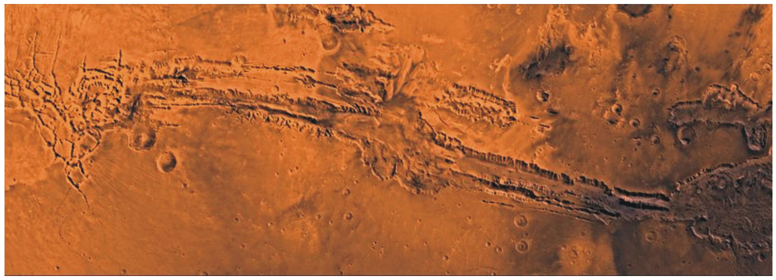

Figure 25.17: The Martian canyon Valles Marineris is the largest canyon in the solar system. (19)

Although Mars has mountains, canyons, and other features similar to Earth, it doesn't have as much geological activity as Earth. There is no evidence of plate tectonics on Mars. There are also more craters on Mars than on Earth, though fewer than on the Moon.

Is There Water on Mars?

Water cannot stay in liquid form on Mars because the pressure of the atmosphere is too low. However, there is a lot of water in the form of ice. **Figure** 25.15 shows a prominent ice cap at the south pole of Mars. Scientists also believe there is also a lot of ice water present just under the Martian surface. This ice can melt when volcanoes erupt, and water can flow across the surface temporarily.

Scientists have reason to think that water once flowed over the surface of Mars because they can see surface features that look like water-eroded canyons, and the Mars rover collected round clumps of crystals that, on Earth, usually form in water. The presence of water on Mars, even though it is now frozen as ice, suggests that it might have been possible for life to exist on Mars in the past.

Two Martian Moons

Mars has two very small moons, Phobos and Deimos. As you can see in **Figure** 25.18, these moons are not spherical in shape, but instead just look like irregular rocks. Phobos and Deimos were discovered in 1877. They are named after characters in Greek mythology—the two sons of Ares, who followed their father into war. Ares is equivalent to the Roman god Mars.

Lesson Summary

- The four inner planets, or terrestrial planets, have solid, rocky surfaces.

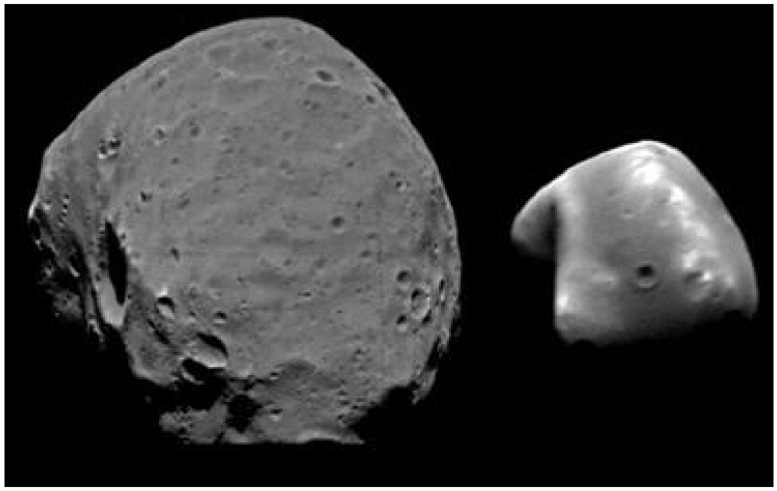

Figure 25.18: Mars has two small moons, Phobos (left) and Deimos (right). (8)

- Mercury is the smallest planet and the closest to the Sun. It has an extremely thin atmosphere, with surface temperatures ranging from very hot to very cold. Like the Moon, it is covered with craters.
- Venus is the second planet from the Sun and the closest planet to Earth, in distance and in size. It has a very thick, corrosive atmosphere, and the surface temperature is extremely high.
- Radar maps of Venus show that it has mountainous areas, as well as volcanoes surrounded by plains of lava.
- Venus rotates slowly in a direction opposite to the direction of its orbit.
- Earth is the third planet from the Sun. It is the only planet with large amounts of liquid water, and the only planet known to support life. Earth has a large moon, the only large moon around a terrestrial planet.
- Mars is the fourth planet from the Sun. It has two small moons. Mars is reddish in color because of oxidized iron (rust) in its soil. Mars has the largest mountain and the largest canyon in the solar system.
- There is a lot of water ice in the polar ice caps and under the surface of Mars.

Review Questions

1. Name the inner planets in order from the Sun outward. Then name them from smallest to largest.
2. Why do the temperatures on Mercury vary widely?
3. Venus is farther from the Sun than Mercury. Why does Venus have higher temperatures than Mercury?
4. How are maps of Venus made?
5. Name two major ways in which Earth is unlike any other planets.

6. Why does Mars appear to be red?
7. Suppose you are planning a mission to Mars. Identify two places where you might be able to get water on the planet.

Further Reading / Supplemental Links

- http://www.nasa.gov/worldbook/venus_worldbook.html
- http://solarsystem.nasa.gov/planetselector.cfm?Object=Mercury
- http://solarsystem.jpl.nasa.gov/planets/profile.cfm?Object=Mercury&Display=Kids
- http://mars.jpl.nasa.gov/extreme/
- http://www.google.com/mars/
- http://www.youtube.com/watch?v=U8-DTJpygyk
- http://www.youtube.com/watch?v=U8-DTJpygyk
- http://www.youtube.com/watch?v=HqFVxWfVtoo&feature=related
- http://www.youtube.com/watch?v=M-KfYEQUg2s

Vocabulary

day

The time it takes a planet to rotate once on its axis.

inner planets

The four planets inside the asteroid belt of our solar system; Mercury, Venus, Earth and Mars.

terrestrial planets

The solid, dense, rocky planets that are like Earth.

year

The time it takes for a planet to orbit the Sun.

Points to Consider

- We are planning to send humans to Mars sometime in the next few decades. What do you think it would be like to be on Mars? Why do you think we are going to Mars instead of Mercury or Venus?
- Why do you think the four inner planets are also called terrestrial planets? What might a planet be like if it weren't a terrestrial planet?

25.3 Outer Planets

Lesson Objectives

- Describe key features of the outer planets and their moons.
- Compare the outer planets to each other and to Earth.

Introduction

The four planets farthest from the sun—Jupiter, Saturn, Uranus, and Neptune—are called the **outer planets** of our solar system. **Figure** 25.19 shows the relative sizes of the outer planets and the Sun. Because they are much larger than Earth and the other inner planets, and because they are made primarily of gases and liquids rather than solid matter, the outer planets are also called **gas giants**.

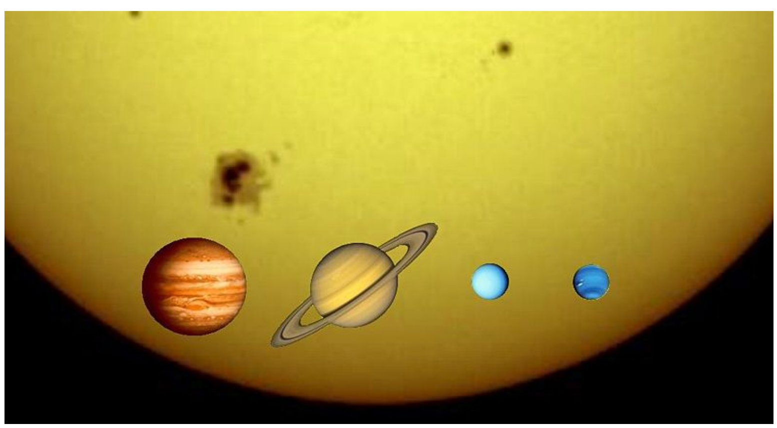

Figure 25.19: This image shows the four outer planets and the Sun, with sizes to scale. From left to right, the outer planets are Jupiter, Saturn, Uranus, and Neptune. (18)

The gas giants are made up primarily of hydrogen and helium, the same elements that make up most of the Sun. Astronomers believe that hydrogen and helium gases were found in large amounts throughout the solar system when it first formed. However, the inner planets didn't have enough mass to hold on to these very light gases. As a result, the hydrogen and helium initially on these inner planets floated away into space. Only the Sun and the massive outer planets had enough gravity to keep hydrogen and helium from drifting away.

All of the outer planets have numerous moons. All of the outer planets also have **planetary rings**, which are rings of dust and other small particles encircling a planet in a thin plane. Only the rings of Saturn can be easily seen from Earth.

Jupiter

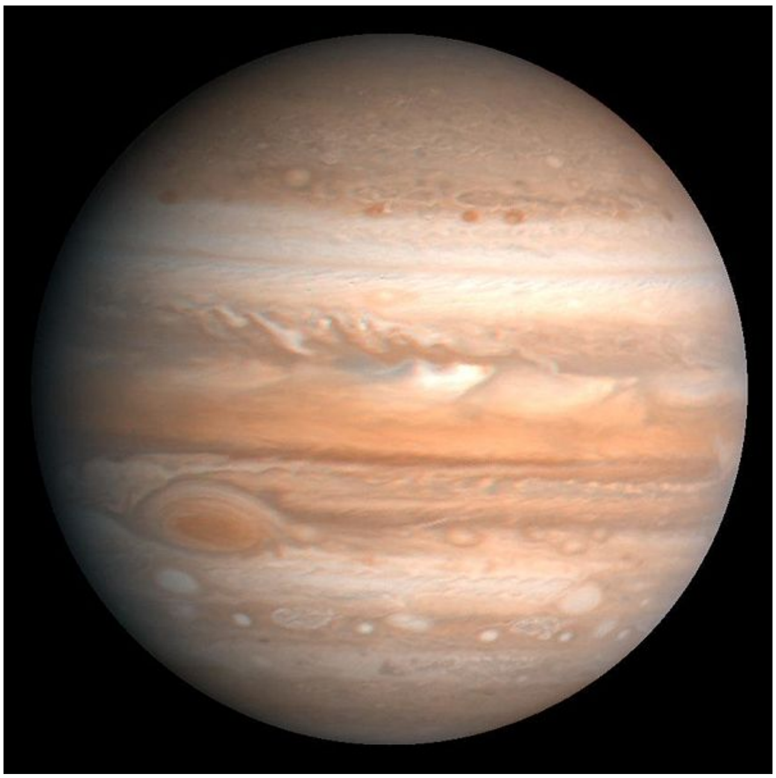

Figure 25.20: This image of Jupiter was taken by Voyager 2 in 1979. The colors were later enhanced to bring out more details. (3)

Jupiter, shown in **Figure** 25.20, is the largest planet in our solar system, and the largest object in the solar system besides the Sun. Jupiter is named for the king of the gods in Roman mythology. Jupiter is truly a giant! It is much less dense than Earth—it has 318 times the mass of Earth, but over 1,300 times Earth's volume. Because Jupiter is so large, it reflects a lot of sunlight. When it is visible, it is the brightest object in the night sky besides the Moon and Venus. This brightness is all the more impressive, since Jupiter is quite far from the Earth — 5.20 AUs away. It takes Jupiter about 12 Earth years to orbit once around the Sun.

A Ball of Gas and Liquid

If a spaceship were to try to land on the surface of Jupiter, the astronauts would find that there is no solid surface at all! Jupiter is made mostly of hydrogen, with some helium, and small amounts of other elements. The outer layers of the planet are gas. Deeper within the planet, pressure compresses the gases into a liquid. Some evidence suggests that Jupiter may have a small rocky core at its center.

A Stormy Atmosphere

The upper layer of Jupiter's atmosphere contains clouds of ammonia (NH_3) in bands of different colors. These bands rotate around the planet, but also swirl around in turbulent storms. The **Great Red Spot,** shown in **Figure** 25.21, is an enormous, oval-shaped storm found south of Jupiter's equator. It is more than three times as wide as the entire Earth! Clouds in the storm rotate in a counterclockwise direction, making one complete turn every six days or so. The Great Red Spot has been on Jupiter for at least 300 years. It is possible, but not certain, that this storm is a permanent feature on Jupiter.

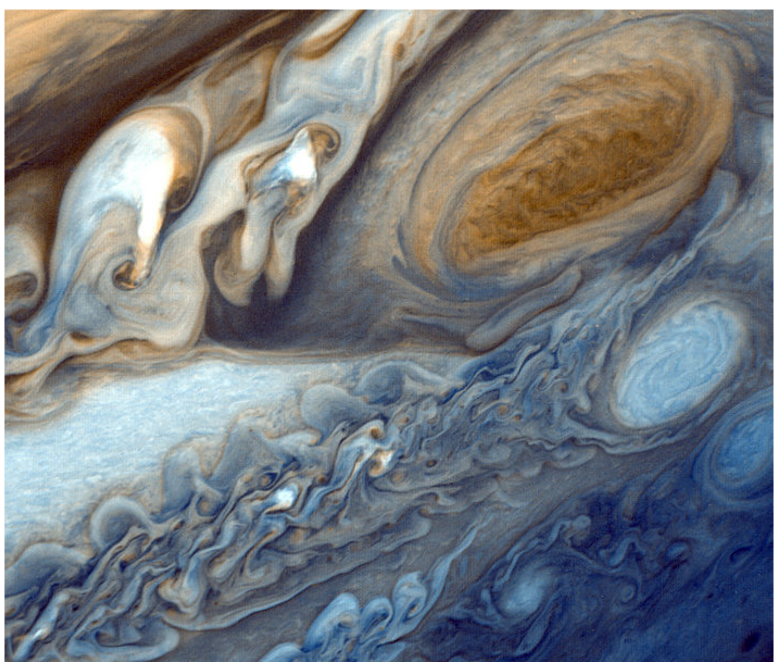

Figure 25.21: This image of Jupiter's Great Red Spot (upper right of image) was taken by the Voyager 1 spacecraft. The white storm just below the Great Red Spot is about the same diameter as Earth. (7)

Jupiter's Moons and Rings

Jupiter has a very large number of moons. As of 2008, we have discovered over 60 natural satellites of Jupiter. Of these, four are big enough and bright enough to be seen from Earth, using no more than a pair of binoculars. These four moons—named Io, Europa, Ganymede, and Callisto—were first discovered by Galileo in 1610, so they are sometimes referred to as the **Galilean moons**.

Figure 25.22 shows the four Galilean moons and their sizes relative to the Great Red Spot. The Galilean moons are larger than the dwarf planets Pluto, Ceres, and Eris. In fact, Ganymede, which is the biggest moon in the solar system, is even larger than the planet Mercury!

Scientists are particularly interested in Europa, the smallest of the Galilean moons, because it may be a likely place to find extraterrestrial life. The surface of Europa is a smooth layer of ice. Evidence suggests that there is an ocean of liquid water under the ice. Europa also has a continual source of energy—it is heated as it is stretched and squashed by tidal forces from Jupiter. Because it has liquid water and a continual heat source, astrobiologists surmise that life might have formed on Europa much as it did on Earth. Numerous missions have been planned to explore Europa, including plans to drill through the ice and send a probe into the ocean. However, no such mission has yet been attempted.

In 1979, two spacecrafts—Voyager 1 and Voyager 2—visited Jupiter and its moons. Photos from the Voyager missions showed that Jupiter has a ring system. This ring system is very faint, so it is very difficult to observe from Earth.

Saturn

Saturn, shown in **Figure** 25.23, is famous for its beautiful rings. Saturn's mass is about 95 times the mass of Earth, and its volume is 755 times Earth's volume, making it the second largest planet in the solar system. Despite its large size, Saturn is the least dense planet in our solar system. It is less dense than water, which means if there could be a bathtub big enough, Saturn would float. In Roman mythology, Saturn was the father of Jupiter. So, it is an appropriate name for the next planet beyond Jupiter. Saturn orbits the Sun once about every 30 Earth years.

Saturn's composition is similar to Jupiter. It is made mostly of hydrogen and helium, which are gases in the outer layers and liquids at deeper layers. It may also have a small solid core. The upper atmosphere has clouds in bands of different colors. These rotate rapidly around the planet, but there seems to be less turbulence and fewer storms on Saturn than on Jupiter.

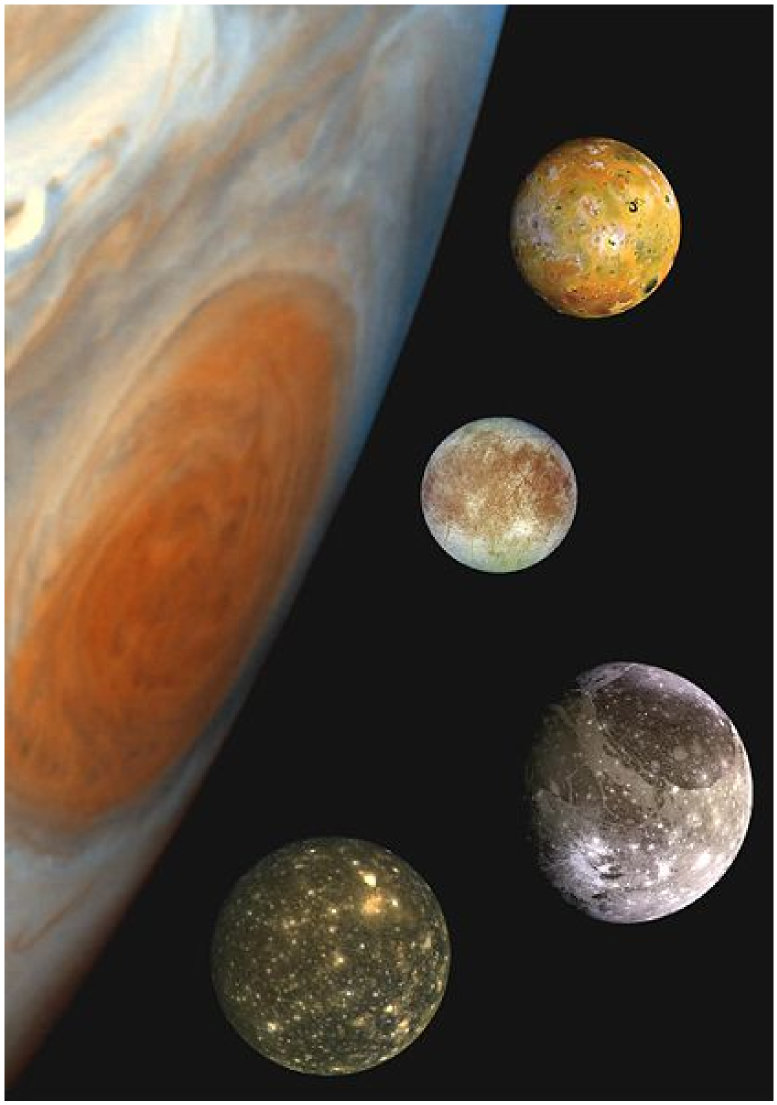

Figure 25.22: This composite image shows the the four Galilean moons and Jupiter. From top to bottom, the moons are Io, Europa, Ganymede and Callisto. Jupiter's Great Red Spot is in the background. Sizes are to scale. (37)

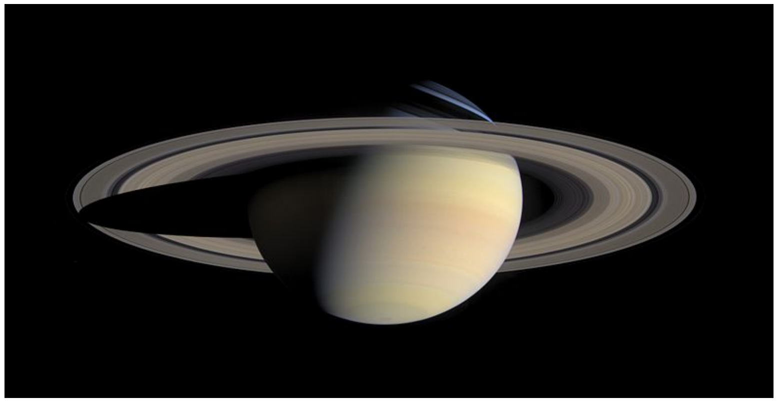

Figure 25.23: This image of Saturn and its rings is a composite of pictures taken by the Cassini orbiter in 2004. (16)

A Weird Hexagon

There is a strange feature at Saturn's north pole—the clouds form a hexagonal pattern, as shown in the infrared image in **Figure** 25.24. This hexagon was viewed by Voyager 1 in the 1980's, and again by the Cassini Orbiter in 2006, so it seems to be a long-lasting feature. Though astronomers have hypothesized and speculated about what causes these hexagonal cloud, no one has yet come up with a convincing explanation.

Saturn's Rings

The rings of Saturn were first observed by Galileo in 1610. However, he could not see them clearly enough to realize they were rings; he thought they might be two large moons, one on either side of Saturn. In 1659, the Dutch astronomer Christiaan Huygens was the first to realize that the rings were in fact rings. The rings circle Saturn's equator. They appear tilted because Saturn itself is tilted about 27 degrees to the side. The rings do not touch the planet.

The Voyager 1 spacecraft visited Saturn in 1980, followed by Voyager 2 in 1981. The Voyager probes sent back detailed pictures of Saturn, its rings, and some of its moons. From the Voyager data, we learned that Saturn's rings are made of particles of water and ice, with a little bit of dust as well. There are several gaps in the rings. Some of the gaps have been cleared out by moons that are within the rings. Scientists believe the moons' gravity caused ring dust and gas to fall towards the moon, leaving a gap in the rings. Other gaps in the rings are caused by the competing gravitational forces of Saturn and of moons outside the rings.

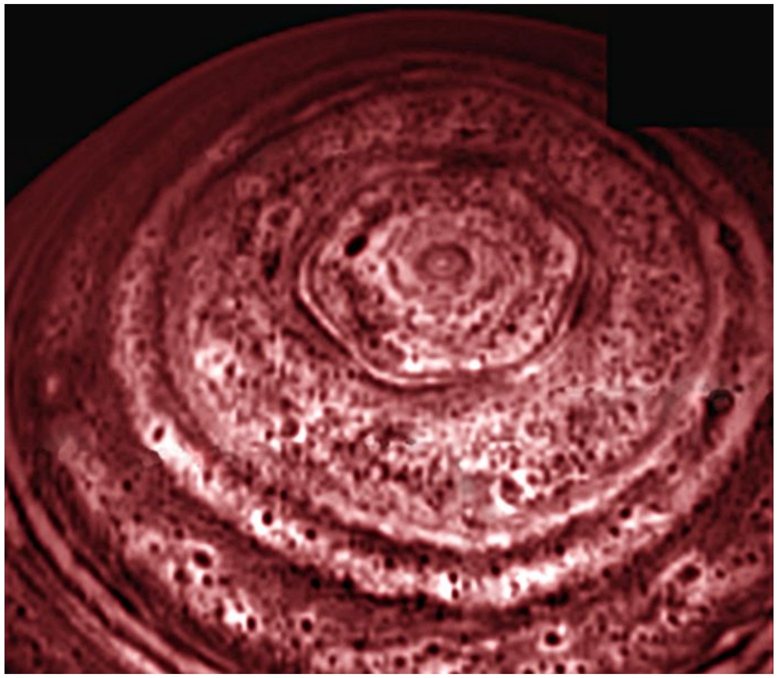

Figure 25.24: This infrared image taken of Saturn's north pole shows that the clouds are in a hexagon (six-sided) shape. (11)

Saturn's Moons

As of 2008, over 60 moons have been identified around Saturn. Most of them are very small. Some are even found within the rings. In a sense, all the particles in the rings are like little moons, too, because they orbit around Saturn. Only seven of Saturn's moons are large enough for gravity to have made them spherical, and all but one are smaller than Earth's moon.

Saturn's largest moon, Titan, is about one and a half times the size of Earth's Moon and is also larger than the planet Mercury. **Figure** 25.25 compares the size of Titan to Earth. Scientists are very interested in Titan because it has an atmosphere that is similar to what Earth's atmosphere might have been like before life developed on Earth. Titan may have a layer of liquid water under a layer of ice on the surface. Scientists now believe there are also lakes on the surface of Titan, but these lakes contain liquid methane (CH_4) and ethane (C_2H_6) instead of water! Methane and ethane are compounds found in natural gas, a mixture of gases found naturally on Earth and often used as fuel.

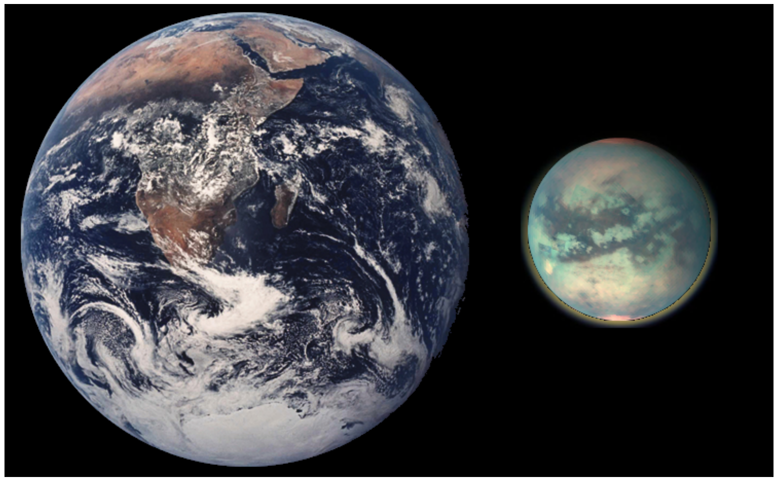

Figure 25.25: This composite image compares Saturn's largest moon, Titan (right) to Earth (left). Titan has an atmosphere similar to what Earth's might have been like before life formed on Earth. (24)

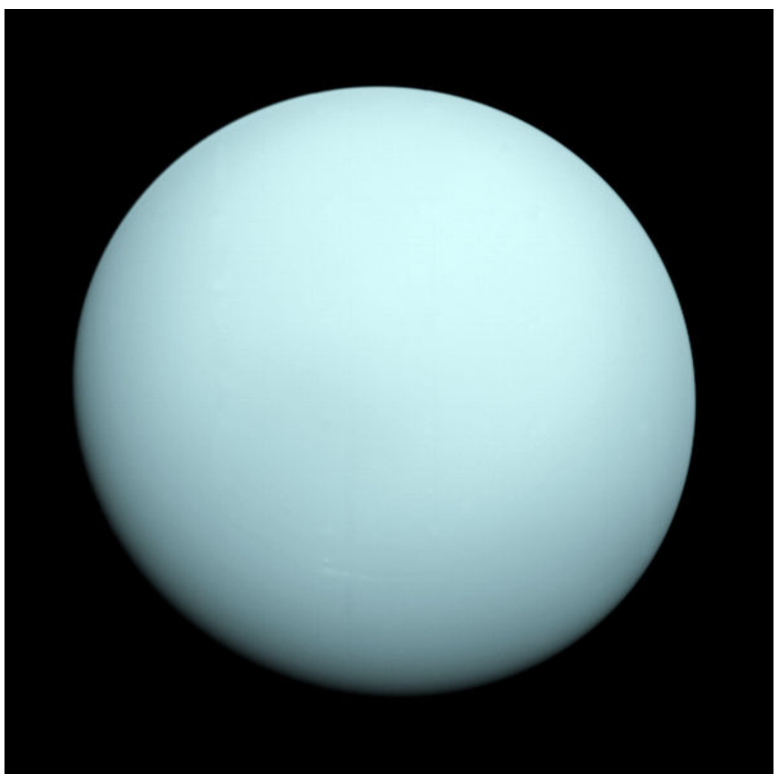

Figure 25.26: This image of Uranus was taken by Voyager 2 in 1986. (23)

Uranus

Uranus, shown in **Figure** 25.26, is named for the Greek god of the sky. In Greek mythology, Uranus was the father of Cronos, the Greek equivalent of the Roman god Saturn. By the way, astronomers pronounce the name "YOOR-uh-nuhs."

Uranus was not known to ancient observers. It was first discovered by the astronomer William Herschel in 1781. Uranus can be seen from Earth with the unaided eye, but it was overlooked for centuries because it is very faint. Uranus is faint because it is very far away, not because it is small. It is about 2.8 billion kilometers (1.8 billion miles) from the Sun. Light from the Sun takes about 2 hours and 40 minutes to reach Uranus. Uranus orbits the Sun once about every 84 Earth years.

An Icy Blue-Green Ball

Like Jupiter and Saturn, Uranus is composed mainly of hydrogen and helium. It has a thick layer of gas on the outside, then liquid further on the inside. However, Uranus has a higher percentage of icy materials, such as water, ammonia (NH_3), and methane (CH_4), than Jupiter and Saturn do. When sunlight reflects off Uranus, clouds of methane filter out red light, giving the planet a blue-green color. There are bands of clouds in the atmosphere of Uranus, but they are hard to see in normal light, so the planet looks like a plain blue ball.

Uranus is the lightest of the outer planets, with a mass about 14 times the mass of Earth. Even though it has much more mass than Earth, it is much less dense than Earth. At the "surface" of Uranus, the gravity is actually weaker than on Earth's surface. If you were at the top of the clouds on Uranus, you would weigh about 10% less than what you weigh on Earth.

The Sideways Planet

Most of the planets in the solar system rotate on their axes in the same direction that they move around the Sun. Uranus, though, is tilted on its side so its axis is almost parallel to its orbit. In other words, it rotates like a top that was turned so that it was spinning parallel to the floor. Scientists think that Uranus was probably knocked over by a collision with another planet-sized object billions of years ago.

Rings and Moons of Uranus

Uranus has a faint system of rings, as shown in **Figure** 25.27. The rings circle the planet's equator, but because Uranus is tilted on its side, the rings are almost perpendicular to the planet's orbit.

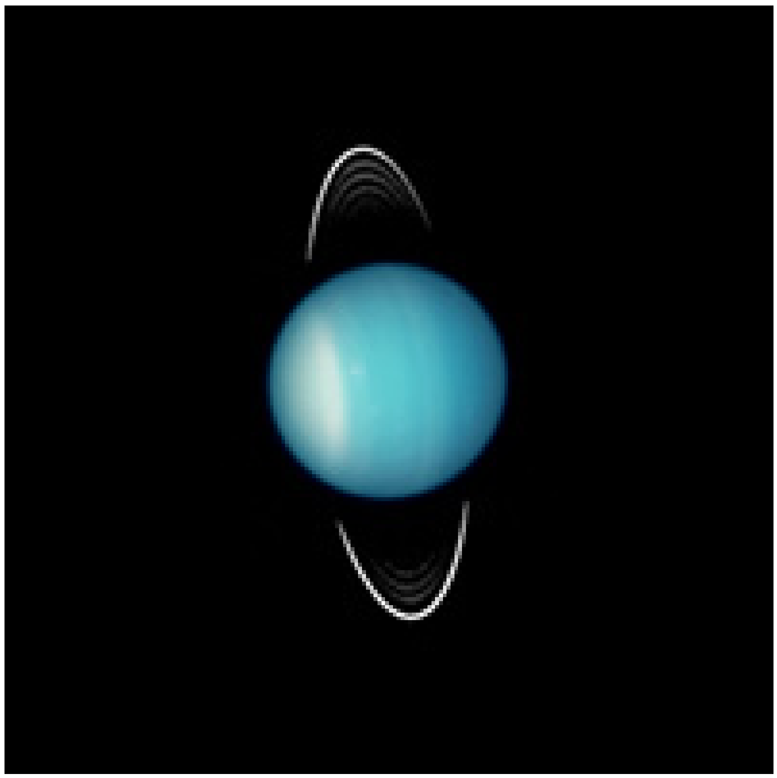

Figure 25.27: This image from the Hubble Space Telescope shows the faint rings of Uranus. The planet is tilted on its side, so the rings are nearly vertical. (12)

Uranus has 27 moons that we know of. All but a few of them are named for characters from the plays of William Shakespeare. The five biggest moons of Uranus—Miranda, Ariel, Umbriel, Titania and Oberon—are shown in **Figure** 25.28.

Figure 25.28: These Voyager 2 photos have been resized to show the relative sizes of the five main moons of Uranus. (14)

Neptune

Neptune, shown in **Figure** 25.29, is the eighth planet from the Sun. It is the only major planet that can't be seen from Earth without a telescope. Scientists predicted the existence of Neptune before it was actually discovered. They noticed that Uranus did not always appear exactly where it should appear. They knew there must be another planet beyond Uranus whose gravity was affecting Uranus' orbit. This planet was discovered in 1846, in the position that had been predicted, and it was named Neptune for the Roman god of the sea due to its blush color.

Neptune has slightly more mass than Uranus, but it is slightly smaller in size. In many respects, it is similar to Uranus. Uranus and Neptune are often considered "sister planets." Neptune, which is nearly 4.5 billion kilometers (2.8 billion miles) from the Sun, is much farther from the Sun than even distant Uranus. It moves very slowly in its orbit, taking 165 Earth years to complete one orbit around the Sun.

Extremes of Cold and Wind

Neptune is blue in color, with a few darker and lighter spots. The blue color is caused by atmospheric gases, including methane (CH_4). When Voyager 2 visited Neptune in 1986, there was a large dark-blue spot south of the equator. This spot was called the Great Dark Spot. However, when the Hubble Space Telescope took pictures of Neptune in 1994, the Great Dark Spot had disappeared. Instead, another dark spot had appeared north of the equator. Astronomers believe both of these spots represent gaps in the methane clouds on Neptune.

The changing appearance of Neptune is due to its turbulent atmosphere. The winds on Neptune are stronger than on any other planet in the solar system, reaching speeds of 1,100

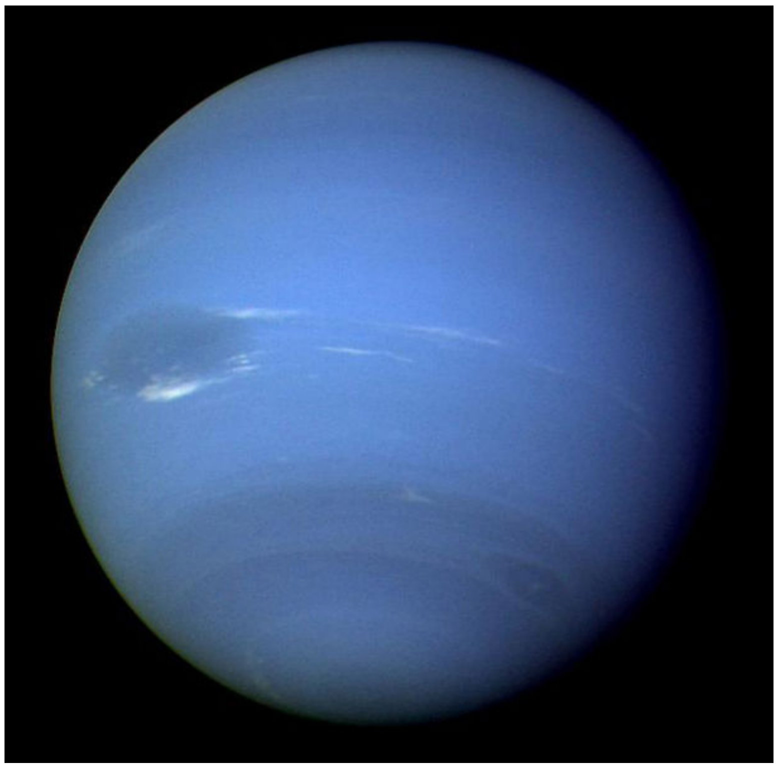

Figure 25.29: This image of Neptune was taken by Voyager 2 in 1989. The Great Dark Spot seen on the left center in the picture has since disappeared, but a similar dark spot has appeared on another part of the planet. (22)

km/h (700 mi/h), close to the speed of sound. This extreme weather surprised astronomers, since the planet receives little energy from the Sun to power weather systems. Neptune is also one of the coldest places in the solar system. Temperatures at the top of the clouds are about –218$_o$C (–360$_o$F).

Neptune's Rings and Moons

Like the other outer planets, Neptune has rings of ice and dust. These rings are much thinner and fainter than those of Saturn. Some evidence suggests that the rings of Neptune may be unstable, and may change or disappear in a relatively short time.

Neptune has 13 known moons. Triton, shown in **Figure** 25.30, is the only one of them that has enough mass to be spherical in shape. Triton orbits in the direction opposite to the orbit of Neptune. Scientists think Triton did not form around Neptune, but instead was captured by Neptune's gravity as it passed by.

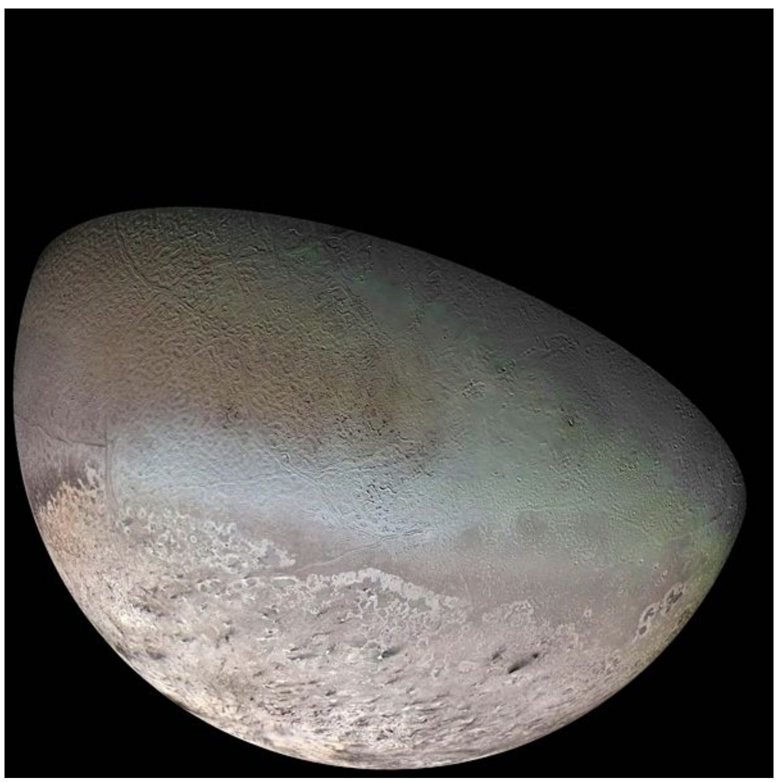

Figure 25.30: This image Triton, Neptune's largest moon, was taken by Voyager 2 in 1989. (15)

Pluto

Pluto was once considered one of the outer planets, but when the definition of a planet was changed in 2006, Pluto became one of the leaders of the dwarf planets. It is one of the largest and brightest objects that make up this group. Look for Pluto in the next section in the discussion of dwarf planets.

Lesson Summary

- The four outer planets—Jupiter, Saturn, Uranus, and Neptune—are all gas giants made primarily of hydrogen and helium. They have thick gaseous outer layers and liquid interiors.
- All of the outer planets have numerous moons, as well as planetary rings made of dust and other particles.
- Jupiter is by far the largest planet in the solar system. It has bands of different colored clouds, and a long-lasting storm called the Great Red Spot.
- Jupiter has over 60 moons. The four biggest were discovered by Galileo, and are called the Galilean moons.
- One of the Galilean moons, Europa, may have an ocean of liquid water under a layer of ice. The conditions in this ocean might be right for life to have developed.
- Saturn is smaller than Jupiter, but similar in composition and structure.
- Saturn has a large system of beautiful rings. Saturn's largest moon, Titan, has an atmosphere similar to Earth's atmosphere before life formed.
- Uranus and Neptune were discovered in modern times. They are similar to each other in size and composition. They are both smaller than Jupiter and Saturn, and also have more icy materials.
- Uranus is tilted on its side, probably due to a collision with a large object in the past.
- Neptune is very cold and has very strong winds. It had a large dark spot that disappeared, then another dark spot appeared on another part of the planet. These dark spots are storms in Neptune's atmosphere.
- Pluto is no longer considered one of the outer planets. It is now considered a dwarf planet.

Review Questions

1. Name the outer planets a) in order from the Sun outward, b) from largest to smallest by mass, and c) from largest to smallest by size.
2. Why are the outer planets called gas giants?
3. How do the Great Red Spot and Great Dark Spot differ?
4. Name the Galilean moons, and explain why they are called that.
5. Why might Europa be a likely place to find extraterrestrial life?

6. What causes gaps in Saturn's rings?
7. Why are scientists interested in the atmosphere of Saturn's moon Titan?
8. What liquid is found on the surface of Titan?
9. Why is Uranus blue-green in color?
10. What is the name of Neptune's largest moon?

Further Reading / Supplemental Links

- http://www.nasa.gov/worldbook/jupiter_worldbook.html
- http://solarsystem.nasa.gov/planetselector.cfm?Object=Jupiter
- http://www.youtube.com/watch?v=5iVw72sX3Bg
- http://www.youtube.com/watch?v=iLXeUVCNoX8
- http://www.youtube.com/watch?v=29wfzotaBIg
- http://www.youtube.com/watch?v=FqX2YdnwtRc

Vocabulary

Galilean moons The four largest moons of Jupiter discovered by Galileo.

gas giants The four large outer planets composed of the gases hydrogen and helium.

Great Red Spot An enormous, oval shaped storm on Jupiter.

outer planets The four large planets beyond the asteroid belt in our solar system.

planetary rings Rings of dust and rock encircling a planet in a thin plane.

Points to Consider

- The inner planets are small and rocky, while the outer planets are large and gaseous. Why might the planets have formed into two groups like they are?
- We have discussed the Sun, the planets, and the moons of the planets. What other objects can you think of that can be found in our solar system?

25.4 Other Objects in the Solar System

Lesson Objectives

- Locate and describe the asteroid belt.

- Explain where comets come from and what causes their tails.
- Differentiate between meteors, meteoroids, and meteorites.

Introduction

When our solar system formed, most of the matter ended up in the Sun, the star at the center of the system. Material spinning in a disk around the Sun clumped together into larger and larger pieces, forming the eight planets and their moons. But some of the smaller pieces of matter in the solar system never joined one of these larger bodies. In this lesson, we will talk about some of these other objects in the solar system.

Asteroids

Asteroids are very small, rocky bodies that orbit the Sun. "Asteroid" means "star-like," and in a telescope, asteroids look like points of light, just like stars. Asteroids are also sometimes called *planetoids or minor planets,* because in some ways they are similar to miniature planets. Unlike planets, though, asteroids are irregularly shaped because they do not have enough gravity to become round like planets. They do not have atmospheres, and they are not geologically active. The only geological changes to an asteroid are due to collisions, which may break up the asteroid or create craters on the asteroid's surface. **Figure** 25.31 shows a typical asteroid.

The Asteroid Belt

Hundreds of thousands of asteroids have been discovered in our solar system. They are still being discovered at a rate of about 5,000 new asteroids per month! The majority of the asteroids are found in between the orbits of Mars and Jupiter, in a region called the **asteroid belt**, as shown in **Figure** 25.32. Although there are many thousands of asteroids in the asteroid belt, their total mass adds up to only about 4% of Earth's moon.

Scientists believe that the bodies in the asteroid belt formed there during the formation of the solar system. However, they have never been able to form into a single planet because the gravity of Jupiter, which is very massive, continually disrupts the asteroids.

Near-Earth Asteroids

Near-Earth asteroids are asteroids whose orbits cross Earth's orbit. Any object whose orbit crosses Earth can collide with Earth. There are over 4,500 known near-Earth asteroids; between 500 and 1,000 of these are over 1 kilometer in diameter. Small asteroids do in fact collide with Earth on a regular basis—asteroids 5–10 m in diameter hit Earth on average about once per year. Evidence suggests that large asteroids hitting Earth in the past have

Figure 25.31: Asteroid 951 Gaspra was the first asteroid photographed at close range. This picture was taken in 1991 by the Galileo probe on its way to Jupiter. 951 Gaspra is a medium-sized asteroid, measuring about 19 by 12 by 11 kilometers (12 by 7.5 by 7 miles). (6)

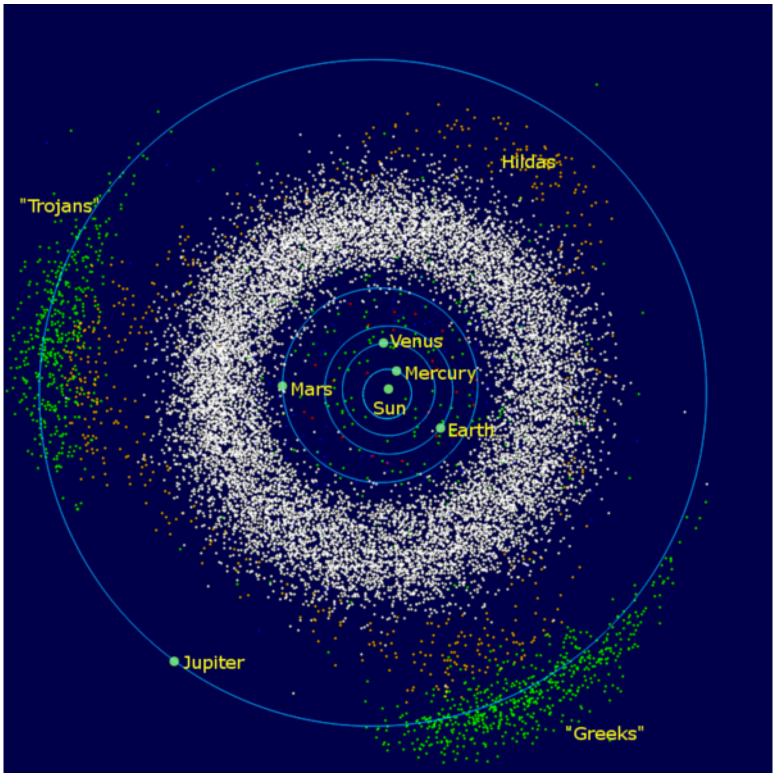

Figure 25.32: The asteroid belt is a ring of many asteroids between the orbits of Mars and Jupiter. The white dots in the figure are asteroids in the main asteroid belt. Other groups of asteroids closer to Jupiter are called the Hildas (orange), the Trojans (green), and the Greeks (also green). (25)

caused many organisms to die and many species to go extinct. Astronomers are always on the lookout for new asteroids, and follow the known near-Earth asteroids closely, so they can predict a possible collision as early as possible.

Asteroid Missions

Scientists are interested in asteroids in part because knowing more about what they are made of can tell us about our solar system and how it might have formed. They may also eventually be mined for rare minerals or for construction projects in space. Some asteroids have been photographed as spacecraft have flown by on their way to the outer planets. A few missions have been sent out to study asteroids directly. In 1997, the NEAR Shoemaker probe went into orbit around an asteroid called 433 Eros, and finally landed on its surface in 2001. The Japanese Hayabusa probe is currently studying an asteroid and may return samples of its surface to Earth. In 2007, NASA launched the Dawn mission, which is scheduled to visit some of the largest asteroids in 2011-2015.

Meteors

If you have spent much time looking at the sky on a dark night, you have probably seen a 'shooting star', like in **Figure** 25.33. A shooting star is a streak of light across the sky. The proper scientific name for a shooting star is a **meteor**. Meteors are not stars at all. Rather, they are small pieces of matter burning up as they enter Earth's atmosphere from space.

Meteoroids

Before these small pieces of matter enter Earth's atmosphere, they are called **meteoroids**. Meteoroids are like asteroids, only smaller. Meteoroids range from the size of boulders down to the size of tiny sand grains. Objects larger than meteoroids are considered asteroids, and objects smaller than meteoroids are considered *interplanetary dust.* Meteoroids are sometimes found clustered together in long trails. These are remnants left behind by comets. When Earth passes through one of these clusters, there is a **meteor shower**, an increase in the number of bright meteors in a particular region of the sky for a period of time.

Meteorites

Suppose a small rocky object—a meteoroid—enters Earth's atmosphere. Friction in the atmosphere heats the object quickly so it starts to vaporize, leaving a trail of glowing gases. At this point, it has become a meteor. Most meteoroids vaporize completely before they ever reach Earth's surface, but larger meteoroids may have a small core of material that travels

Figure 25.33: This photo captures a meteor - also called a 'shooting star,' streaking across the sky to the right of the Milky Way. (13)

all the way through the atmosphere and hits the Earth's surface. The solid remains of a meteoroid found on Earth's surface is called a **meteorite**.

Meteorites provide clues about our solar system. Many meteorites come from meteoroids that formed when the solar system formed (**Figure** 25.34). Some are from the insides of asteroids that have split apart. A few meteorites are made of materials more like the rocks on Mars. Scientists believe the material in these meteorites was actually knocked off the surface of Mars by an asteroid impact, and then entered Earth's atmosphere as a meteor.

Comets

Comets are small, icy objects that orbit the Sun in very elliptical orbits. Their orbits carry them from the outer solar system to the inner solar system, close to the Sun. When a comet gets close to the Sun, the outer layers of ice melt and evaporate. The gas and dust released in this way forms an atmosphere—called a *coma*—around the comet. Radiation and particles streaming from the Sun also push some of this gas and dust into a long *tail*, which always points away from the Sun no matter which way the comet is moving. **Figure** 25.35 shows Comet Hale-Bopp, which shone brightly for several months in 1997.

Gases in the coma and tail of a comet glow, and also reflect light from the Sun. Comets are very hard to see except when they have their comas and tails. For this reason, comets appear for only a short time when they are near the Sun, then seem to disappear again as

Figure 25.34: A lunar meteorite (27)

they move back to the outer solar system. The time between one appearance of a comet and the next is called the comet's *period*. For example, the first comet whose period was known, Halley's comet, has a period of 75 years. It last traveled through the inner solar system in 1986, and will appear again in 2061.

Where Comets Come From

Comets that have periods of about 200 years or less are considered short period comets. Most short-period comets come from a region beyond the orbit of Neptune. This area, which contains not only comets but also asteroids and at least two dwarf planets, is called the *Kuiper belt.* (Kuiper is pronounced "KI-per," rhyming with "viper.")

Some comets have much longer periods, as long as thousands or even millions of years. Most long-period comets come from a very distant region of the solar system called the *Oort cloud*, which is about 50,000–100,000 AU from the Sun (50,000–100,000 times the distance from the Sun to Earth). Comets carry materials from the outer solar system to the inner solar system. Comets may have brought water and other substances to Earth during collisions early in Earth's history.

Figure 25.35: Comet Hale-Bopp, also called the Great Comet of 1997, shone brightly for several months in 1997. The comet has two visible tails: a bright, curved dust tail and a fainter, straight tail of ions (charged atoms) pointing directly away from the Sun. (20)

Dwarf Planets

The **dwarf planets** of our solar system are exciting proof of how much we are learning about our solar system. With the discovery of many new objects in our solar system, in 2006, astronomers refined the definition of a planet. According to the new definition, a planet must:

1. orbit a star
2. be big enough that its own gravity causes it to be shaped like a sphere
3. be small enough that it isn't a star itself
4. have cleared the area of its orbit of smaller objects

At the same time, astronomers defined a new type of object: dwarf planets. A dwarf planet is an object that meets numbers 1–3 above, but not number 4. There are four dwarf planets in our solar system: Ceres, Pluto, Makemake and Eris.

Figure 25.36 shows Ceres, a rocky, spherical body that is by far the largest object in the asteroid belt. Before 2006, Ceres was considered the largest of the asteroids. Ceres has enough mass that its gravity causes it to be shaped like a sphere. Still, Ceres only has about 1.3% of the mass of the Earth's Moon. Ceres orbits the Sun, is round and is not a star but the area of its orbit is full of other smaller bodies, so Ceres fails the fourth criterion for being a planet, and is now considered a dwarf planet.

Figure 25.36: This composite image compares the size of the dwarf planet Ceres to Earth and the Moon. (31)

Pluto

From the time it was discovered in 1930 until 2006, Pluto was considered the ninth planet of the solar system. However, it was always thought of as an oddball planet. Unlike the other outer planets in the solar system, which are all gas giants, it is small, icy and rocky. Its diameter is about 2400 kilometers. It is only about 1/5 the mass of Earth's Moon. Its orbit is tilted relative to the other planets and is shaped like a long, narrow ellipse, sometimes even passing inside the orbit of Neptune.

Starting in 1992, many objects have been discovered in the same area as Pluto's orbit, an area now known as the Kuiper belt. The Kuiper belt begins outside the orbit of Neptune and continues out at least 500 AU. We have discovered more than 200 million Kuiper belt objects. Pluto orbits within this region. When the definition of a planet was changed in 2006, Pluto failed the test of clearing out its orbit of other bodies, so it is now considered a dwarf planet.

Pluto has 3 moons of its own. The largest, Charon, is big enough that the Pluto-Charon system is sometimes considered to be a double dwarf planet (**Figure** 25.37). Two smaller moons, Nix and Hydra, were discovered in 2005.

Makemake

Makemake is the third largest and second brightest dwarf planet we have discovered so far (**Figure** 25.37). It is about three quarters the size of Pluto. Its diameter is estimated to be between 1300 and 1900 kilometers. Makemake is named after the deity that created humanity in the mythology of the people of Easter Island. It orbits the Sun in 310 years at a distance between 38.5 to 53 AU. It is believed to be made of methane, ethane and nitrogen ices.

Eris

Eris is the largest known dwarf planet in the solar system — about 27% more massive than Pluto (**Figure** 25.37). It was not discovered until 2003 because it is extremely far away from the Sun. Although Pluto, Makemake and Eris are in the Kuiper belt, Eris is about 3 times farther from the Sun than Pluto is, and almost 100 times farther from the Sun than Earth is. When it was first discovered, it was considered for a short time to be the "tenth planet" in the solar system. The discovery of Eris helped prompt the new definition of planets and dwarf planets in 2006. Eris also has a small moon, Dysnomia that orbits it once about every 16 days.

Astronomers already know there may be other dwarf planets in the outer reaches of the solar system. Look for Haumea, Quaoar, Varuna and Orcus to be possibly added to the list of dwarf planets in the future. We still have a lot to discover and explore!

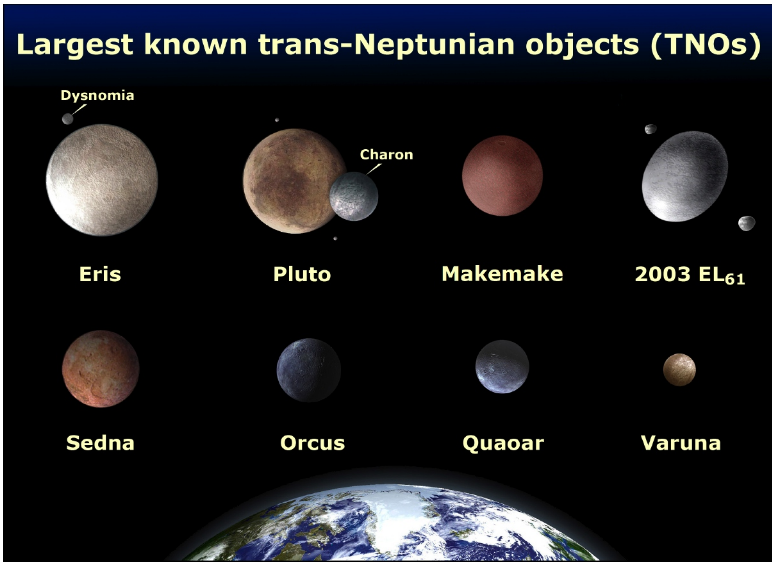

Figure 25.37: Largest Known Trans-Neptunian Objects. (36)

Lesson Summary

- Asteroids are irregularly-shaped, rocky bodies that orbit the Sun. Most of them are found in the asteroid belt, between the orbits of Mars and Jupiter.
- Meteoroids are smaller than asteroids, ranging from the size of boulders to the size of sand grains. When meteoroids enter Earth's atmosphere, they vaporize, creating a trail of glowing gas called a meteor. If any of the meteoroid reaches Earth, the remaining object is called a meteorite.
- Comets are small, icy objects that orbit the Sun in very elliptical orbits. When they are close to the Sun, they form comas and tails, which glow and make the comet more visible.
- Short-period comets come from the Kuiper belt, beyond Neptune. Long-period comets come from the very distant Oort cloud.
- Dwarf planets are spherical bodies that orbit the Sun, but that have not cleared their orbit of smaller bodies. Ceres is a dwarf planet in the asteroid belt. Pluto, Makemake and Eris are dwarf planets in the Kuiper belt.

Review Questions

1. Arrange the following from smallest to largest: asteroid, star, meteoroid, planet, dwarf planet.
2. Where are most asteroids found?
3. What is the difference between a meteor, a meteoroid, and a meteorite?
4. What kind of objects would scientists study to learn about the composition of the Oort

cloud?
5. Why is Pluto no longer considered a planet?
6. Name the four known dwarf planets in our solar system.

Further Reading / Supplemental Links

- http://www.nasa.gov/worldbook/asteroid_worldbook.html
- http://www.iau.org/iau0602.423.0.html
- http://en.wikipedia.org/

Vocabulary

asteroid

Rocky objects larger than a few hundred meters that orbit the Sun in the region known as the asteroid belt.

asteroid belt

Region between the orbits of Mars and Jupiter where many asteroids are found.

comet

Asmall, icy, dusty object in orbit around the Sun.

dwarf planet

Around celestial object orbiting the Sun that has not cleared its orbit of other objects.

Kuiper belt

Aregion of space around the Sun beyond the orbit of Neptune that contains millions of frozen objects.

meteor

Material from outer space that burns up as it enters Earth's atmosphere.

meteorite

The solid portion of a meteor that hits Earth's surface.

meteoroid

Asmall rock in interplanetary space that has not yet entered Earth's atmosphere.

meteor shower

An area of frequent meteors appearing to originate in a particular part of the sky.

Points to Consider

- In 2006, astronomers changed the definition of a planet and created a new category of dwarf planets. Do you think planets, dwarf planets, moons, asteroids, and meteoroids are clearly separate groups?
- What defines each of these groups, and what do objects in these different groups have in common? Could an object change from being in one group to another? How?
- We have learned about many different kinds of objects that are found within our solar system. What objects or systems of objects can you think of that are found outside our solar system?

Image Sources

(1) NASA. http://en.wikipedia.org/wiki/Image:Venus2_mag_big.png. Public Domain.

(2) NASA. http://en.wikipedia.org/wiki/File:Venuspioneeruv.jpg. Public Domain.

(3) NASA. http://en.wikipedia.org/wiki/Image:Jupiter.jpg. Public Domain.

(4) NASA. http://commons.wikimedia.org/wiki/File:MESSENGER_EN0108828359M.png. Public Domain.

(5) CK-12 Foundation. http://en.wikipedia.org/wiki/Image:Geoz_wb_en.jpg. CC-BY-SA.

(6) NASA. http://en.wikipedia.org/wiki/Image:951_Gaspra.jpg. Public Domain.

(7) NASA. http://en.wikipedia.org/wiki/Image:Jupiter_from_Voyager_1.jpg. Public Domain.

(8) NASA. http://en.wikipedia.org/wiki/Image:Phobos_deimos_diff_rotated.jpg. Public Domain.

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(11) NASA. http://en.wikipedia.org/wiki/Image:Saturn_hexagonal_north_pole_feature.jpg. Public Domain.

(12) http://hubblesite.org/newscenter/archive/releases/2007/32/image/b/. Public Domain.

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(14) http://news.softpedia.com/news/Chaos-Uranus-its-moons-and-rings-15545.shtml.

(15) NASA. http://en.wikipedia.org/wiki/Image:Triton_moon_mosaic_Voyager_2_%28large%29.jpg. GNU-FDL.

(16) NASA. http://en.wikipedia.org/wiki/Image:Saturn_from_Cassini_Orbiter_%282004-10-06%29.jpg. Public Domain.

(17) http://commons.wikimedia.org/wiki/Image:Mercury_inside_Lmb.png. Public Domain.

(18) http://en.wikipedia.org/wiki/Image:Gas_giants_and_the_Sun_%281_px_%3D_1000_km%29.jpg. Public Domain.

(19) NASA. http://mars.jpl.nasa.gov/mer/funzone/marsrover4/images/valles_marineris_hires.jpg. Public Domain.

(20) http://en.wikipedia.org/wiki/Image:Comet-Hale-Bopp-29-03-1997_hires_adj.jpg. CC-BY-SA.

(21) NASA. http://commons.wikimedia.org/wiki/File:Nasa_blue_marble.jpg. Public Domain.

(22) NASA. http://en.wikipedia.org/wiki/Image:Neptune.jpg. GNU-FDL.

(23) NASA. http://en.wikipedia.org/wiki/File:Uranus2.jpg. Public Domain.

(24) NASA. http://en.wikipedia.org/wiki/Image:Titan_Earth_Comparison_at_29_km_per_px.png. Public Domain.

(25) http://en.wikipedia.org/wiki/Image:InnerSolarSystem-en.png. Public Domain.

(26) http://en.wikipedia.org/wiki/File:Ptolemaic_elements.svg. Public Domain.

(27) NASA. http://upload.wikimedia.org/wikipedia/commons/0/0d/Lunar_Meteorite.jpg. Public Domain.

(28) NASA. http://en.wikipedia.org/wiki/Image:Oort_cloud_Sedna_orbit.jpg. Public Domain.

(29) NASA. http://en.wikipedia.org/wiki/Image:Olympus_Mons.jpg. Public Domain.

(30) NASA. http://en.wikipedia.org/wiki/Image:UpdatedPlanets2006.jpg. Public Domain.

(31) NASA. http://en.wikipedia.org/wiki/Image:Ceres_Earth_Moon_Comparison.png. GNU-FDL.

(32) NASA. http://en.wikipedia.org/wiki/Image:Mariner10.gif. Public Domain.

(33) http://hubblesite.org/newscenter/archive/releases/2003/22/image/a/. Public Domain.

(34) http://en.wikipedia.org/wiki/Image:Ptolemaicsystem-small.png. Public Domain.

(35) NASA. http://en.wikipedia.org/wiki/Image:Terrestrial_planet_size_comparisons.jpg. Public Domain.

(36) http://commons.wikimedia.org/wiki/File:EightTNOS_new.png. CC-BY-SA 2.5.

(37) NASA. http://en.wikipedia.org/wiki/Image:Jupitermoon.jpg. Public Domain.

Chapter 26

Stars, Galaxies, and the Universe

26.1 Stars

Lesson Objectives

- Define constellation.
- Describe the flow of energy in a star.
- Classify stars based on their properties.
- Outline the life cycle of a star.
- Use light-years as a unit of distance.

Introduction

When you look at the sky on a clear night, you can see dozens, perhaps even hundreds, of tiny points of light. Almost every one of these points of light is a star, a giant ball of glowing gas at a very, very high temperature. Some of these stars are smaller than our Sun, and some are larger. Except for our own Sun, all stars are so far away that they only look like single points, even through a telescope.

Constellations

For centuries, people have seen the same stars you can see in the night sky. People of many different cultures have identified **constellations,** which are apparent patterns of stars in the sky. **Figure** 26.1 shows one of the most easily recognized constellations. The ancient Greeks thought this group of stars looked like a hunter from one of their myths, so they named it Orion after him. The line of three stars at the center of the picture is "Orion's Belt".

Figure 26.1: The constellation Orion is a familiar pattern of stars in the sky. (13)

The patterns in constellations and in groups or clusters of stars, called asterisms, stay the same night after night. However, in a single night, the stars move across the sky, keeping the same patterns. This apparent nightly motion of the stars is actually due to the rotation of Earth on its axis. It isn't the stars that are moving; it is actually Earth spinning that makes the stars seem to move. The patterns shift slightly with the seasons, too, as Earth revolves around the Sun. As a result, you can see different constellations in the winter than in the summer. For example, Orion is a prominent constellation in the winter sky, but not in the summer sky.

Apparent Versus Real Distances

Although the stars in a constellation appear close together as we see them in our night sky, they are usually at very different distances from us, and therefore they are not at all close together out in space. For example, in the constellation Orion, the stars visible to the naked eye are at distances ranging from just 26 light-years (which is relatively close to Earth) to several thousand light-years away. A light-year is the distance that light can travel in one year; it is a large unit of distance used to measure the distance between objects in space.

Energy of Stars

Only a small portion of the light from the Sun reaches Earth; yet that light is enough to keep the entire planet warm and to provide energy for all the living things on Earth. The Sun is a fairly average star. The reason the Sun appears so much bigger and brighter than any of the other stars is that it is very close to us. Some other stars produce much more energy than the Sun. How do stars generate so much energy?

Nuclear Fusion

Stars are made mostly of hydrogen and helium. These are both very lightweight gases. However, there is so much hydrogen and helium in a star that the weight of these gases is enormous. In the center of a star, the pressure is great enough to heat the gases and cause **nuclear fusion reactions**. In a nuclear fusion reaction, the nuclei, or centers of two atoms join together and create a new atom from two original atoms. In the core of a star, the most common reaction turns two hydrogen atoms into a helium atom. Nuclear fusion reactions require a lot of energy to get started, but once they are started, they produce even more energy.

The energy from nuclear reactions in the core pushes outward, balancing the inward pull of gravity on all the gas in the star. This energy slowly moves outward through the layers of the star until it finally reaches the outer surface of the star. The outer layer of the star glows brightly, sending the energy out into space as electromagnetic radiation, including visible light, heat, ultraviolet light, and radio waves.

Scientists have built machines called accelerators that can propel subatomic particles until they have attained almost the same amount of energy as found in the core of a star. When these particles collide with each other head-on, new particles are created. This process simulates the nuclear fusion that takes place in the cores of stars. It also simulates the conditions that allowed for the first Helium atom to be produced from the collision of two hydrogen atoms when the Universe was only a few minutes old. Two well-known accelerators are SLAC in California, USA and CERN in Switzerland.

How Stars Are Classified

Stars come in many different colors. If you look at the stars in Orion (as shown in **Figure** 26.1), you will notice that there is a bright, red star in the upper left and a bright, and a blue star in the lower right. The red star is named Betelgeuse (pronounced BET-ul-juice), and the blue star is named Rigel.

Color and Temperature

If you watch a piece of metal, such as a coil of an electric stove as it heats up, you can see how color is related to temperature. When you first turn on the heat, the coil looks black, but you can feel the heat with your hand held several inches from the coil. As the coil gets hotter, it starts to glow a dull red. As it gets hotter still, it becomes a brighter red, then orange. If it gets extremely hot, it might look yellow-white, or even blue-white. Like a coil on a stove, a star's color is determined by the temperature of the star's surface. Relatively cool stars are red, warmer stars are orange or yellow, and extremely hot stars are blue or blue-white.

Classifying Stars by Color

The most common way of classifying stars is by color. **Table** 26.1 shows how this classification system works. The class of a star is given by a letter. Each letter corresponds to a color, and also to a range of temperatures. Note that these letters don't match the color names; they are left over from an older system that is no longer used.

Table 26.1: **Classification of Stars By Color and Temperature**

Class	Color	Temperature range	Sample Star
O	Blue	30,000 K or more	Zeta Ophiuchi
B	Blue-white	10,000–30,000 K	Rigel
A	White	7,500–10,000 K	Altair

Table 26.1: (continued)

Class	Color	Temperature range	Sample Star
F	Yellowish-white	6,000–7,500 K	Procyon A
G	Yellow	5,500–6,000 K	Sun
K	Orange	3,500–5,000 K	Epsilon Indi
M	Red	2,000–3,500 K	Betelgeuse, Proxima Centauri

(*Sources:* http://en.wikipedia.org/wiki/Stellar_classification; http://en.wikipedia.org/wiki/Star, *License:* GNU-FDL)

For most stars, surface temperature is also related to size. Bigger stars produce more energy, so their surfaces are hotter. **Figure** 26.2 shows a typical star of each class, with the colors about the same as you would see in the sky.

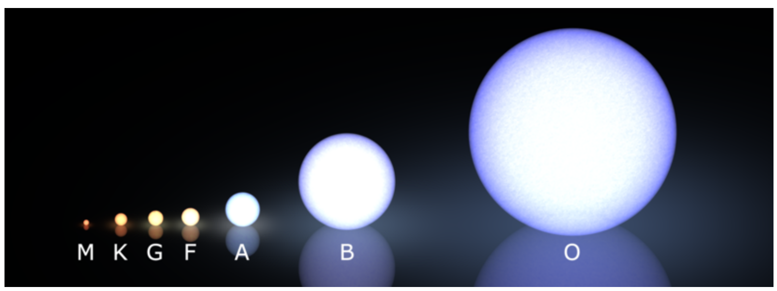

Figure 26.2: Typical stars by class, color and size. For most stars, size is related to class and to color. This image shows a typical star of each class. The colors are approximately the same as you would see in the sky. (6)

Lifetime of Stars

As a way of describing the stages in a star's development, we could say that stars are born, grow, change over time, and eventually die. Most stars change in size, color, and class at least once during this journey.

Formation of Stars

Stars are born in clouds of gas and dust called **nebulas**, like the one shown in **Figure** 26.3. In **Figure** 26.1, the fuzzy area beneath the central three stars across the constellation Orion, often called Orion's sword, contains another nebula called the Orion nebula.

Star formation starts when gravity starts to pull gas and dust in the nebula together. As the gas and dust falls together, it forms into one or more spheres. As one of these spheres collapses further, the pressure inside increases. As the pressure increases, the temperature of the gas also increases. Eventually, the pressure and temperature become great enough to cause nuclear fusion to start in the center. At this point, the ball of gas has become a star.

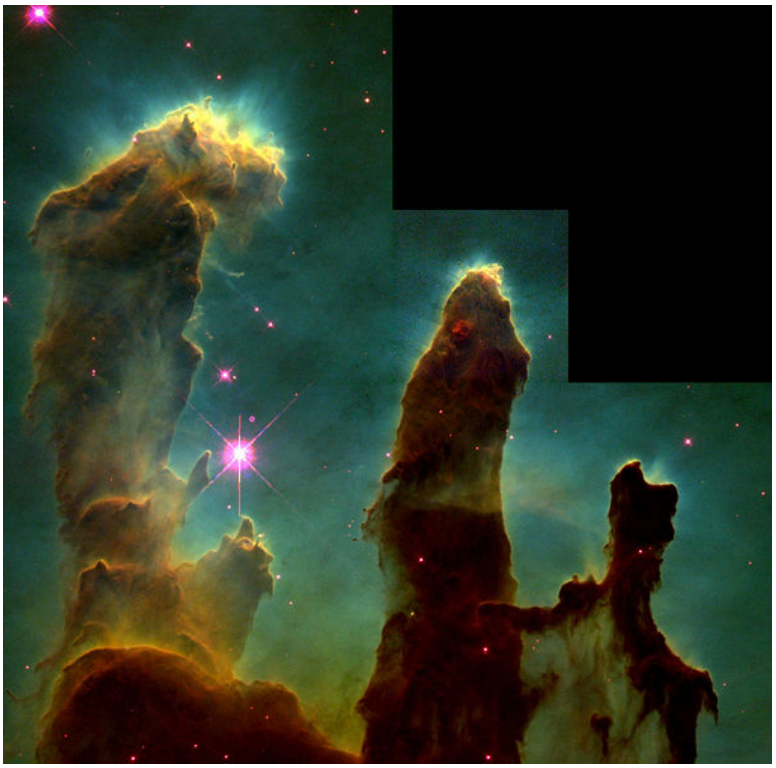

Figure 26.3: The Eagle Nebula and the Pillars of Creation. The pillars of gas and dust shown here are in the Eagle Nebula. (16)

The Main Sequence

For most of a star's life, the nuclear fusion in the core combines hydrogen atoms to form helium atoms. A star in this stage is said to be a **main sequence star**, or to be on the main sequence. This term comes from the Hertzsprung-Russell diagram, that plots a star's surface temperature against its true brightness or magnitude. For stars on the main sequence, the hotter they are, the brighter they are. The length of time a star is on the main sequence depends on how long a star is able to balance the inward force of gravity with the outward force provided by the nuclear fusion going on in its core. More massive stars have higher pressure in the core, so they have to burn more of their hydrogen "fuel" to prevent gravitational collapse. Because of this, more massive stars have higher temperatures, and also run out of hydrogen sooner than smaller stars do.

Our Sun, which is a medium-sized star, has been a main sequence star for about 5 billion years. It will continue to shine without changing for about 5 billion more years. Very large stars may be on the main sequence for "only" 10 million years or so. Very small stars may be main sequence stars for tens to hundreds of billions of years.

Red Giants and White Dwarfs

As a star begins to use up its hydrogen, it then begins to fuse helium atoms together into heavier atoms like carbon. Eventually, stars contain fewer light elements to fuse. The star can no longer hold up against gravity and it starts to collapse inward. Meanwhile, the outer layers spread out and cool. The star becomes larger, but cooler on the surface and red in color. Stars in this stage are called **red giants**.

Eventually, a red giant burns up all of the helium in its core. What happens next depends on how massive the star is. A typical star like the Sun, stops fusion completely at this point. Gravitational collapse shrinks the star's core to a white, glowing object about the size of Earth. A star at this point is called a **white dwarf**. Eventually, a white dwarf cools down and its light fades out.

Supergiants and Supernovas

A star that has much more mass than the Sun will end its life in a more dramatic way. When very massive stars leave the main sequence, they become *red supergiants*. The red star Betelgeuse in Orion is a red supergiant.

Unlike red giants, when all the helium in a red supergiant is gone, fusion does not stop. The star continues fusing atoms into heavier atoms, until eventually its nuclear fusion reactions produce iron atoms. Producing elements heavier than iron through fusion takes more energy than it produces. Therefore, stars will ordinarily not form any elements heavier than iron. When a star exhausts the elements that it is fusing together, the core succumbs to gravity and collapses violently, creating a violent explosion called a **supernova**. A supernova explosion contains so much energy that some of this energy can actually fuse heavy atoms together, producing heavier elements such as gold, silver, and uranium. A supernova can shine as brightly as an entire galaxy for a short time, as shown in **Figure** 26.4.

Neutron Stars and Black Holes

After a large star explodes in a supernova, the leftover material in the core is extremely dense. If the core is less than about four times the mass of the Sun, the star will be a **neutron star**, as shown in **Figure** 26.5. A neutron star is made almost entirely of neutrons. Even though it is more massive than the sun, it is only a few kilometers in diameter.

Figure 26.4: Supernova 1994D: When very large stars stop nuclear fusion, they explode as supernovas. A bright supernova, like the one in the bottom left of the figure, can shine as brightly as an entire galaxy for a short time. (18)

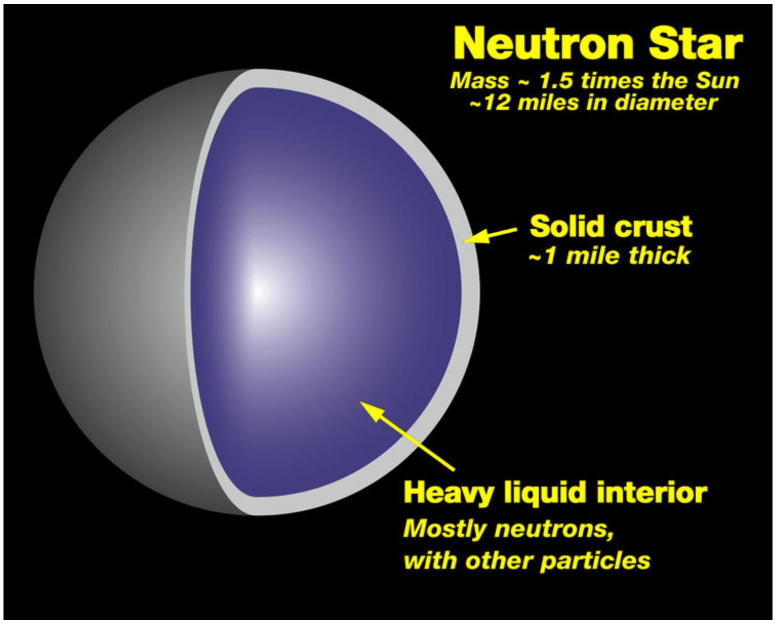

Figure 26.5: After a supernova, the remaining core may end up as a neutron star. (20)

If the core remaining after a supernova is more than about 5 times the mass of the Sun, the core will collapse so far that it becomes a **black hole**. Black holes are so dense that not even light can escape their gravity. For that reason, black holes cannot be observed directly. But we can identify a black hole by the effect that it has on objects around it, and by radiation that leaks out around its edges.

Measuring Star Distances

The Sun is much closer to Earth than any other star. Light from the Sun takes about 8 minutes to reach Earth. Light from the next nearest star, Proxima Centauri, takes more than 4 years to reach Earth. Traveling to Proxima Centauri in spacecraft similar to those we have today would take tens of thousands of years.

Light-years

Because astronomical distances are so large, it helps to use units of distance that are large as well. A **light-year** is defined the distance that light travels in one year. One light-year is 9,500,000,000,000 (9.5 trillion) kilometers, or 5,900,000,000,000 (5.9 trillion) miles. Proxima Centauri is 4.22 light-years away, which means that its light takes 4.22 years to reach us.

One light-year is approximately equal to 60,000 AU and 4.22 light-years is almost 267,000 AU. Recalling that Neptune, the farthest planet from the Sun, orbits roughly 30 AU from the Sun, we can realize that the distance from the Earth to stars other than our own Sun is much greater than the distance from the Earth to other planets within our own solar system.

Parallax

So how do astronomers measure the distance to stars? Distances to stars that are relatively close to us can be measured using **parallax.** Parallax is an apparent shift in position that takes place when the position of the observer changes.

To see an example or parallax, try holding your finger about 1 foot (30 cm) in front of your eyes. Now, while focusing on your finger, close one eye and then the other. Alternate back and forth between eyes, and pay attention to how your finger appears to move. The shift in position of your finger is an example of parallax. Now try moving your finger closer to your eyes, and repeat the experiment. Do you notice any difference? The closer your finger is to your eyes, the greater the position changes due to parallax.

As **Figure** 26.6 shows, astronomers use this same principle to measure the distance to stars. However, instead of a finger, they focus on a star. And instead of switching back and forth between eyes, they use the biggest possible difference in observing position. To do that, they first look at the star from one position, and they note where the star appears to be relative to more distant stars. Then, they wait 6 months; during this time, Earth moves from one side of its orbit around the Sun to the other side. When they look at the star again, parallax will cause the star to appear in a different position relative to more distant stars. From the size of this shift, they can calculate the distance to the star.

Parallax

Other Methods

For stars that are more than a few hundred light years away, parallax is too small to measure, even with the most precise instruments available. For these more distant stars, astronomers use more indirect methods of determining distance. Most of these other methods involve determining how bright the star they are looking at really is. For example, if the star has properties similar to the Sun, then it should be about as bright as the Sun. Then, they can compare the observed brightness to the expected brightness. This is like asking, "How far away would the Sun have to be to appear this dim?"

Lesson Summary

- Constellations and asterisms are apparent patterns of stars in the sky.
- Stars in the same constellation are often not close to each other in space.
- A star generates energy by nuclear fusion reactions in its core.

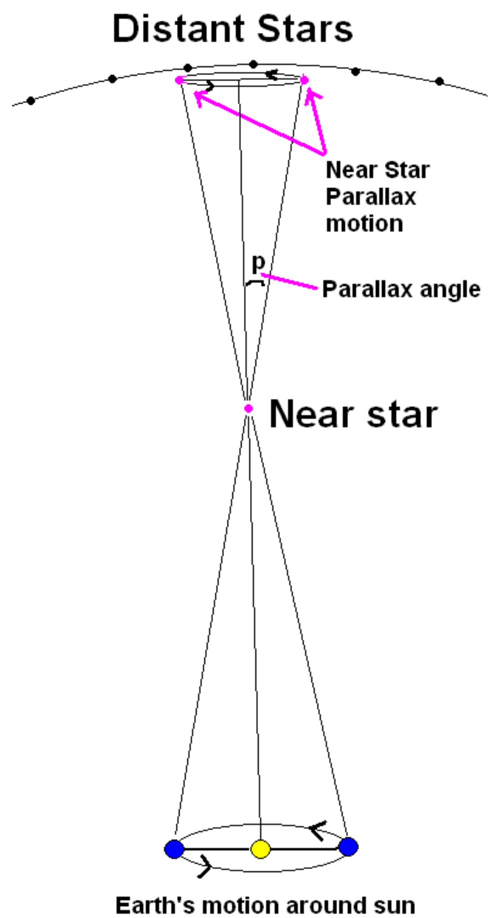

Figure 26.6: Parallax is used to measure the distance to stars that are relatively nearby. (2)

- The color of a star is determined by its surface temperature.
- Stars are classified by color and temperature. The most common system uses the letters O (blue), B (bluish white), A (white), F (yellowish white), G (yellow), K (orange), and M (red), from hottest to coolest.
- Stars form from clouds of gas and dust called nebulas. Stars collapse until nuclear fusion starts in the core.
- Stars spend most of their lives on the main sequence, fusing hydrogen into helium.
- Typical, Sun-like stars expand into red giants, then fade out as white dwarfs.
- Very large stars expand into red supergiants, explode in supernovas, then end up as neutron stars or black holes.
- Astronomical distances can be measured in light-years. A light year is the distance that light travels in one year. 1 light-year = 9.5 trillion kilometers (5.9 trillion miles).
- Parallax is an apparent shift in an object's position when the position of the observer changes. Astronomers use parallax to measure the distance to relatively nearby stars.

Review Questions

1. What distinguishes a nebula and a star?
2. What kind of reactions provide a star with energy?
3. Which has a higher surface temperature: a blue star or a red star?
4. List the seven main classes of stars, from hottest to coolest.
5. What is the primary reaction that occurs in the core of a star, when the star is on the main sequence?
6. What kind of star will the Sun be after it leaves the main sequence?
7. Suppose a large star explodes in a supernova, leaving a core that is 10 times the mass of the Sun. What would happen to the core of the star?
8. What is the definition of a light-year?
9. Why don't astronomers use parallax to measure the distance to stars that are very far away?

Further Reading / Supplemental Links

- http://www.ianridpath.com/startales/contents.htm
- http://hsci.cas.ou.edu/exhibits/exhibit.php?exbgrp=3&exbid=20&exbpg=0
- http://www.nasa.gov/worldbook/star_worldbook.html
- http://imagine.gsfc.nasa.gov/docs/science/know_l1/stars.html
- http://www.spacetelescope.org/science/formation_of_stars.html
- http://hurricanes.nasa.gov/universe/science/stars.html
- http://starchild.gsfc.nasa.gov/docs/StarChild/questions/parallax.html
- http://imagine.gsfc.nasa.gov/YBA/HTCas-size/parallax1-more.html

- http://www-spof.gsfc.nasa.gov/stargaze/Sparalax.
- http://www.youtube.com/watch?v=VMnLVkV_ovc

Vocabulary

asterism A group or cluster of stars that appear close together in the sky.

black hole The super dense core left after a supergiant explodes as a supernova.

constellation An apparent pattern of stars in the night sky.

light-year The distance that light travels in one year; 9.5 trillion kilometers.

main sequence star A star that is fusing hydrogen atoms to helium; a star in the main portion of its "life."

nebula An interstellar cloud of gas and dust.

neutron star The remnant of a massive star after it explodes as a supernova.

nuclear fusion reaction When nuclei of two atoms fuse together, giving off tremendous amounts of energy.

parallax A method used by astronomers to calculate the distance to nearby stars, using the apparent shift relative to distant stars.

red giant Stage in a star's development when the inner helium core contracts while the outer layers of hydrogen expand.

supernova A tremendous explosion that occurs when the core of a star is mostly iron.

star A glowing sphere of gases that produces light through nuclear fusion reactions.

Points to Consider

- Although stars may appear to be close together in constellations, they are usually not close together out in space. Can you think of any groups of astronomical objects that are relatively close together in space?
- Most nebulas contain more mass than a single star. If a large nebula collapsed into several different stars, what would the result be like?

26.2 Galaxies

Lesson Objectives

- Distinguish between star systems and star clusters.
- Identify different types of galaxies.
- Describe our own galaxy, the Milky Way Galaxy.

Introduction

Compared to your neighborhood, your country, or even planet Earth, the solar system is an extremely big place. But there are even bigger systems in the universe; groups of two, two hundred, or two billion stars! Small groups of stars are called star systems, and somewhat larger groups are called star clusters. There are even larger groups of stars, called galaxies. Our solar system is in the Milky Way Galaxy, which is just one galaxy in the universe. There are several different types of galaxies and there are possibly billions of galaxies in the universe.

Star Systems and Star Clusters

Constellations are patterns of stars that we see in the same part of the night sky, but these stars may not be close together at all out in space. However, some stars are actually grouped closely together in space. These small groups of stars are called **star systems** and larger groups of hundreds or thousands of stars are called **star clusters.**

Star Systems

Our solar system has only one star, the Sun. But many stars—in fact, more than half of the bright stars in our galaxy—are in systems of two or more stars. A system of two stars orbiting each other is called a **binary star**. A system with more than two stars is called a *multiple star system*. In a multiple star system, each of the stars orbits around the others.

Often, the stars in a multiple star system are so close together that you can only tell there are multiple stars using binoculars or a telescope. **Figure** 26.7 shows Sirius A, the brightest star in the sky. Sirius A is a very large star. If you look to the lower left of Sirius A in the figure, you can see a much smaller star. This is Sirius B, a white dwarf companion to Sirius A.

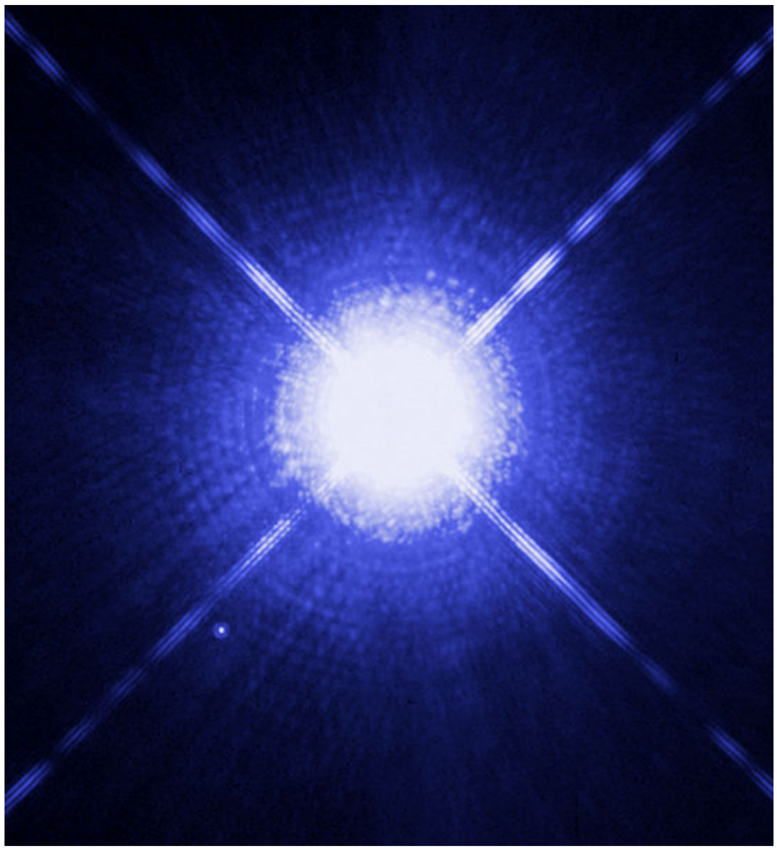

Figure 26.7: The bright star Sirius is actually a binary system with one large star (Sirius A) and one small star (Sirius B). This image from the Hubble Space Telescope shows Sirius B to the lower left of Sirius A. As you might guess, Sirius A is much, much brighter than Sirius B. Sirius B once was brighter than its companion, but it became a red giant and collapsed into its current dim state about 100-125 million years ago. (4)

Star Clusters

Star clusters are divided into two main types, **open clusters** and **globular clusters**. Open clusters are groups of up to a few thousand stars that are loosely held together by gravity. The Pleiades, shown in **Figure** 26.8, is a well-known open cluster. The Pleiades are also called the Seven Sisters, because you can see seven stars in the cluster without a telescope, but with good vision. Using a telescope reveals that the Pleiades has close to a thousand stars.

Figure 26.8: The Pleiades is an open cluster containing several hundred stars surrounded by gas. Note that the stars are mostly blue. (5)

Open clusters tend to be blue in color and often contain glowing gas and dust. That is because the stars in an open cluster are young stars that formed from the same nebula. Eventually, the stars may be pulled apart by gravitational attraction to other objects.

Figure 26.9 shows an example of a globular cluster. Globular clusters are groups of tens to hundreds of thousands of stars held tightly together by gravity. Unlike open clusters, globular clusters have a definite, spherical shape. Globular clusters contain mostly old, reddish stars. As you get closer to the center of a globular cluster, the stars are closer together. Globular clusters don't have much dust in them — the dust has already formed into stars.

Types of Galaxies

The biggest groups of stars are called **galaxies.** Galaxies can contain anywhere from a few million stars to many billions of stars. Every star you can see in the sky is part of the Milky Way Galaxy, the galaxy we live in. Other galaxies are extremely far away, much farther away

Figure 26.9: M80 is a large globular cluster containing hundreds of thousands of stars. Note that the cluster is spherical and contains mostly red stars. (8)

than even the most distant stars you can see. The closest major galaxy—the Andromeda Galaxy, shown in **Figure** 26.10—looks like only a dim, fuzzy spot to the naked eye. But that fuzzy spot contains one trillion stars; that is a thousand billion, or 1,000,000,000,000 stars!

Figure 26.10: The Andromeda Galaxy is the closest major galaxy to our own. Andromeda is a large spiral galaxy that contains about a trillion stars. (3)

Spiral Galaxies

Galaxies are divided into three types according to shape: spiral galaxies, elliptical galaxies, and irregular galaxies. **Spiral galaxies** rotate or spin, so they have a rotating disk of stars and dust, a bulge in the middle, and several arms spiraling out from the center. Spiral galaxies have lots of gas and dust and lots of young stars. **Figure** 26.11 shows a spiral galaxy from the side, so you can see the disk and central bulge.

Figure 26.12 shows a spiral galaxy face-on, so you can see the spiral arms. The spiral arms of a galaxy contain lots of dust. New stars form from this dust. Because they contain lots of young stars, spiral arms tend to be blue.

Elliptical Galaxies

Figure 26.13 shows a typical **elliptical galaxy**. As you might have guessed, elliptical galaxies are elliptical, or egg-shaped. The smallest elliptical galaxies are as small as some globular clusters. *Giant elliptical galaxies*, on the other hand, can contain over a trillion stars. Elliptical galaxies are reddish to yellowish in color because they contain mostly old stars.

Figure 26.11: The Sombrero Galaxy is a spiral galaxy that we see from the side. (1)

Figure 26.12: The Pinwheel Galaxy is a spiral galaxy we see face-on. Note the blue spiral arms. (14)

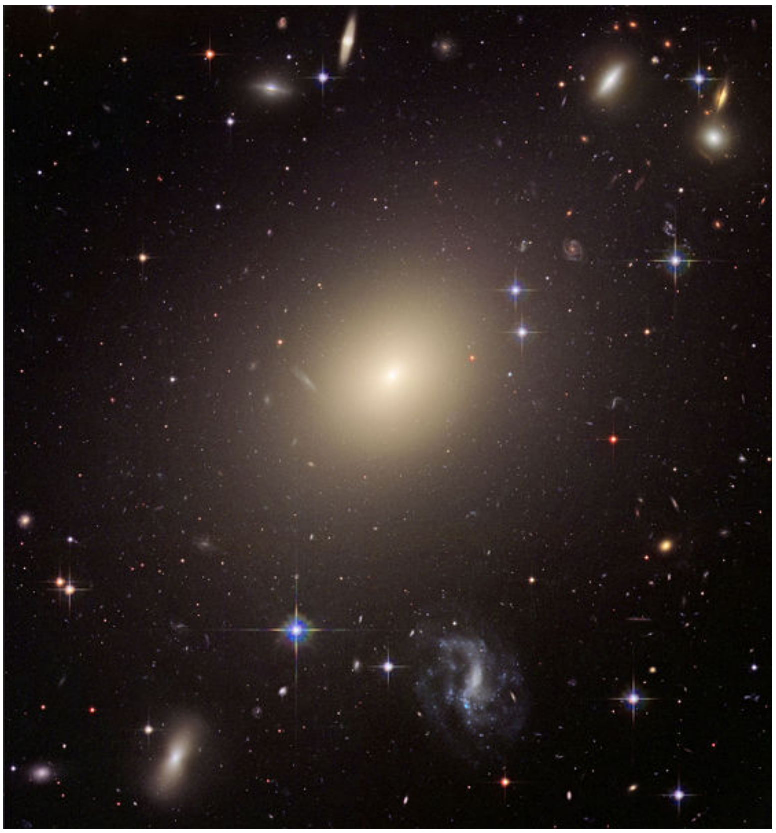

Figure 26.13: The large, reddish-yellow object in the middle of this figure is a typical elliptical galaxy. Can you find other galaxies in the figure? What kind? (7)

Typically, elliptical galaxies contain very little gas and dust because the gas and dust has already formed into stars. However, some elliptical galaxies, like the one shown in **Figure** 26.14, contain lots of dust. Astronomers believe that these dusty elliptical galaxies form when two galaxies of similar size collide.

Figure 26.14: This elliptical galaxy probably formed when two galaxies of similar size collided with each other. (9)

Irregular Galaxies and Dwarf Galaxies

Look at the galaxy in **Figure** 26.15. Do you think this is a spiral galaxy or an elliptical galaxy? It is neither one! Galaxies that are not clearly elliptical galaxies or spiral galaxies are called **irregular galaxies**. Most irregular galaxies were once spiral or elliptical galaxies that were then deformed either by gravitational attraction to a larger galaxy or by a collision with another galaxy.

Dwarf galaxies are small galaxies containing "only" a few million to a few billion stars. Most dwarf galaxies are irregular in shape. However, there are also *dwarf elliptical galaxies* and *dwarf spiral galaxies*. Dwarf galaxies are the most common type in the universe. However, because they are relatively small and dim, we don't see as many dwarf galaxies as we do their full-sized cousins.

Figure 26.15: This galaxy, called NGC 1427A, is an irregular galaxy. It has neither a spiral nor an elliptical shape. (15)

Look back at **Figure 4**. In the figure, you can see two dwarf elliptical galaxies that are companions to the Andromeda Galaxy. One is a bright sphere to the left of center, and the other is a long ellipse below and to the right of center. Dwarf galaxies are often found near larger galaxies. They sometimes collide with and merge into their larger neighbors.

The Milky Way Galaxy

If you look up in the sky on a very clear night, you may see a milky band of light stretching across the sky, as in **Figure** 26.16. This band is called the **Milky Way**, and it consists of millions of stars along with a lot of gas and dust. This band is the disk of a galaxy, the **Milky Way Galaxy**, which is our galaxy. The Milky Way Galaxy looks different to us than other galaxies because we are actually living inside of it!

Figure 26.16: The band of light called the Milky Way can be seen on a clear, dark night. Looking at this band, you are looking along the main disk of our galaxy. (19)

Shape and Size

Because we live inside the Milky Way Galaxy, it is hard to know exactly what it looks like. But astronomers believe the Milky Way Galaxy is a typical spiral galaxy that contains about 100 billion to 400 billion stars. **Figure** 26.17 shows what our Galaxy would probably look like if seen from the outside.

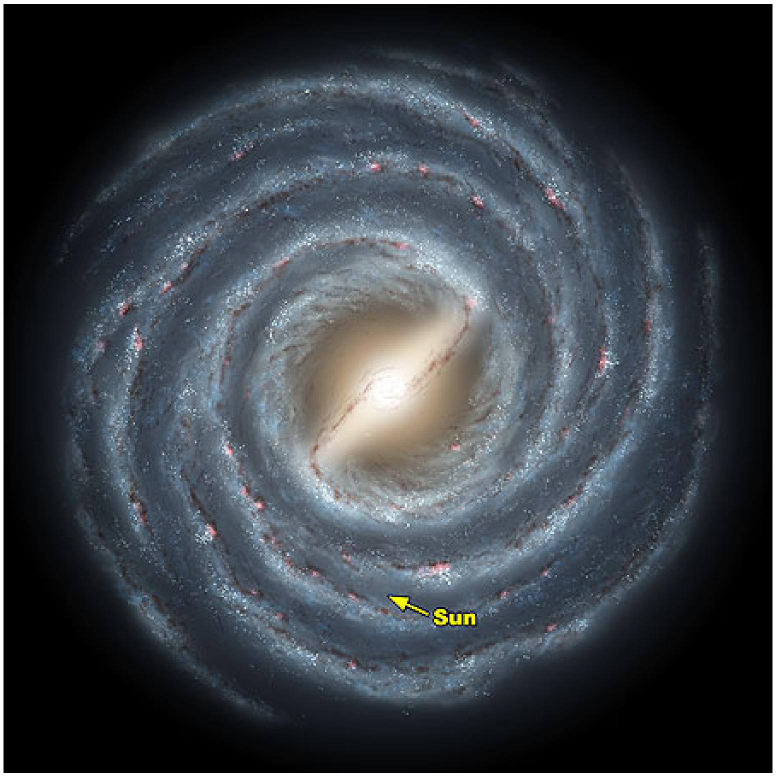

Figure 26.17: This artist's rendering shows what we currently think the Milky Way Galaxy would look like seen from above. The Sun and solar system (and you!) are a little more than halfway out from the center. (10)

Like other spiral galaxies, our galaxy has a disk, a central bulge, and spiral arms. The disk is about 100,000 light-years across and 3,000 light-years thick. Most of the Galaxy's gas, dust, young stars, and open clusters are in the disk.

The central bulge is about 12,000 to 16,000 light-years wide and 6,000 to 10,000 light-years thick. The central bulge contains mostly older stars and globular clusters. Some recent evidence suggests the bulge might not be spherical, but is instead shaped like a bar. The bar might be as long as 27,000 light-years long. The disk and bulge are surrounded by a faint, spherical halo, which also contains old stars and globular clusters. Some astronomers believe there is a gigantic black hole at the center of the Galaxy.

The Milky Way Galaxy is a big place. If our solar system were the size of your fist, the

Galaxy's disk would still be wider than the entire United States!

Where We Are

Our solar system, including the Sun, Earth, and all the other planets, is within one of the spiral arms in the disk of the Milky Way Galaxy. Most of the stars we see in the sky are relatively nearby stars, that are also in this spiral arm. We are about 26,000 light years from the center of the Galaxy. In other words, we live a little more than halfway out from the center of the Galaxy to the edge, as shown in **Figure 11**.

Just as Earth orbits the Sun, the Sun and solar system orbit the center of the Galaxy. One orbit of the solar system takes about 225 to 250 million years. The solar system has orbited 20 to 25 times since it formed 4.6 billion years ago.

Lesson Summary

- Most stars are in systems of two or more stars.
- Open clusters are groups of young stars loosely held together by gravity.
- Globular clusters are spherical groups of old stars held tightly together by gravity.
- Galaxies are collections of millions to many billions of stars.
- Spiral galaxies have a rotating disk of stars and dust, a bulge in the middle, and several arms spiraling out from the center. The disk and arms contain many young, blue stars.
- Typical elliptical galaxies are egg-shaped, reddish, and contain mostly old stars.
- Galaxies that are not elliptical or spiral galaxies are called irregular galaxies. Often these galaxies were deformed by other galaxies.
- The band of light called the Milky Way is the disk of our galaxy, the Milky Way Galaxy, which is a typical spiral galaxy.
- Our solar system is in a spiral arm of the Milky Way Galaxy, a little more than halfway from the center to the edge of the disk. Most of the stars we see are in our spiral arm.

Review Questions

1. What is a binary star?
2. Compare globular clusters with open clusters.
3. Name the three main types of galaxies.
4. List three main features of a spiral galaxy.
5. Suppose you see a round galaxy that is reddish in color and contains very little dust. What kind of galaxy is it?
6. What galaxy do we live in, and what kind of galaxy is it?
7. Describe the location of our solar system in our galaxy.

Further Reading / Supplemental Links

- http://www.cfa.harvard.edu/press/2006/pr200611.html
- http://hypertextbook.com/facts/2000/MarissaWager.shtml
- http://seds.lpl.arizona.edu/messier/more/mw.html
- http://www.space.com/scienceastronomy/050816_milky_way.html
- http://seds.org/messier/cluster.html; http://hubblesite.org/newscenter/archive/releases/star-cluster/
- http://stardate.org/resources/btss/galaxies/; http://casswww.ucsd.edu/public/tutorial/Galaxies.html; http://www.smv.org/hastings/student1.htm
- http://en.wikipedia.org

Vocabulary

binary star One of two stars that orbit each other.

elliptical galaxy An oval or egg shaped galaxy with older stars and little gas and dust.

galaxy A very large group of stars held together by gravity; few million to a few billion stars.

globular cluster Groups of tens to hundreds of thousands of stars held together by gravity.

irregular galaxy A category of galaxy that is neither a spiral nor an elliptical galaxy.

Milky Way The name of our galaxy; also the whitish band of stars visible in the night sky.

open cluster Groups of up to a few thousand stars loosely held together by gravity.

spiral arm Regions of gas and dust plus young stars that wind outward from the central area of a spiral galaxy.

spiral galaxy A rotating type of galaxy with a central bulge and spiral arms with young stars, gas and dust.

star system Small groups of stars.

star cluster Larger groups of hundreds of thousands of stars.

Points to Consider

- Objects in the universe tend to be grouped together. What forces or factors do you think cause objects to form and stay in groups?
- Some people used to call galaxies "island universes." Are they really universes? Why or why not?
- Can you think of anything, either an object or a group of objects, that is bigger than a galaxy?

26.3 The Universe

Lesson Objectives

- Explain the evidence for an expanding universe.
- Describe the formation of the universe according to the Big Bang Theory.
- Define dark matter and dark energy.

So far we have talked about bigger and bigger systems, from stars to star systems to star clusters and galaxies. The **universe** contains all these systems, including all the matter and energy that exists now, that existed in the past, and that will exist in the future. The universe also includes all of space and time.

Our understanding of the universe has changed a lot over time. The ancient Greeks thought the universe contained only Earth at the center, the Sun, the Moon, five planets, and a sphere to which all the stars were attached. Most people had this basic idea of the universe for centuries, until Galileo first used a telescope to look at the stars. Then people realized that Earth is not the center of the universe, and there are many more stars than thought before. Even as recently as the early 1900s, some scientists still thought the universe was no larger than the Milky Way Galaxy.

In the early 20^{th} century, an astronomer named Edwin Hubble (**Figure** 26.18) discovered that the "Andromeda Nebula" is actually over 2 million light years away—many times farther than the farthest distances we had measured before. He realized that many of the objects astronomers called nebulas were not clouds of gas, but collections of millions or billions of stars—what we now call galaxies. Our view of the universe changed again—we now knew that the universe was much larger than our own galaxy. Today, we know that the universe contains about a hundred billion galaxies—about the same number of galaxies as there are stars in the Milky Way Galaxy.

Figure 26.18: Edwin Hubble used the 100-inch reflecting telescope at the Mount Wilson Observatory in California to show that some distant specks of light seen through telescopes are actually other galaxies. He also measured these distances to hundreds of galaxies, and discovered that the universe is expanding. (11)

Expansion of the Universe

After discovering that there are galaxies outside our own, Edwin Hubble went on to measure the distance to hundreds of other galaxies. His data would eventually show us how the universe is changing, and even give us clues as to how the universe formed.

Redshift

If you look at a star through a prism, you will see a **spectrum,** or a range of colors through the rainbow. Interestingly, the spectrum will have specific dark bands where elements in the star absorbed light of certain energies. By examining the arrangement of these dark absorption lines, astronomer can actually determine which elements are in a distant star. In fact, the element helium was first discovered in our Sun — not on Earth — by analyzing the absorption lines in the spectrum of the Sun.

When astronomers started to study the spectrum of light from distant galaxies, they noticed something strange. The dark lines in the spectrum were in the patterns they expected, but they were shifted toward the red end of the spectrum, as shown in **Figure** 26.19. This shift of absorption bands toward the red end of the spectrum is known as **redshift**.

Redshift occurs when the source of light is moving away from the observer. So when astronomers see redshift in the light from a galaxy, they know that the galaxy is moving away from Earth. The strange part is that almost every galaxy in the universe has a redshift, which means that almost every galaxy is moving away from us.

An analogy to redshift is the noise a siren makes as it passes by you. You may have noticed that an ambulance lowers the pitch of its siren after it passes you. The sound waves shift towards a lower pitch when the ambulance speeds away from you. Though redshift involves light instead of sound, a similar principle operates in both situations.

The Expanding Universe

Edwin Hubble combined his measurements of the distances to galaxies with other astronomers' measurements of redshift. He noticed a relationship, which is now called *Hubble's Law:* The farther away a galaxy is, the faster it is moving away from us. In other words, the universe is expanding!

Figure 26.20 shows a simplified diagram of the expansion of the universe. Another way to picture this is to imagine a balloon covered with tiny dots. Each dot represents a galaxy. When you inflate the balloon, the dots slowly move away from each other because the rubber stretches in the space between them. If it were a giant balloon and you were standing on one of the dots, you would see the other dots moving away from you. Not only that, but dots farther away from you on the balloon would move away faster than dots nearby.

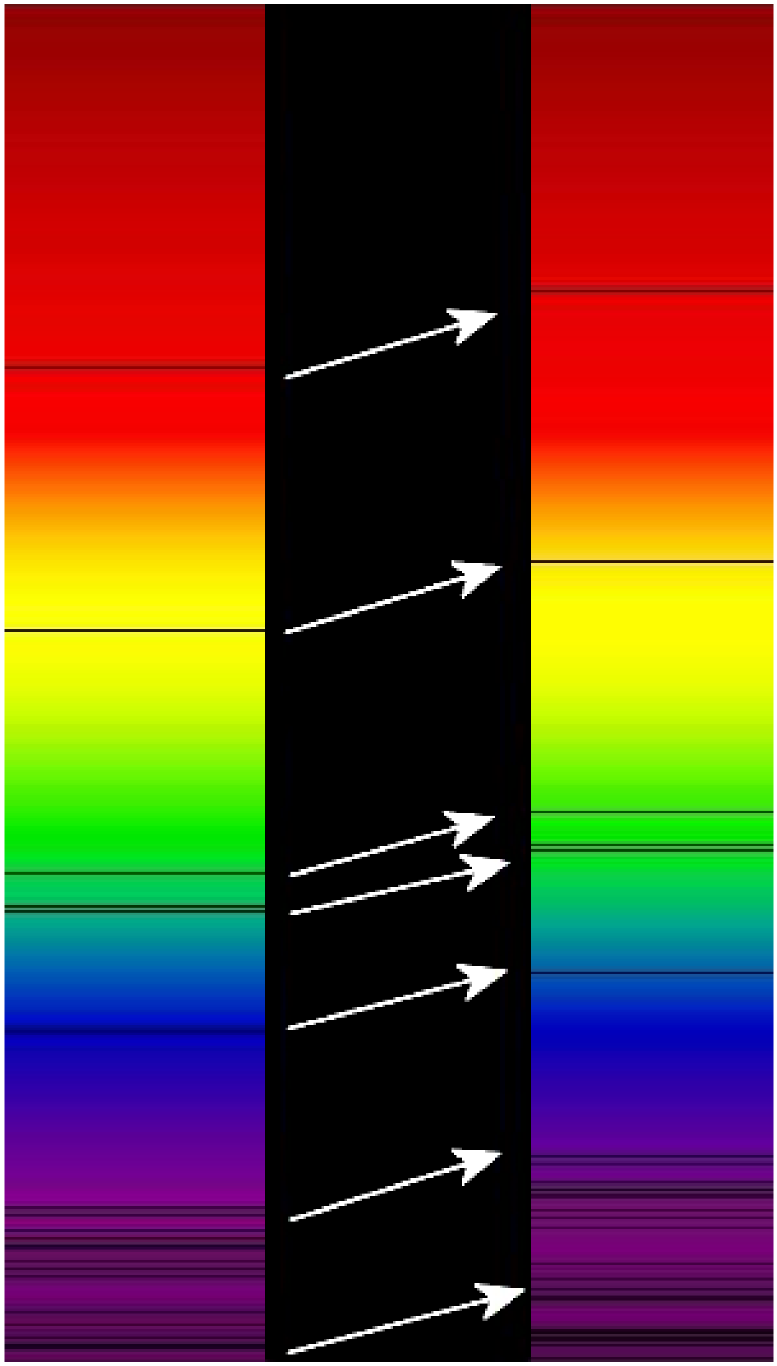

Figure 26.19: Redshift is a shift in absorption bands toward the red end of the spectrum. Redshift occurs when the light source is moving away from you or when the space between you and the source is stretched. (12)

Expansion of the universe diagram

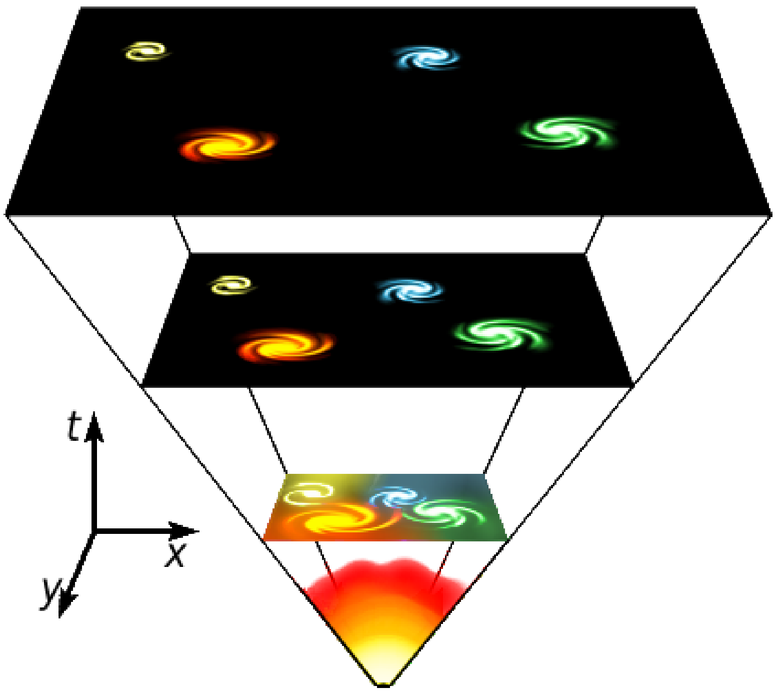

Figure 26.20: This is a simplified diagram of the expansion of the universe over time. Note that the distance between galaxies gets bigger as you go forward in time, but the size of each galaxy stays about the same. (17)

An inflating balloon is not exactly like the expanding universe. For one thing, the surface of a balloon has only two dimensions, while space has three dimensions. But it is true that space itself is stretching out between galaxies like the rubber stretches when a balloon is inflated. This stretching of space, which causes the distance between galaxies to increase, is what astronomers mean by the expansion of the universe.

One other difference between the universe and our balloon model involves the actual size of the galaxies. On the inflating balloon, the dots you made will become larger in size as you inflate it. In our universe, however, the galaxies stay the same size; it is just the space between the galaxies that increases as the universe expands.

Formation of the Universe

The discovery that the universe is expanding also told astronomers something about how the universe might have formed. Before this discovery, there were many ideas about the universe, most of them thinking of the universe as constant. Once scientists learned that the universe is expanding, the next logical thought is that at one time it had to have been smaller.

The Big Bang Theory

The Big Bang theory is the most widely accepted scientific explanation of how the universe formed. To understand this theory, start by picturing the universe expanding steadily. Then, reverse the direction of time, like pressing the "rewind" button on a video player. Now the universe is contracting, getting smaller and smaller. If you go far enough back in time, you will reach a point when the universe was squeezed into a very small volume.

According to the Big Bang theory, the universe began about 13.7 billion years ago, when everything in the universe was squeezed into a very small volume, as described above. There was an enormous explosion—a big bang—which caused the universe to start expanding rapidly. All the matter and energy in the universe—and even space itself—came out of this explosion.

After the Big Bang

In the first few moments after the Big Bang, the universe was extremely hot and dense. As the universe expanded, it became less dense and it cooled. After only a few seconds, the universe had cooled enough that protons, neutrons, and electrons could form. After a few minutes, hydrogen could form and the energy in the universe was great enough to allow for nuclear fusion, creating helium atoms in the same way we learned that a star can make helium out of hydrogen atoms, even though there were no stars at this point in the universe's history. The first neutral atoms with neutrons, protons, and electrons, did not form until about 380,000 years after the big bang.

The matter in the early universe was not smoothly distributed across space. Some parts of the universe were more dense than others. These clumps of matter were held close together by gravity. Eventually, these clumps became the gas clouds, stars, galaxies, and other structures that we see in the universe today.

Dark Matter and Dark Energy

The Big Bang theory is still the best scientific model we have for explaining the formation of the universe. However, recent discoveries in astronomy have shaken up our understanding of the universe. Astronomers and other scientists are now wrestling with some big unanswered questions about what the universe is made of and why it is expanding like it is.

Dark Matter

Most of the things we see out in space are objects that emit light, such as stars or glowing gases. When we see other galaxies, we are seeing the glowing stars or gases in that galaxy.

However, scientists think that matter that emits light only makes up a small part of the matter in the universe. The rest of the matter is called **dark matter**.

Because dark matter doesn't emit light, we can't observe it directly. However, we know it is there because its gravity affects the motion of objects around it. For example, when astronomers measure how spiral galaxies rotate, they find that the outside edges of a galaxy rotate at the same speed as parts closer to the center. This can only be explained if there is a lot of extra matter in a galaxy that we cannot see.

So what is dark matter? Actually, we don't really know. One possibility is that it could just be ordinary matter—protons, neutrons, and electrons, like what makes up the Earth and all the matter around us. The universe could contain lots of objects that don't have enough mass to glow on their own, such as large planets and *brown dwarfs*, objects larger than Jupiter but smaller than the smallest stars. Or, there could be large numbers of undetected black holes.

Another possibility is that the universe contains a lot of matter that is unlike anything we have ever encountered. For example, scientists have proposed that there might be particles that have mass but don't interact much with other matter. Scientists call these theoretical particles WIMPs, which stands for Weakly Interactive Massive Particles. WIMPs would have a gravitational effect on other matter because of their mass. But because they don't interact much with ordinary matter, they would be very difficult or impossible to detect directly.

Most scientists who study dark matter believe that the universe's dark matter is a combination of ordinary matter and some kind of exotic matter that we haven't discovered yet. Most scientists also think that ordinary matter is much less than half of the total matter in the universe. Researching dark matter is clearly an active area of scientific research, and astronomers' knowledge about dark matter changing rapidly.

Dark Energy

Astronomers who study the expansion of the universe are interested in finding out just how fast the universe is expanding. For years, the big question was whether the universe was expanding fast enough to overcome the attractive pull of gravity. If yes, then the universe would expand forever, although the expansion would slow down over time. If no, then the universe would someday start to contract, and eventually would get squeezed together in a *big crunch*, the opposite of the Big Bang.

Recently, however, these astronomers have made a strange discovery: the rate at which the universe is expanding is actually increasing. In other words, the universe is expanding faster now than ever before, and in the future it will expand even faster! This answers the old question: the universe will keep expanding forever. But it also proposes a perplexing new question: what is causing the expansion of the universe to accelerate?

One possible hypothesis involves a new, as-yet-undiscovered form of energy called **dark energy**. We know even less about dark energy than we know about dark matter. However, some scientists believe that dark energy makes up more than half the total content of the universe. Other scientists have other hypotheses about why the universe is continuing to expand; the causes of the universe's expansion is another unanswered question that scientists are researching.

Lesson Summary

- The universe contains all the matter and energy that exists now, that existed in the past, and that will exist in the future. The universe also includes all of space and time.
- Redshift is a shift of element lines toward the red end of the spectrum. Redshift occurs when the source of light is moving away from the observer.
- Light from almost every galaxy is redshifted. The farther away a galaxy is, the more its light is redshifted, and the faster it is moving away from us.
- The redshift of galaxies tells us that the universe is expanding.
- The current expansion of the universe suggests that in the past the universe was squeezed into a very small volume.
- The Big Bang theory proposes that the universe formed in an enormous explosion about 13.7 billion years ago.
- Recent evidence shows that there is a lot of matter in the universe that we cannot detect directly. This matter is called dark matter.
- The rate of the expansion of the universe is increasing. The cause of this increase is unknown; one possible explanation involves a new form of energy called dark energy.

Review Questions

1. What is redshift, and what causes it to occur?
2. What is Hubble's law?
3. What is the most widely accepted scientific theory of the formation of the universe called?
4. How old is the universe, according to the Big Bang theory?
5. Describe two different possibilities for the nature of dark matter.
6. What makes scientists believe that dark matter exists?
7. What observation caused astronomers to propose the existence of dark energy?

Further Reading / Supplemental Links

- http://cdms.berkeley.edu/Education/DMpages/index.shtml
- http://stardate.org/resources/btss/cosmology/
- http://hurricanes.nasa.gov/universe/science/bang.html

- http://imagine.gsfc.nasa.gov/docs/science/know_l1/dark_matter. html
- http://www.youtube.com/watch?v=gCgTJ6ID6ZA
- http://en.wikipedia.org

Vocabulary

Big Bang Theory The hypothesis that all matter and energy were at one time compresses into a very small volume; then there was an explosion that sent everything moving outward, causing the universe to expand.

dark energy An as yet undiscovered form of energy that we cannot see.

dark matter Matter in the universe that doesn't emit light.

redshift Shift of wavelengths of light towards the red end of the spectrum; happens as a light source moves away from us.

universe Everything that exists; all matter and energy; also includes all of space and time.

Points to Consider

- The expansion of the universe is sometimes modeled using a balloon with dots marked on it, as described earlier in the lesson. In what ways is this a good model, and it what ways does it not correctly represent the expanding universe? Can you think of a different way to model the expansion of the universe?
- The Big Bang theory is currently the most widely accepted scientific theory for how the universe formed. What is another explanation of how the universe could have formed? Is your explanation one that a scientist would accept?

Image Sources

(1) NASA. http://en.wikipedia.org/wiki/Image:M104_ngc4594_sombrero_galaxy_hi-res.jpg. GNU-FDL.

(2) http://commons.wikimedia.org/wiki/Image:Stellarparallax2.png. Public Domain.

(3) http://en.wikipedia.org/wiki/Image:M31_Lanoue.png. Public Domain.

(4) NASA. http://en.wikipedia.org/wiki/Image:Sirius_A_and_B_Hubble_photo.jpg. Public Domain.

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(11) NASA. http://quest.arc.nasa.gov/hst/about/edwin.html. Public Domain.

(12) Harold T. Stokes, Ian Tresman, Georg Wiora. http://en.wikipedia.org/wiki/Image:Redshift.png. CC-BY-SA and GNU-FDL.

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