FUNDAMENTALS OF GEOLOGY



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Book: Fundamentals of Geology (Schulte)

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1: SCIENCE OF GEOLOGY

Learning Objectives

Define geology as a science and identify methods used in its study.

- Define the science of geology.
- Identify and use scientific processes and the scientific methods as used by geologists and with other related scientific disciplines.
- List tools and concepts commonly used by geologists.

Geology is the study of the solid Earth. Geologists study how rocks and minerals form. The way mountains rise up is part of geology. The way mountains erode away is another part. Geologists also study fossils and Earth's history. There are many other branches of geology. There is so much to know about our home planet that most geologists become specialists in one area. For example, a mineralogist studies minerals.

1.1: Why It Matters

1.2: What is Geology?

1.3: The Science of Geology

1.4: Scientific Processes in Geology

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1.6: Putting it Together

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1.1: Why It Matters

DEFINE GEOLOGY AS A SCIENCE AND UNDERSTAND THE BASIC METHODS OF SCIENCE USED IN GEOLOGY AND RELATED SCIENTIFIC DISCIPLINES

Introduction

When you ask the question “What is geology?” most people will initially respond that it is the study of rocks. This is true, but geology is also so much more than that. What if I told you geology is an intricate part of your everyday life? You may have to stop and think for a minute about that statement, but let’s consider the following questions:

1. Where do your energy resources come from—not just the gas in car, but the components in your cell phones and tablets as well?
2. Why does Japan have so many active volcanoes and earthquakes?
3. Do you enjoy eating or cooking or gardening?
4. Do you enjoy bottled, spring, or tap water?

While some of those questions are obviously geology related, it may take so exploring to find the answers to all of them. Throughout the course, you will learn the information necessary to answer these questions and others like them. We will see that geology is not just rocks but is far more encompassing than that. However, I can’t let this introduction go by without saying GEOLOGY ROCKS!

Learning Outcomes

- Define the science of geology
- Identify and use scientific processes and the scientific methods as used by geologists and with other related scientific disciplines.

Ok, let's get started!

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1.2: What is Geology?

DEFINE THE SCIENCE OF GEOLOGY

[Insert brief introductory statement here.]

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- Reading: The Science of Geology

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1.3: The Science of Geology

INTRODUCTION

Earth Science is the study of all aspects of our planet Earth. Earth Science is not just about the molten lava, icy mountain peaks, steep canyons and towering waterfalls of the continents. Earth Science includes the atmosphere and oceans. The field also looks out into the solar system, galaxy, and universe. Earth scientists seek to understand the beautiful planet on which we depend (figure 1).



Figure 1

Different branches of Earth Science study one particular part of Earth. Since all of the branches are connected, 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 Earth. Geologists study how rocks and minerals form. The way mountains rise up is part of geology. The way mountains erode away is another part. Geologists also study fossils and Earth's history. There are many other branches of geology. There is so much to know about our home planet that most geologists become specialists in one area. For example, a mineralogist studies minerals, as seen in (figure 2).



Figure 2. (A) Mineralogists focus on all kinds of minerals. (B) Seismographs are used to measure earthquakes and pinpoint their origins.

Some volcanologists brave molten lava to study volcanoes. Seismologists monitor earthquakes worldwide to help protect people and property from harm (figure 2). Paleontologists are interested in fossils and how ancient organisms lived. Scientists who compare the geology of other planets to Earth are planetary geologists. Some geologists study the Moon. Others look for petroleum. Still others specialize in studying soil. Some geologists can tell how old rocks are and determine how different rock layers formed. There is probably an expert in almost anything you can think of related to Earth!

Geologists might study rivers and lakes, the underground water found between soil and rock particles, or even water that is frozen in glaciers. Earth scientists also need geographers who explore the features of Earth's surface and work with cartographers, who make maps. Studying the layers of rock beneath the surface helps us to understand the history of planet Earth (figure 3).



Figure 3. These folded rock layers have bent over time. Studying rock layers helps scientists to explain these layers and the geologic history of the area.

CLIMATOLOGY AND METEOROLOGY

Meteorologists don't study meteors—they study the atmosphere! The word "meteor" refers to things in the air. **Meteorology** includes the study of weather patterns, clouds, hurricanes, and tornadoes. Meteorology is very important. Using radars and satellites, meteorologists work to predict, or forecast, the weather (figure 4).



Figure 4. Meteorologists can help us to prepare for major storms or know if it's a good day for a picnic.

The atmosphere is a thin layer of gas that surrounds Earth. Climatologists study the atmosphere. These scientists work to understand the climate as it is now. They also study how climate will change in response to global warming.

The atmosphere contains small amounts of carbon dioxide. Climatologists have found that humans are putting a lot of extra carbon dioxide into the atmosphere. This is mostly from burning fossil fuels. The extra carbon dioxide traps heat from the Sun. Trapped heat causes the atmosphere to heat up. We call this global warming (figure 5).



Figure 5. Carbon dioxide released into the atmosphere is causing global warming.

LESSON SUMMARY

- Earth science includes many fields of science related to our home planet.
- Geology is the study of Earth's material and structures and the processes that create them.
- Meteorologists study the atmosphere including climate and weather.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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1.4: Scientific Processes in Geology

IDENTIFY AND USE SCIENTIFIC PROCESSES AND THE SCIENTIFIC METHODS AS USED BY GEOLOGISTS AND WITH OTHER RELATED SCIENTIFIC DISCIPLINES

[Insert brief introductory statement here.]

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- Reading: The Nature of Science

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1.5: The Nature of Science

INTRODUCTION

Sometime in your life you've asked a question about the world around you. Probably you've asked a lot of questions over the years. The best way to answer questions about the natural world is by using science. Scientists ask questions every day, and then use a set of steps to answer those questions. The steps are known as the scientific method. By following the scientific method, scientists come up with the best information about the natural world. As a scientist, you need to do experiments to find out about the world. You also need to wonder, observe, talk, and think. Everything we learn helps us to ask new and better questions.

SCIENTIFIC METHOD

The scientific method is a set of steps that help us to answer questions. When we use logical steps and control the number of things that can be changed, we get better answers. As we test our ideas, we may come up with more questions. The basic sequence of steps followed in the scientific method is illustrated in figure 1.

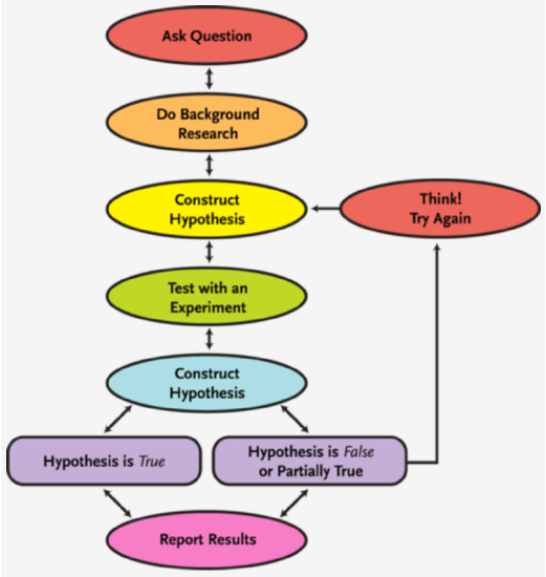


Figure 1. The Scientific Method

Questions

Asking a question is one really good way to begin to learn about the natural world. You might have seen something that makes you curious. You might want to know what to change to produce a better result. Let's say a farmer is having an erosion problem. She wants to keep more soil on her farm. The farmer learns that a farming method called "no-till farming" allows farmers to plant seeds without plowing the land. She wonders if planting seeds without plowing will reduce the erosion problem and help keep more soil on her farmland. Her question is this: "Will using the no-till method of farming help me to lose less soil on my farm?" (figure 2).



Figure 2. Soil is often lost from ground that has been plowed.

Research

Before she begins, the farmer needs to learn more about this farming method. She can look up information in books and magazines in the library. She may also search the Internet. A good way for her to learn is to talk to people who have tried this way of farming. She can use all of this information to figure out how she is going to test her question about no-till farming. Farming machines are shown in the figure 3.



Figure 3. Rather than breaking up soil like in this picture, the farmer could try no-till farming methods.

Hypothesis

After doing the research, the farmer will try to answer the question. She might think, “If I don’t plow my fields, I will lose less soil than if I do plow the fields. Plowing disrupts the soil and breaks up roots that help hold soil in place.” This answer to her question is a **hypothesis**. A hypothesis is a reasonable explanation. A hypothesis can be tested. It may be the right answer, it may be a wrong answer, but it must be testable. Once she has a hypothesis, the next step is to do experiments to test the hypothesis. A hypothesis can be proved or disproved by testing. If a hypothesis is repeatedly tested and shown to be true, then scientists call it a **theory**.

Experiment

When we design experiments, we choose just one thing to change. The thing we change is called the **independent variable**. In the example, the farmer chooses two fields and then changes only one thing between them. She changes how she plows her fields. One field will be tilled and one will not. Everything else will be the same on both fields: the type of crop she grows, the amount of water and fertilizer that she uses, and the slope of the fields she plants on. The fields should be facing the same direction to get about the same amount of sunlight. These are the experimental **controls**. If the farmer only changes how she plows her fields, she can see the impact of the one change. After the experiment is complete, scientists then measure the result. The farmer measures how much soil is lost from each field. This is the **dependent variable**. How much soil is lost from each field "depends" on the plowing method.

Data and Experimental Error

During an experiment, a scientist collects data. The data might be measurements, like the farmer is taking in figure 4. The scientist should record the data in a notebook or onto a computer. The data is kept in charts that are clearly labeled. Labeling helps the scientist to know what each number represents. A scientist may also write descriptions of what happened during the experiment. At the end of the experiment the scientist studies the data. The scientist may create a graph or drawing to show the data. If the scientist can picture the data the results may be easier to understand. Then it is easier to draw logical conclusions.

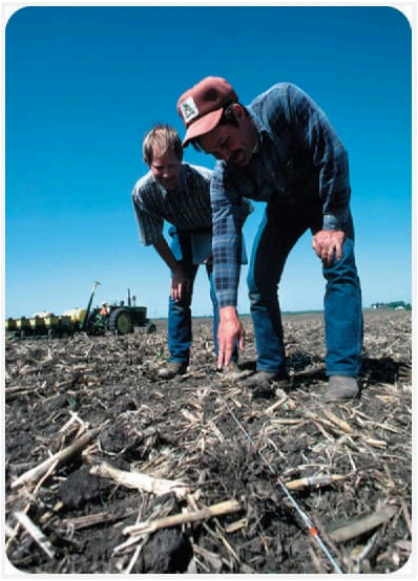


Figure 4. A pair of farmers take careful measurements in the field.

Even if the scientist is really careful it is possible to make a mistake. One kind of mistake is with the equipment. For example, an electronic balance may always measure one gram high. To fix this, the balance should be adjusted. If it can't be adjusted, each measurement should be corrected. A mistake can come if a measurement is hard to make. For example, the scientist may stop a stopwatch too soon or too late. To fix this, the scientist should run the experiment many times and make many measurements. The average of the measurements will be the accurate answer. Sometimes the result from one experiment is very different from the other results. If one data point is really different, it may be thrown out. It is likely a mistake was made in that experiment.

Conclusions

The scientist must next form a conclusion. The scientist must study all of the data. What statement best explains the data? Did the experiment prove the hypothesis? Sometimes an experiment shows that a hypothesis is correct. Other times the data disproves the hypothesis. Sometimes it's not possible to tell. If there is no conclusion, the scientist may test the hypothesis again. This time he will use some different experiments. No matter what the experiment shows the scientist has learned something. Even a disproved hypothesis can lead to new questions.

The farmer grows crops on the two fields for a season. She finds that 2.2 times as much soil was lost on the plowed field as compared to the unplowed field. She concludes that her hypothesis was correct. The farmer also notices some other differences

in the two plots. The plants in the no-till plots are taller. The soil moisture seems higher. She decides to repeat the experiment. This time she will measure soil moisture, plant growth, and the total amount of water the plants consume. From now on she will use no-till methods of farming. She will also research other factors that may reduce soil erosion.

Theory

When scientists have the data and conclusions, they write a paper. They publish their paper in a scientific journal. A journal is a magazine for the scientists who are interested in a certain field. Before the paper is printed, other scientists look at it to try to find mistakes. They see if the conclusions follow from the data. This is called peer review. If the paper is sound it is printed in the journal.

Other papers are published on the same topic in the journal. The evidence for or against a hypothesis is discussed by many scientists. Sometimes a hypothesis is repeatedly shown to be true and never shown to be false. The hypothesis then becomes a theory. Sometimes people say they have a "theory" when what they have is a hypothesis.

In science, a theory has been repeatedly shown to be true. A theory is supported by many observations. However, a theory may be disproved if conflicting data is discovered. Many important theories have been shown to be true by many observations and experiments and are extremely unlikely to be disproved. These include the theory of plate tectonics and the theory of evolution.

SCIENTIFIC MODELS

Scientists use models to help them understand and explain ideas. Models explain objects or systems in a more simple way. Models often only show only a part of a system. The real situation is more complicated. Models help scientists to make predictions about complex systems. Some models are something that you can see or touch. Other types of models use an idea or numbers. Each type is useful in certain ways.

Scientists create models with computers. Computers can handle enormous amounts of data. This can more accurately represent the real situation. For example, Earth's climate depends on an enormous number of factors. Climate models can predict how climate will change as certain gases are added to the atmosphere. To test how good a model is, scientists might start a test run at a time in the past. If the model can predict the present it is probably a good model. It is more likely to be accurate when predicting the future.

Physical Models

A **physical model** is a representation of something using objects. It can be three-dimensional, like a globe. It can also be a two-dimensional drawing or diagram. Models are usually smaller and simpler than the real object. They most likely leave out some parts, but contain the important parts. In a good model the parts are made or drawn to scale. Physical models allow us to see, feel and move their parts. This allows us to better understand the real system.

An example of a physical model is a drawing of the layers of Earth (figure 5). A drawing helps us to understand the structure of the planet. Yet there are many differences between a drawing and the real thing. The size of a model is much smaller, for example. A drawing also doesn't give good idea of how substances move. Arrows showing the direction the material moves can help. A physical model is very useful but it can't explain the real Earth perfectly.

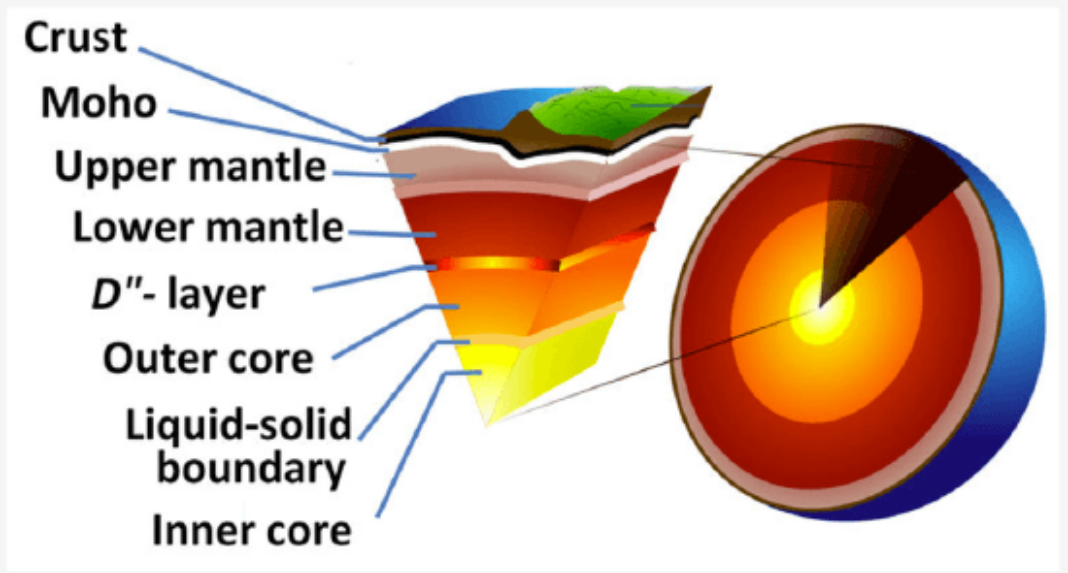


Figure 5. Earth's Center.

Ideas as Models

Some models are based on an idea that helps scientists explain something. A good idea explains all the known facts. An example is how Earth got its Moon. A Mars-sized planet hit Earth and rocky material broke off of both bodies (figure 6). This material orbited Earth and then came together to form the Moon. This is a model of something that happened billions of years ago. It brings together many facts known from our studies of the Moon's surface. It accounts for the chemical makeup of rocks from the Moon, Earth, and meteorites. The physical properties of Earth and Moon figure in as well. Not all known data fits this model, but much does. There is also more information that we simply don't yet know.



Figure 6. A collision showing a meteor striking Earth.

Models that Use Numbers

Models may use formulas or equations to describe something. Sometimes math may be the only way to describe it. For example, equations help scientists to explain what happened in the early days of the universe. The universe formed so long ago that math is the only way to describe it. A climate model includes lots of numbers, including temperature readings, ice density, snowfall levels, and humidity. These numbers are put into equations to make a model. The results are used to predict future climate. For example,

if there are more clouds, does global temperature go up or down? Models are not perfect because they are simple versions of the real situation. Even so, these models are very useful to scientists. These days, models of complex things are made on computers.

LESSON SUMMARY

- Scientists ask questions about the natural world.
- Scientific method is a set of logical steps that can be used to answer these questions.
- A hypothesis is a reasonable explanation of something.
- A theory is a hypothesis that has been shown to be true many times over.
- Models represent real things but are simpler.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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1.6: Putting it Together

SUMMARY

In this section, you learned the following:

1. The extensive definition of geology
2. The various fields within geology and what they study
3. How scientists use the scientific method to answer questions

SYNTHESIS

While we have not thoroughly answered our questions from the beginning of the outcome, we should be able to understand the connection these questions have to geology. We now know that geology is more than rocks—it deals with the resources we use in our everyday life, and it explains why some areas are more tectonically active than others. As we move through the course, keep these questions in mind.

So let's get started on this course and see why geology *rocks*.

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2: ROCK FORMING MINERALS

Learning Objectives

Identify processes of the rock cycle and the different rock types associated with each step.

- Identify igneous rocks and the steps of the rock cycle related to their formation.
- Identify sedimentary rocks and the steps of the rock cycle related to their formation.
- Identify metamorphic rocks and the steps of the rock cycle related to their formation.

One of the related fields of geology is mineralogy: the study of minerals. Geologists rely on minerals for many reasons. Not only are some minerals considered resources we use, such as gypsum, but they are the basis for the formation of rocks. Minerals are classified in different ways based on the elements that they contain. Matter (elements) makes up the minerals and minerals make up rocks. We can't understand rocks and rock forming process or some of the other areas of geology until we have a basic knowledge of minerals.

2.1: Why It Matters

2.2: Identifying Minerals

2.3: Mineral Identification

2.4: Mineral Basics

2.5: Mineral Chemistry

2.6: Classes of Minerals

2.7: Most Common Elements

2.8: Abundance of Elements in Earth's Crust

2.9: Putting It Together

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2.1: Why It Matters

IDENTIFY AND COMPARE COMMON ROCK FORMING MINERALS, INTERPRET AND UNDERSTAND MINERAL STRUCTURES, MINERAL PROPERTIES

One of the related fields of geology is mineralogy: the study of minerals. Geologists rely on minerals for many reasons. Not only are some minerals considered resources we use, such as gypsum, but they are the basis for the formation of rocks. Minerals are classified in different ways based on the elements that they contain. Matter (elements) makes up the minerals and minerals make up rocks. We can't understand rocks and rock forming process or some of the other areas of geology until we have a basic knowledge of minerals.

Occupation Focus: Mineralogist

Mineralogists specialize in minerals—their identification, their chemistry, and their formation. Mineralogists work can work in laboratories, in museums, for corporations, or for the government, but they mainly work "in the field." It is not uncommon to find them in very remote locations such as caves. They can focus on mineral identification for resource locations, the economic value of the mineral such as diamonds, they can examine the chemical content of minerals to help learn about the interior of the Earth and the various geologic processes. Regardless of what they area they are focusing on, mineralogists need a solid foundation in both chemistry and geology.

Learning Outcomes

- Identify and classify common rock forming minerals
- Define the key characteristics of minerals versus other materials
- Compare the most common elements in the Earth's crust and their order of abundance

Ok, let's get started!

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2.2: Identifying Minerals

IDENTIFY AND CLASSIFY COMMON ROCK FORMING MINERALS

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Mineral Identification
- Reading: Mineral Basics

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2.3: Mineral Identification

INTRODUCTION

Minerals can be identified by their physical characteristics. The physical properties of minerals are related to their chemical composition and bonding. Some characteristics, such as a mineral's hardness, are more useful for mineral identification. Color is readily observable and certainly obvious, but it is usually less reliable than other physical properties.

HOW ARE MINERALS IDENTIFIED?

Mineralogists are scientists who study minerals. One of the things mineralogists must do is identify and categorize minerals. While a mineralogist might use a high-powered microscope to identify some minerals, most are recognizable using physical properties.



Figure 1. This mineral has shiny, gold, cubic crystals with striations, so it is pyrite.

Check out the mineral in figure 1. What is the mineral's color? What is its shape? Are the individual crystals shiny or dull? Are there lines (striations) running across the minerals? In this lesson, the properties used to identify minerals are described in more detail.

COLOR, STREAK, AND LUSTER

Diamonds are popular gemstones because the way they reflect light makes them very sparkly. Turquoise is prized for its striking greenish-blue color. Notice that specific terms are being used to describe the appearance of minerals.

Color

Color is rarely very useful for identifying a mineral. Different minerals may be the same color. Real gold, as seen in figure 2, is very similar in color to the pyrite in figure 1.



Figure 2. This mineral is shiny, very soft, heavy, and gold in color, and is actually gold.

The same mineral may also be found in different colors. Figure 3 shows one sample of quartz that is colorless and another quartz that is purple. A tiny amount of iron makes the quartz purple. Many minerals are colored by chemical impurities.



Figure 3. Purple quartz, known as amethyst, and clear quartz are the same mineral despite the different colors.

Streak

Streak is the color of a mineral's powder. Streak is a more reliable property than color because streak does not vary. Minerals that are the same color may have a different colored streak. Many minerals, such as the quartz in the figure 3, do not have streak.

To check streak, scrape the mineral across an unglazed porcelain plate (Figure 4). Yellow-gold pyrite has a blackish streak, another indicator that pyrite is not gold, which has a golden yellow streak.



Figure 4. The streak of hematite across an unglazed porcelain plate is red-brown.

Luster

Luster describes the reflection of light off a mineral's surface. Mineralogists have special terms to describe luster. One simple way to classify luster is based on whether the mineral is metallic or non-metallic. Minerals that are opaque and shiny, such as pyrite, have a metallic luster. Minerals such as quartz have a non-metallic luster. Different types of non-metallic luster are described in table 1.

Table 1. Six types of non-metallic luster.

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

Can you match the minerals in figure 5 with the correct luster from table 1?



Figure 5. (a) Diamond has an adamantine luster. (b) Quartz is not sparkly and has a vitreous, or glassy, luster. (b) Sulfur reflects less light than quartz, so it has a resinous luster.

SPECIFIC GRAVITY

Density describes how much matter is in a certain amount of space: density = mass/volume.

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. The density of an object depends on its mass and its volume. For example, the water in a drinking glass has the same density as the water in the same volume of a swimming pool.

Gold has a density of about 19 g/cm^3; pyrite has a density of about 5 g/cm^3—that's another way to tell pyrite from gold. Quartz is even less dense than pyrite and has a density of 2.7 g/cm^3.

The specific gravity of a substance compares its density to that of water. Substances that are more dense have higher specific gravity.

HARDNESS

Hardness is a measure of whether a mineral will scratch or be scratched. Mohs Hardness Scale, shown in table 2, is a reference for mineral hardness.

Table 2. Mohs Hardness Scale: 1 (softest) to 10 (hardest).

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

With a Mohs scale, anyone can test an unknown mineral for its hardness. Imagine you have an unknown mineral. You find that it can scratch fluorite or even apatite, but feldspar scratches it. You know then that the mineral's hardness is between 5 and 6. Note that no other mineral can scratch diamond.

CLEAVAGE AND FRACTURE

Breaking a mineral breaks its chemical bonds. Since some bonds are weaker than other bonds, each type of mineral is likely to break where the bonds between the atoms are weaker. For that reason, minerals break apart in characteristic ways.

Cleavage is the tendency of a mineral to break along certain planes to make smooth surfaces. Halite breaks between layers of sodium and chlorine to form cubes with smooth surfaces (figure 6).

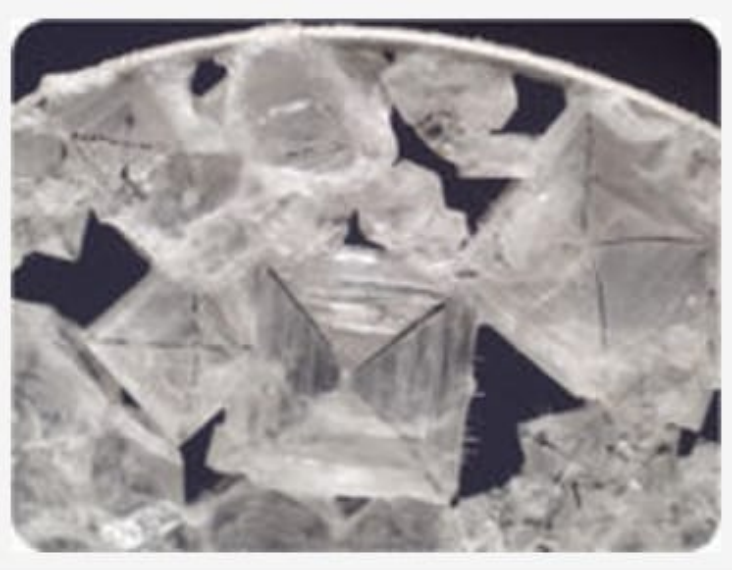


Figure 6. A close-up view of sodium chloride in a water bubble aboard the International Space Station.

Mica has cleavage in one direction and forms sheets (figure 7).



Figure 7. Sheets of mica.

Minerals can cleave into polygons. Fluorite forms octahedrons (figure 8).



Figure 8. This rough diamond shows its octahedral cleavage.

One reason gemstones are beautiful is that the cleavage planes make an attractive crystal shape with smooth faces.

Fracture is a break in a mineral that is not along a cleavage plane. Fracture is not always the same in the same mineral because fracture is not determined by the structure of the mineral.

Minerals may have characteristic fractures (figure 9). Metals usually fracture into jagged edges. If a mineral splinters like wood, it may be fibrous. Some minerals, such as quartz, form smooth curved surfaces when they fracture.



Figure 9. Chrysotile has splintery fracture.

OTHER IDENTIFYING CHARACTERISTICS

Some minerals have other unique properties, some of which are listed in table 3. Can you name a unique property that would allow you to instantly identify a mineral that's been described quite a bit in this chapter? (Hint: It is most likely found on your dinner table.)

Table 3. Some minerals have unusual properties that can be used for identification.

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)
Taste	Some minerals taste salty	Halite

A simple lesson on how to identify minerals is seen in this video.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

LESSON SUMMARY

- Minerals have distinctive properties that can be used to help identify them.
- Color and luster describe the mineral's outer appearance. Streak is the color of the powder.
- A mineral has a characteristic density.
- Mohs Hardness Scale is used to compare the hardness of minerals.
- Cleavage or the characteristic way a mineral breaks depends on the crystal structure of the mineral.
- Some minerals have special properties that can be used to help identify them.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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2.4: Mineral Basics

The solid earth is made of rocks, which are made of minerals. To understand rocks you need to become familiar with minerals and how they are identified. This basics page gives you the background needed to understand the terms used in the minerals classification table, which contains information for identifying minerals.

WHAT ARE MINERALS?

All rocks except obsidian and coal are made of minerals. (Obsidian is a volcanic rock made of glass and coal is made of organic carbon.) Most rocks contain several minerals in a mixture characteristic of the particular rock type. When identifying a rock you must first identify the individual minerals that make up that rock. Minerals are naturally occurring, inorganic solids with a definite chemical composition and a crystal lattice structure. Although thousands of minerals in the earth have been identified, just ten minerals make up most of the volume of the earth's crust–plagioclase, quartz, orthoclase, amphibole, pyroxene, olivine, calcite, biotite, garnet, and clay.

Together, the chemical formula (the types and proportions of the chemical elements) and the crystal lattice (the geometry of how the atoms are arranged and bonded together) determine the physical properties of minerals. The chemical formula and crystal lattice of a mineral can only be determined in a laboratory, but by examining a mineral and determining several of its physical properties, you can identify the mineral. First, you need to become familiar with the physical properties of minerals and how to recognize them.

THE CHEMISTRY OF MINERALS

Why study the chemistry of minerals? Minerals are made of atoms. To understand, explain, and predict the behavior of minerals, and rocks, which are made of minerals, we must understand some basic facts about atoms and how they behave. This requires understanding some chemistry. We will begin by constructing atoms in our thinking in terms of the three sub-atomic particles of which atoms are made.

Atoms

Atoms consist of protons, neutrons, and electrons. Protons have a positive (+) electrical charge. Neutrons are electrically neutral. Electrons have a negative (-) charge that is exactly equal and opposite to the electrical charge of a proton. /

Most of the mass of an atom is packed into its tiny nucleus. An atomic nucleus is made of protons and neutrons. Arranged in specific orbitals around the nucleus of an atom are the electrons. Even though the mass of an electron is a tiny mass compared to the mass of a proton or a neutron, the electrons occupy most of the volume of an atom.

Ions

A neutral atom has the same number of electrons as it does protons. An atom that has lost or gained any electrons is no longer an electrically neutral atom. That type of atom, which is not electrically neutral and has an electrical charge associated with it, is called an ion. Atoms that have gained electrons are negatively (-) charged ions, or anions. Atoms that have lost electrons are positively (+) charged ions, or cations. It is also possible to have ions that are actually small groups of atoms bonded together. These are known as polyatomic ions. One example of a polyatomic ion is the carbonate ion, $(CO_3)^{2-}$, which has two extra electrons, giving it the net electrical charge of 2-.

The Periodic Table

Naturally occurring atoms found in the earth range from hydrogen, with just one proton in its nucleus, to uranium, with 92 protons in its nucleus. These are the naturally occurring chemical elements, which includes such commonly known elements as carbon, oxygen, iron, and so on. The periodic table lists all the chemical elements in a way that tells us how many protons each of them

has, how its electrons are arranged, and what the general chemical behavior of each element is.

Follow this link to a large version of the Periodic Table. The link will open in a new window so you can easily refer to it as you read through this Basics page.

Each chemical element is distinguished by the number of protons in its nucleus. The atomic number of an element tells you how many protons it has. For example, every atom of the element oxygen has eight protons in its nucleus. That is why the atomic number of oxygen is 8. If an atom has greater or fewer than eight protons in its nucleus, it is not oxygen, it is some other chemical element. In the periodic table, the atomic number of each element is listed above the chemical symbol of the element.

The chemical elements in the periodic table form columns that are called groups. All the elements in a group have a similar chemical behavior. That is because all the elements in a group have a similar arrangement of electrons in their atoms, and it is the electron arrangement that determines the chemical behavior of an element.

Isotopes

An atom of a specific chemical element must have in its nucleus the number of protons given by its atomic number. However, there is a range of possible numbers of neutrons it can have in its nucleus. The fact that atoms of a chemical element may have different numbers of neutrons results in each chemical element having several isotopes. Isotopes are atoms of a given chemical element that have different numbers of neutrons in their nuclei.

For example, while all atoms of the element oxygen have eight protons in their nuclei, those oxygen atoms may have eight, nine, or ten neutrons. The different numbers of neutrons in the nucleus distinguishes the three isotopes of oxygen. Oxygen-16 is the isotope of oxygen with 8 neutrons in its nucleus. The number 16 is called the atomic mass number. The atomic mass number is the total number of protons and neutrons in the nucleus of an isotope. From this definition, and knowing that all oxygen atoms have 8 protons in the nucleus, you can deduce that oxygen-17 is the oxygen isotope with 9 neutrons and oxygen-18 is the oxygen isotope with 10 neutrons. Abbreviated into symbols, the three isotopes of oxygen are written as ^{16}O, ^{17}O and ^{18}O.

Isotopes are not very important for understanding minerals, but are important in understanding how to apply chemistry and nuclear physics to geology, such as how to use measurements of radioactive isotopes to measure the ages of rocks and minerals and how to use oxygen isotopes from layers of glacial ice to determine what the temperature of the earth was during an ice age.

Chemical Reactions

Minerals form as a result of chemical reactions. Chemical reactions are driven mainly by the arrangement and re-arrangement of electrons in atoms. In a mineral, the atoms are held together by chemical bonds, which derive from the electrons.

Electrons can be thought of as occupying energy levels, or shells, in an atom. The lowest-energy shell is closest to the nucleus. Each shell can accommodate only a limited number of electrons. The first shell can hold two electrons, the second and third shells can hold eight electrons, and the next two shells can hold eighteen electrons. Unless energy is added to an atom to excite it from its low-energy state, the electrons in the atom will occupy the lowest-energy shells available to them.

Chemical Bonds

If atoms interact with other atoms, they can gain or lose electrons to the other atoms, or share electrons with other atoms. In an individual atom, the most stable arrangement is a full outer shell of electrons. Therefore, chemical reactions will occur, and chemical bonds will form that hold atoms together to each other, when atoms encounter other atoms and change their electron configurations toward more stable, lower-energy arrangements, which generally involves achieving full outer electron shells in the atoms.

This stable configuration—a full outer shell of electrons—is exemplified by the inert gases. In the periodic table the inert gases are the elements of group 18 or VIIIA, the last column on the right. Inert gases do not have to undergo any chemical reactions or form any chemical bonds with other atoms in order to have a full outer shell of electrons. The inert gases already have full outer shells of electrons. That is why they are chemically inert. Their electrons are as stable as can be arranged. For this reason, inert gases are extremely unlikely to undergo any chemical reactions and it is almost impossible for them to bond with any other atoms. Because they do not bond with any other atoms to form a liquid, a solid, a molecule, or a mineral, the inert gases consist

of atoms that stay separate from each other, in the gas state.

Individual atoms of all the other chemical elements, when they are neutral atoms, do not have full outer shells of electrons like the inert gases do. Therefore, they do not have the most stable arrangement of electrons that they possibly can. That is why most chemical elements have a strong tendency to either gain or lose electrons, or to enter into other arrangements of their valence electrons, the electrons in their outer shell. Chemical reactions and chemical bonds are generally a result of electrons being rearranged within and among atoms to give the atoms full outer electron shells.

For an atom to lose or gain one electron takes less energy than to lose or gain two, which in turn takes less energy than to lose or gain a third electron. For an individual atom to gain or lose four electrons will only occur in extremely high-energy environments such as in a star. In common chemical reactions on earth, and in the formation of chemical bonds, no element will completely gain or lose four electrons. This limits the charges of atomic cations to +1, +2 or +3 and the charges of atomic anions to –1, –2, or –3.

Reading this far, you have learned about one group of elements in the periodic table, group 18, the inert gases. Another group of chemical elements in the periodic table is the alkali elements. The alkali elements compose group 1 or IA, the left hand column, including the elements sodium (Na) and potassium (K).

Hydrogen is not usually considered as an alkali element because, even though it is shown in group 1 in the periodic table. Hydrogen is so light and small, with just a single proton in its nucleus, that it has some unique behaviors and is considered in a class by itself.

The alkali elements have a single electron in their outer electron shell. If an alkali element loses a single electron, it becomes an ion with a +1 charge and a full outer shell. If an opportunity arises, alkali elements will easily turned into +1 cations.

Ionic Bonds

Now look at group 17 or VIIA in the periodic table, which includes the chemical elements fluorine (F), chlorine (Cl) and so on. These are the halogen elements. If a halogen element gains a single electron, it becomes an ion with a -1 charge and a full outer electron shell. If an opportunity arises, halogen elements have a strong tendency to take in an extra electron and become -1 anions because by doing so they achieve a full outer shell of electrons, which is the most stable arrangement of electrons possible.

If sodium and chlorine atoms get together in the right conditions, such as in an evaporating solution of salt water, each sodium atoms will give up an electron to a chlorine atom. This turns the sodium atoms into sodium ions, Na^+, and the chlorine atoms into chloride ions, Cl^-. Opposite electrical charges attract, so the sodium ions and chloride ions will tend to stick together with each other, joined by what are called ionic bonds.

Not only will the sodium and chloride ions have a very strong tendency to join together with each other via ionic bonds, in most situations they will naturally arrange into a configuration where there is no wasted space and no wasted energy. This leads them to form the crystal lattice of the mineral halite. Halite is a mineral with the chemical formula NaCl, sodium chloride, in which the bonds between the atoms are all ionic bonds.

Look at the diagram of halite showing the sodium and chloride ions arranged into the crystal lattice. All the ionic bonds are at the same angle and the same distance, so they are all of equal strength. This is the lowest-energy arrangement of the ions, the most stable arrangement. If any of the ions were spaced located at different angles or at different distances, there would be extra energy available. This extra energy would drive the ions toward equal angles and distances from each other, until the extra energy is used up and the ions are arranged into their lowest energy state. That is why minerals form, as a natural way for atoms to arrange themselves into the lowest energy state currently available to them.

Covalent Bonds

Some elements, such as carbon (C) and silicon (Si) have a half-full valence shell. (The valence shell is another name for the outer shell, where the most reactive electrons are.) If an element such as carbon were to gain 4 electrons or lose 4 electrons, it would have a full valence shell. However, it is very difficult for an atom to gain or lose four electrons – the energy barrier becomes too strong. Therefore, carbon and silicon, along with a few other elements, tend to form a different type of bond in which they share their outer electrons with other atoms, which in turn share their outer electrons with the carbon (or silicon) atom. The atoms all

end up with a full outer shell of electrons, even though some or all of those electrons are being shared with neighboring atoms. This electron sharing keeps the atoms bonded together. This type of chemical bond is called a covalent bond.

It is not uncommon for covalent bonds to be relatively strong. An extreme example can be in diamond. Diamond is a mineral consisting of nothing but carbon atoms, so its chemical formula is simply C. Each carbon atom in the diamond crystal lattice is covalently bonded to – sharing its valence electrons with – four neighboring carbon atoms. A diamond crystal is held together by nothing but extremely strong covalent bonds in all directions, which makes diamond a very hard mineral, the hardest known.

Metallic Bonds

Gold forms a naturally occurring mineral of more or less pure gold, Au, held together by another type of bond, the metallic bond. Metallic elements such as gold and copper, when they bond with other metallic elements, are sharing some of their electrons not just with adjacent atoms, but throughout the whole substance. That is why metallic substances such as copper, gold, and aluminum make such good electrical conductors, because it is so easy to get the "loose" electrons to respond through the whole extent of the metal.

Hydrogen Bonds

Another type of chemical bond that occurs in some minerals is the hydrogen bond. Hydrogen bonds are caused by the positive and negative ends of polar molecules attracting each other strongly enough to hold each other in fixed positions. For example, water molecules can join together through hydrogen bonds to form the mineral known as ice. In a water molecule, H_2O, each of the hydrogen atoms forms a covalent bond with the oxygen atom. To form the covalent bonds, each hydrogen atom shares a pair of electrons with the oxygen atom. (This gives all the atoms in the molecule a full outer electron shell.) In the molecule the two hydrogen atoms are bonded to the oxygen atom toward one side of the oxygen atom, rather than at opposite ends. Because the oxygen atom is so electronegative, the pairs of electrons it shares with the hydrogen atoms are skewed toward the nucleus of the oxygen. This leaves a net positive charge on the hydrogen side of the molecule and a net negative charge on the oxygen end of the molecule, resulting in water molecule being a polar molecule, a molecule with a positive end and a negative end. Such molecules can form hydrogen bonds.

If the temperature is low enough, water molecules will move slowly enough to settle into fixed positions relative to each other, held together by hydrogen bonds, forming ice. In a crystal of ice, the water molecules have formed hydrogen bonds by arranging themselves so the negative ends of water molecules face toward positive ends of other water molecules. Ice is a mineral with a six-sided symmetry in its crystal lattice. The hydrogen bonds between water molecules in ice are relatively weak. That is why ice melts at a temperature that is not very high compared to the melting temperatures of minerals held together by ionic or covalent bonds.

Van Der Waals Bonds

There is one other type of chemical bond to consider, a weak type of bond which occurs in some minerals. It is called the van der Waals bond after its discoverer. van der Waals bonds form between parallel sheets or parallel lines of atoms, and are caused by the electric charges in the sheets or lines of atoms fluctuating and responding to the flux—for example, the electrical charge of part of a sheet of atoms may fluctuate and become more negative. In response, this may cause the adjacent sheet to fluctuate toward the positive. There will be an attraction between these positive and negative areas, tending to hold the sheets of atoms together. The electrical attractions shift and fluctuate as the electrical charges shift and fluctuate among the atoms, but even though the electrical attractions do not remain in one place for very long, they are occurring at all times in some parts of the parallel structure. The result is a weak bonding effect, the van der Waals bond.

Graphite is a mineral held together, in part, by van der Waals bonds. Graphite consists of sheets of covalently bonded carbon atoms. Each sheet of carbon atoms is strongly bonded in two dimensions throughout the sheet. But in the third dimension, only weak van der Waals bonds hold the sheets of carbon atoms together. It is very easy to get the sheets of graphite to flake apart from each other, as easy as writing on a piece of paper with a pencil. Under a microscope, you can see that pencil marks are made of many tiny flakes of graphite.

Silicate Minerals and the Silicate Tetrahedron

Most of the minerals in the earth are silicate minerals. The building block of silicate minerals – the essential component that

makes them silicate minerals – is the silicate tetrahedron. The silicate tetrahedron consists of four oxygen atoms arranged as close as they can get around a central silicon atom. The result is a pyramidal shape known as a tetrahedron, with an oxygen atom at each of its four apices. (The apices are the points on the tetrahedron where three corners come together.)

The silicon atom by itself has four electrons in its outer shell. In the silicate tetrahedron each of those four electrons is being shared with one of the four attached oxygen atoms. In turn, each oxygen atom is sharing one of the 6 electrons it has in its outer shell.

The result is that the silicon at the center of the tetrahedron has, in effect, a full outer shell with eight electrons in it. Those eight electrons are shared, in pairs, with the four oxygen atoms of the tetrahedron. Each oxygen atom in the tetrahedron, in turn, will have seven electrons in its outer shell – if there is nothing more to the system than the one silicon atom bonded to the four oxygen atoms. This would leave each oxygen atom one electron short of having a full outer shell of electrons.

However, oxygen is a strongly electronegative element, which means that it has the strength to attract electrons from other elements to its nucleus in most situations. In a mineral, each oxygen atom in the silicate tetrahedron will actually have eight electrons: the six electrons that each oxygen atom had in its outer electron shell to begin with, the electron it gained by sharing a pair of electrons in a covalent bond with the silicon atom in the tetrahedron, and one more electron from another atom (or another small group of atoms) in the mineral, outside the tetrahedron.

Silicate tetrahedra are able to bond with many common elements in many different crystal lattice arrangements. In addition, silicate tetrahedra are able to bond with other silicate tetrahedra in a variety of geometric arrangements, including rings, sheets, chains, and three-dimensional networks.

WHY STUDY MINERALS?

Why study minerals? Because the solid earth is made almost entirely of minerals, to understand the earth we must understand the nature of minerals, how they form, and how they can be analyzed as sources of information about the earth and its history. Most rocks are made entirely of minerals, so to understand rocks and the rock cycle in depth requires being able to analyze, identify, and interpret minerals.

Each mineral contains information about the chemistry, pressure, and temperature that was present, in or on the earth, at the place and time the mineral formed. For example, diamond is a mineral, made of pure carbon, which only forms under the high pressures that occur deeper in the earth than the bottom of the crust, in places where unusually high concentrations of carbon are present in the earth's mantle. We can analyze diamonds, and the other minerals with which they co-existed, to get at the temperatures, pressures, and chemistry of these special sites in the earth's mantle. Diamonds thus act as probes of the earth, bringing us geological information from far greater depths in the earth than we could ever dig or drill.

Minerals commonly grow in layers that accrete onto the surface of earlier-formed parts of the mineral. If a mineral has a variable chemical composition that changes as the chemistry, pressure, and temperature of its environment changes, the layers of mineral growth can be analyzed to track the changing conditions in which the mineral grew. For example, analyzing the layers in a crystal of feldspar in a volcanic rock may reveal that the mineral grew as the magma was cooled and then re-heated as it mixed with an intruding batch of hotter magma with a differing chemical composition, which may have occurred just before the magma erupted to the earth's surface and rapidly cooled and solidified as a lava flow.

A mineral may incorporate a radioactive element into its atomic structure as it crystallizes, and the decay of the element into its stable daughter product, which may remain trapped inside the crystal, along with the decay rate of the radioactive element, allows an analysis of the elements in the mineral to be used to measure the age of the mineral. This is how many of the ages of geological materials are measured.

Minerals, of course, provide resources for construction, industry, and technology, from quartz to make silicon chips out of for computers (or to make glass out of for windows), to calcite for making cement for concrete mix, to clay for making ceramics – in fact, there are hundreds of minerals necessary for production of productions and construction of houses, roads, and buildings. Therefore, some geologists, known as economic geologists, specialize in certain minerals that are valuable as resources, and explore the earth to locate places where the mineral is concentrated and accessible.

Gemstones and semiprecious stones, such as emeralds, diamonds, and rubies (which are gemstones) or garnets (which are semiprecious) are all minerals, as is gold. The beauty and durability of such minerals, along with the limitations to their abundance, makes them valuable to people. Even common minerals such as quartz are collected by some people and put on display, if they

are found in the form of beautiful or unusually colorful crystals.

What are the Physical Properties of Minerals?

The physical properties of a mineral are controlled by its chemical composition (which types of atoms it consists of, and in what proportions) and its **crystal lattice** (the three-dimensional geometric pattern in which those atoms are arranged and bonded together).

It is no coincidence that crystals of quartz (SiO_2) are six-sided, while crystals of halite (NaCl) are cubic. This is because of the geometry of their crystal lattices. It is also no coincidence that quartz is hard enough to scratch glass and will not dissolve in water to any visible extent, whereas halite will not scratch glass and will easily dissolve in water. These differences are due to the different chemical compositions of the minerals. The sodium (Na) and chlorine (Cl), by their chemical nature, readily break their bonds and become dissolved ions in water. The silicon (Si) and oxygen (O) in quartz are linked by strong bonds, which do not yield easily to the dissolving force of water.

Each mineral exhibits a unique set of physical properties. Therefore, the main task in identifying a mineral is to determine its physical properties. The physical properties that we will consider are **color**, **luster**, **streak**, **cleavage**, **fracture**, **hardness**, **crystal shape**, and selected special properties.

Color

Color is often useful, but should not be relied upon. Some minerals come in many different colors. Quartz, for example, may be clear, white, gray, brown, yellow, pink, red, or orange. So color can help, but do not rely on color as the determining property.

Luster

Luster is how the surface of a mineral reflects light. It is not the same thing as color, so it crucial to distinguish luster from color. For example, a mineral described as “shiny yellow” is being described in terms of luster (“shiny”) and color (“yellow”), which are two different physical properties. Standard names for luster include metallic, glassy, pearly, silky, greasy, and dull. It is often useful to first determine if a mineral has a metallic luster. A metallic luster means shiny like polished metal. For example cleaned polished pieces of chrome, steel, titanium, copper, and brass all exhibit metallic luster as do many other minerals. Of the nonmetallic lusters, glassy is the most common and means the surface of the mineral reflects light like glass. Pearly luster is important in identifying the feldspars, which are the most common type of mineral. Pearly luster refers to a subtle irridescence or color play in the reflected light, same way pearls reflect light. Silky means relecting light with a silk- like sheen. Greasy luster looks similar to the luster of solidified bacon grease. Minerals with dull luster reflect very little light. Identifying luster takes a little practice. Remember to distinguish luster from color.

Streak

Streak is the color of the mineral as a powder. It is determined by scratching a mineral against a streak plate and checking the color of the streak left behind. The streak, the color of the mineral as a powder, may be different from the whole mineral color.

Cleavage

A mineral that naturally breaks into perfectly flat surfaces is exhibiting cleavage. Not all minerals have cleavage. A cleavage represents a direction of weakness in the crystal lattice. Cleavage surfaces can be distinguished by how they consistently reflect light, as if polished, smooth, and even. The cleavage properties of a mineral are described in terms of the number of cleavages and, if more than one cleavage, the angles between the cleavages. The number of cleavages is the number or directions in which the mineral cleaves. A mineral may exhibit 100 cleavage surfaces parallel to each other. Those represent a single cleavage because the surfaces are all oriented in the same diretion. The possible number of cleavages a mineral may have are 1,2,3,4, or 6. If more than 1 cleavage is present, and a device for measuring angles is not available, simply state whether the cleavages intersect at 90° or not 90°.

To see mineral cleavage, hold the mineral up beneath a strong light and move it around, move it around some more, to see how the different sides reflect light. A cleavage direction will show up as a smooth, shiny, evenly bright sheen of light reflected by one

set of parallel surfaces on the mineral.

Fracture

All minerals have fracture. Fracture is breakage, which occurs in directions that are not cleavage directions. Some minerals, such as quartz, have no cleavage whatsoever. When a mineral with no cleavage is broken apart by a hammer, it fractures in all directions. Quartz is said to exhibit conchoidal fracture. Conchoidal fracture is the way a thick piece of glass breaks with concentric, curving ridges on the broken surfaces. However, some quartz crystals have so many flaws that instead of exhibiting conchoidal fracture they simply exhibit irregular fracture. Irregular fracture is a standard term for fractures that do not exhibit any of the qualities of the other fracture types. In introductory geology, the key fracture types to remember are irregular, which most minerals exhibit, and conchoidal, seen in quartz.

Hardness

Hardness is the strength with which a mineral resists its surface being scraped or punctured. In working with hand samples without specialized tools, mineral hardness is specified by the Mohs hardness scale. The Mohs hardness scale is based 10 reference minerals, from talc the softest (Mohs hardness of 1), to diamond the hardest (Mohs hardness of 10). It is a relative, or nonlinear, scale. A hardness of 2.5 simply means that the mineral is harder than gypsum (Mohs hardness of 2) and softer than calcite (Mohs hardness of 3). To compare the hardness of two minerals see which mineral scratches the surface of the other.

Mohs Hardness Scale

Index Minerals	Common Objects
1-talc	
2-gypsum	2.5-fingernail
3-calcite	3.5-pure, untarnished copper
4-flourite	
5-feldspar	5 to 5.5-stainless steel
	5.5 to 6-glass
6-apatite	6 to 6.5-hard steel file
7-quartz	
8-topaz	
9-corundum	
10-diamond	

Crystal Shape

All minerals are crystalline, but only some have the opportunity to exhibit the shapes of their crystals, their crystal forms. Many minerals in an introductory geology lab do not exhibit their crystal form. If a mineral has space while it grows, it may form natural crystals, with a crystal shape reflecting the geometry of the mineral's internal crystal lattice. The shape of a crystal follows the symmetry of its crystal lattice. Quartz, for instance, forms six-sided crystals, showing the hexagonal symmetry of its crystal lattice. There are two complicating factors to remember here: (1) minerals do not always form nice crystals when they grow, and (2) a crystal face is different from a cleavage surface. A crystal face forms during the growth of the mineral. A cleavage surface is formed when the mineral is broken.

Special Properties

There are some properties that only help to distinguish a small number of minerals, or even just a single mineral. An example of such a special property is the effervescent reaction of calcite to a weak solution of hydrochloric acid (5% HCl). Calcite fizzes or effervesces as the HCl solution dissolves it and creates CO_2 gas. Calcite is easy to identify even without testing the reaction to

HCl, by its hardness, luster and cleavage.

Another special property is magnetism. This can be tested by seeing if a small magnet responds to the mineral. The most common mineral that is strongly magnetic is the mineral magnetite. A special property that shows up in some sample of plagioclase feldspar is its tendency to exhibit striations on cleavage surfaces. Striations are perfectly straight, fine, parallel lines. Magnification may be required to see striations on plagioclase cleavage surfaces. Other special properties may be encountered on a mineral to mineral basis.

How to Identify Minerals

First, you need good light and a hand lens or magnifying glass. A hand lens is a small, double-lens magnifying glass that has a magnification power of at least 8X and can be purchased at some bookstores and nature stores.

Minerals are identified on the basis of their physical properties, which have been described in the the previous section. To identify a mineral, you look at it closely. At a glance, calcite and quartz look similar. Both are usually colorless, with a glassy luster. However, their other properties they are completely different. Quartz is much harder, hard enough to scratch glass. Calcite is soft, and will not scratch glass. Quartz has no mineral cleavage and fractures the same irregular way glass breaks. Calcite has three cleavage directions which meet at angles other than 90°, so it breaks into solid pieces with perfectly flat, smooth, shiny sides.

When identifying a mineral, you must:

1. Look at it closely on all visible sides to see how it reflects light
2. Test its hardness
3. Identify its cleavage or fracture
4. Name its luster
5. Evaluate any other physical properties necessary to determine the mineral's identity

In the minerals tables that accompanies this section, the minerals are grouped according to their luster and color. They are also classified on the basis of their hardness and their cleavage or fracture. If you can identify several of these physical properties, you can identify the mineral.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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2.5: Mineral Chemistry

DESCRIBE THE BASIC CHEMISTRY INVOLVED IN MINERAL FORMATION AND STRUCTURES

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Classes of Minerals

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2.6: Classes of Minerals

Minerals are classified according to their chemical properties. Except for the native element class, the chemical basis for classifying minerals is the anion, the negatively charged ion that usually shows up at the end of the chemical formula of the mineral. For example, the sulfides are based on the sufur ion, S^{2-}. Pyrite, for example, FeS_2, is a sulfide mineral. In some cases, the anion is of a mineral class is polyatomic, such as $(CO_3)^{2-}$, the carbonate ion. The major classes of minerals are:

- silicates
- sulfides
- carbonates
- oxides
- halides
- sulfates
- phosphates
- native elements

SILICATES

Based on the polyatomic anion, $(SiO_4)^{4-}$, which has a tetrahedral shape. Most minerals in the earth's crust and mantle are silicate minerals. All silicate minerals are built of silicon-oxygen tetrahedra $(SiO_4)^{4-}$ in different bonding arrangements which create different crystal lattices. You can understand the properties of a silicate mineral such as crystal shape and cleavage by knowing which type of crystal lattice it has.

- In **nesosilicates**, also called island silicates, the silicate tetrahedra are separate from each other and bonded completely to non silicate atoms. Olivine is an island silicate.
- In **sorosilicates** or paired silicates, such as epidote, the silicate tetrahedra are bonded in pairs.
- In **cyclosilicates**, also called ring silicates, the silicate tetrahedra are joined in rings. Beryl or emerald is a ring silicate.
- In **phyllosilicates** or sheet silicates, the tetrahedra are bonded at three corners to form flat sheets. Biotite is a sheet silicate.
- In **single-chain inosilicates** the silicate tetrahedra are bonded in single chains. Pyroxenes are singele-chain inosilicates.
- In **double-chain inosilicates** the silicate tetrahedra are bonded in double chains. Amphiboles are double-chain inosilicates.
- In **tectosilicates**, also known as framework silicates, all corners of the silicate tetrahedra are bonded to corners of other silicate tetrahedra, forming a complete framework of silicate tetrahedra in all directions. Feldspar, the most common mineral in earth's crust, and quartz are both framework silicates.

SULFIDES

These are based on the sulfide ion, S^{2-}. Examples include pyrite, FeS_2, galena, PbS, and sphalerite, ZnS in its pure zinc form. Some sulfides are mined as sources of such metals as zinc, lead, copper, and tin.

CARBONATES

These are based on the carbonate ion, $(CO_3)^{2-}$. Calcite, $CaCO_3$, and dolomite, $CaMg(CO_3)2$, are carbonate minerals. Carbonate minerals tend to dissolve relatively easily in water, especially acid water, and natural rain water is slightly acid.

OXIDES

These are based on the oxygen anion, O^{2-}. Examples include iron oxides such as hematite, Fe_2O_3 and magnetite, Fe_3O_4, and pyrolusite, MgO.

HALIDES

These have a halogen element as the anion, whether it be fluoride, F^-, chloride, Cl^-, bromide, Br^-, iodide, I^-, or astatide, At^-. Halite, NaCl, is a halide mineral.

SULFATES

These have the polyatomic sulfate ion, $(SO_4)^{2-}$, as the anion. Anhydrite, $CaSO_4$, is a sulfate.

PHOSPHATES

These have the polyatomic phosphate ion, $(PO_4)^{3-}$, as the anion. Fluorapatite, $Ca_5(PO_4)_3F$, which makes your teeth hard, is a phosphate mineral.

NATIVE ELEMENTS

These are made of nothing but a single element. Gold (Au), native copper (Cu), and diamond and graphite, which are made of carbon, are all native element minerals. Recall that a mineral is defined as naturally occurring. Therefore, elements purified and crystallized in a laboratory do not qualify as minerals, unless they have also been found in nature.

Follow this link to the minerals classification table.

REFLECTION QUESTIONS

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2.7: Most Common Elements

COMPARE THE MOST COMMON ELEMENTS IN THE EARTH'S CRUST AND THEIR ORDER OF ABUNDANCE

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Abundance of Elements in Earth's Crust

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2.8: Abundance of Elements in Earth's Crust

The table shows the **abundance of elements in Earth's crust**. Numbers show percentage or parts per million (ppm) in mass; 10,000 ppm = 1%. Note that numbers are estimates, and they will vary depending on source and method of estimation. Order of magnitude of data can roughly be relied upon.

Rank	Atomic Number	Element	Symbol	Lithosphere abundance
1	8	oxygen	O	460,000
2	14	silicon	Si	277,000
3	13	aluminium	Al	81,300
4	26	iron	Fe	50,000
5	20	calcium	Ca	36,300
6	11	sodium	Na	28,300
7	19	potassium	K	25,900
8	12	magnesium	Mg	20,900
9	22	titanium	Ti	4,400
10	1	hydrogen	H	1,400
11	15	phosphorus	P	1,200
12	25	manganese	Mn	1,000
13	9	fluorine	F	800
14	56	barium	Ba	500
15	6	carbon	C	300
16	38	strontium	Sr	
17	16	sulfur	S	500
18	40	zirconium	Zr	
19	74	tungsten	W	
20	23	vanadium	V	100
21	17	chlorine	Cl	500
22	24	chromium	Cr	100
23	37	rubidium	Rb	300
24	28	nickel	Ni	
25	30	zinc	Zn	
26	29	copper	Cu	100
27	58	cerium	Ce	
28	60	neodymium	Nd	
29	57	lanthanum	La	
30	39	yttrium	Y	
31	7	nitrogen	N	50

32	27	cobalt	Co	
33	3	lithium	Li	
34	41	niobium	Nb	
35	31	gallium	Ga	
36	21	scandium	Sc	
37	82	lead	Pb	
38	62	samarium	Sm	
39	90	thorium	Th	
40	59	praseodymium	Pr	
41	5	boron	B	
42	64	gadolinium	Gd	
43	66	dysprosium	Dy	
44	72	hafnium	Hf	
45	68	erbium	Er	
46	70	ytterbium	Yb	
47	55	caesium	Cs	
48	4	beryllium	Be	
49	50	tin	Sn	0
50	63	europium	Eu	
51	92	uranium	U	
52	73	tantalum	Ta	
53	32	germanium	Ge	
54	42	molybdenum	Mo	
55	33	arsenic	As	
56	67	holmium	Ho	
57	65	terbium	Tb	
58	69	thulium	Tm	
59	35	bromine	Br	
60	81	thallium	Tl	
61	71	lutetium	Lu	
62	51	antimony	Sb	
63	53	iodine	I	
64	48	cadmium	Cd	
65	47	silver	Ag	
66	80	mercury	Hg	
67	34	selenium	Se	
68	49	indium	In	
69	83	bismuth	Bi	

70	52	tellurium	Te	
71	78	platinum	Pt	
72	79	gold	Au	
73	44	ruthenium	Ru	
74	46	palladium	Pd	
75	75	rhenium	Re	
76	77	iridium	Ir	
77	45	rhodium	Rh	
78	76	osmium	Os	

REFLECTION QUESTIONS

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2.9: Putting It Together

SUMMARY

In this section, you learned the following:

1. The basic chemistry involved with mineral formation
2. The most common mineral forming elements
3. Common techniques used to identify minerals
4. How to use these techniques to identify common minerals
5. What a mineralogist does and where they work

SYNTHESIS

In this module we took a closer look at minerals. Minerals are very complex, and they form in a variety of ways and in a variety of settings. We examined some of the ways the mineralogist identifies minerals; some of the methods were very simple while others were a bit more complex (some of these include cleavage and reaction to acid). We can now understand why mineralogists need the firm foundation in chemistry and geology. In mineralogy, chemistry and geology are very tightly woven together. We saw just how those elements go into making up minerals. We stated earlier that elements make up minerals and minerals make up rocks, but we can also look at it in a different more familiar way: chocolate makes up chocolate chips and then the chocolate chips make up the cookie (along with the dough of course). Now that we have an insight into minerals, we can move on to the next concept—ROCKS!

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3: ROCKS AND THE ROCK CYCLE

In this section we will learn about the rock cycle. Learning the rock cycle and understanding the processes involved helps all of us. Aall rocks are eroded into fine particles. This is how soil forms, through the breakdown of rocks. We need soil to survive—imagine trying to grow vegetables without it. This is an immediate connection to the food chain. The rock cycle also gives scientists and engineers an idea on where energy sources (mainly fossil fuels, which are found only in sedimentary rock) and building materials such as marble or granite may be located. We will see throughout the course how this cycle plays into just about every aspect of geology.

3.1: Why It Matters

3.2: The Rock Cycle

3.3: The Rock Cycle

3.4: Identification and Classication

3.5: Types of Rocks

3.6: Igneous Rocks

3.7: Sedimentary Rocks

3.8: Metamorphic Rocks

3.9: Putting It Together

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3.1: Why It Matters

IDENTIFY AND COMPARE COMMON ROCK FORMING MINERALS, INTERPRET AND UNDERSTAND MINERAL STRUCTURES, MINERAL PROPERTIES

In this section we will learn about the rock cycle. Please watch this short video for an introduction:

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

As you can see, the rock cycle is never ending. The video explained how rocks change from one rock type to another, and—just as important—it showed the processes that cause those changes.

Learning the rock cycle and understanding the processes involved helps all of us. For example, you saw in the video how all rocks are eroded into fine particles. This is how soil forms, through the breakdown of rocks. We need soil to survive—imagine trying to grow vegetables without it. This is an immediate connection to the food chain. The rock cycle also gives scientists and engineers an idea on where energy sources (mainly fossil fuels, which are found only in sedimentary rock) and building materials such as marble or granite may be located. We will see throughout the course how this cycle plays into just about every aspect of geology.

Learning Outcomes

- Interpret and explain all processes of the rock cycle
- Differentiate between metamorphic, igneous, and sedimentary rock types

Ok, let's get started!

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3.2: The Rock Cycle

INTERPRET AND EXPLAIN ALL PROCESSES OF THE ROCK CYCLE

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: The Rock Cycle

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3.3: The Rock Cycle

INTRODUCTION

There are three types of rocks: igneous, sedimentary and metamorphic. Each of these types is part of the rock cycle. Through changes in conditions one rock type can become another rock type. Or it can become a different rock of the same type.



Figure 1. The different colors and textures seen in this rock are caused by the presence of different minerals.

WHAT ARE ROCKS?

A rock is a naturally formed, non-living earth material. Rocks are made of collections of mineral grains that are held together in a firm, solid mass (figure 1).

How is a rock different from a mineral? Rocks are made of minerals. The mineral grains in a rock may be so tiny that you can only see them with a microscope, or they may be as big as your fingernail or even your finger (figure 1).



Figure 2. A pegmatite from South Dakota with crystals of lepidolite, tourmaline, and quartz (1 cm scale on the upper left).

Rocks are identified primarily by the minerals they contain and by their texture. Each type of rock has a distinctive set of minerals. A rock may be made of grains of all one mineral type, such as quartzite. Much more commonly, rocks are made of a mixture of different minerals. Texture is a description of the size, shape, and arrangement of mineral grains. Are the two samples in figure 2 the same rock type? Do they have the same minerals? The same texture?

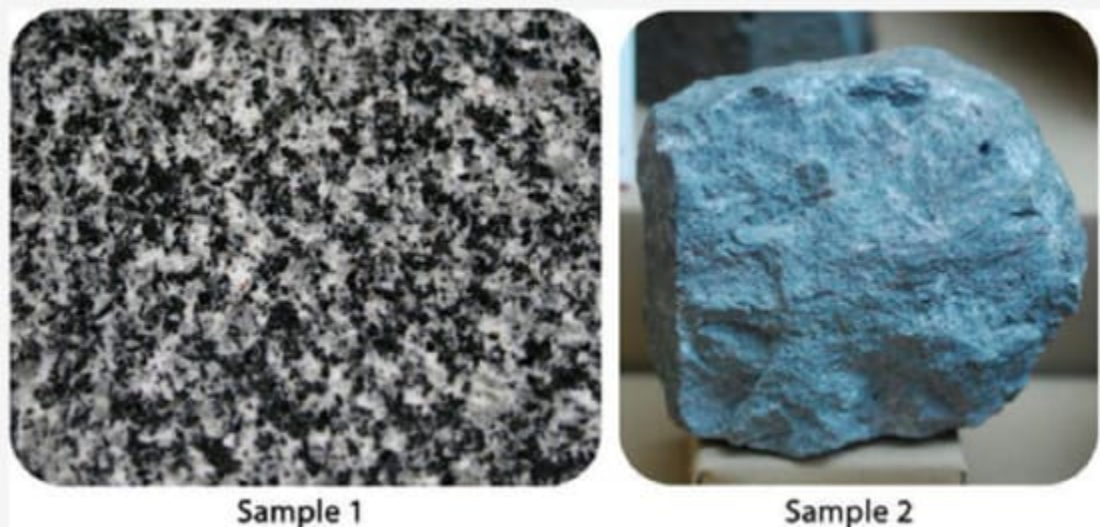


Figure 3. Rock samples.

Sample	Minerals	Texture	Formation	Rock Type
Sample 1	plagioclase, quartz, hornblende, pyroxene	Crystals, visible to the naked eye	Magma cooled slowly	Diorite
Sample 2	plagioclase, hornblende, pyroxene	Crystals are tiny or microscopic	Magma erupted and cooled quickly	Andesite

Table 1

As seen in table 1, these two rocks have the same chemical composition and contain mostly the same minerals, but they do not have the same texture. Sample 1 has visible mineral grains, but Sample 2 has very tiny or invisible grains. The two different textures indicate different histories. Sample 1 is a diorite, a rock that cooled slowly from magma (molten rock) underground. Sample 2 is an andesite, a rock that cooled rapidly from a very similar magma that erupted onto Earth's surface.

THREE MAIN CATEGORIES OF ROCKS

Rocks are classified into three major groups according to how they form. Rocks can be studied in hand samples that can be moved from their original location. Rocks can also be studied in **outcrop**, exposed rock formations that are attached to the ground, at the location where they are found.

Igneous Rocks

Igneous rocks form from cooling magma. Magma that erupts onto Earth's surface is lava, as seen in figure 4. The chemical composition of the magma and the rate at which it cools determine what rock forms as the minerals cool and crystallize.



Figure 4. This flowing lava is molten rock that will harden into an igneous rock.

Sedimentary Rocks

Sedimentary rocks form by the compaction and cementing together of **sediments**, broken pieces of rock-like gravel, sand, silt, or clay (figure 5). Those sediments can be formed from the weathering and erosion of preexisting rocks. Sedimentary rocks also include chemical **precipitates**, the solid materials left behind after a liquid evaporates.



Figure 5. This sedimentary rock is made of sand that is cemented together to form a sandstone.

Metamorphic Rocks

Metamorphic rocks form when the minerals in an existing rock are changed by heat or pressure within the Earth. See figure 6 for an example of a metamorphic rock.



Figure 6. Quartzite is a metamorphic rock formed when quartz sandstone is exposed to heat and pressure within the Earth.

A simple explanation of the three rock types and how to identify them can be seen in this video:

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

This video discusses how to identify igneous rocks:

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

This video discusses how to identify a metamorphic rocks:

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

This *Science Made Fun* video discusses the conditions under which the three main rock types form:

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

THE ROCK CYCLE

Rocks change as a result of natural processes that are taking place all the time. Most changes happen very slowly; many take place below the Earth's surface, so we may not even notice the changes. Although we may not see the changes, the physical and chemical properties of rocks are constantly changing in a natural, never-ending cycle called the **rock cycle**.



Figure 7. James Hutton is considered the Father of Geology

The concept of the rock cycle was first developed by James Hutton, an eighteenth century scientist often called the “Father of Geology” (shown in figure 7). Hutton recognized that geologic processes have “no [sign] of a beginning, and no prospect of an end.” The processes involved in the rock cycle often take place over millions of years. So on the scale of a human lifetime, rocks appear to be “rock solid” and unchanging, but in the longer term, change is always taking place.

In the rock cycle, illustrated in figure 8, the three main rock types—igneous, sedimentary, and metamorphic—are shown. Arrows connecting the three rock types show the processes that change one rock type into another. The cycle has no beginning and no end. Rocks deep within the Earth are right now becoming other types of rocks. Rocks at the surface are lying in place before they are next exposed to a process that will change them.

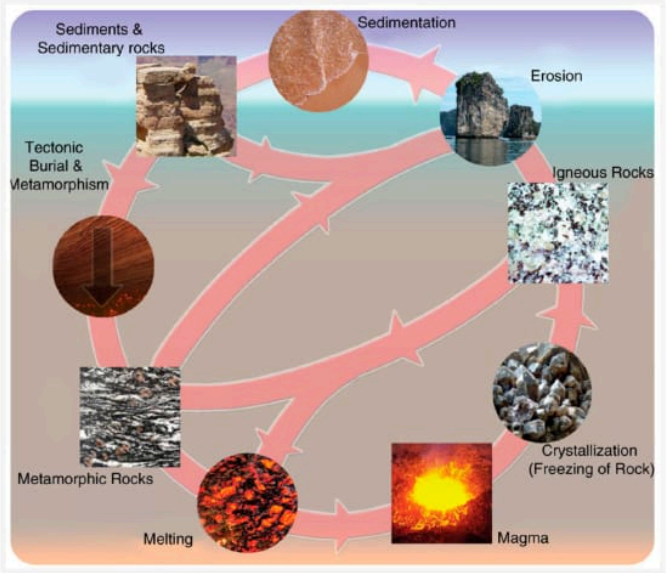


Figure 8. The Rock Cycle.

PROCESSES OF THE ROCK CYCLE

Several processes can turn one type of rock into another type of rock. The key processes of the rock cycle are crystallization, erosion and sedimentation, and metamorphism.

Crystallization

Magma cools either underground or on the surface and hardens into an igneous rock. As the magma cools, different crystals form at different temperatures, undergoing **crystallization**. For example, the mineral olivine crystallizes out of magma at much higher temperatures than quartz. The rate of cooling determines how much time the crystals will have to form. Slow cooling produces larger crystals.

Erosion and Sedimentation

Weathering wears rocks at the Earth's surface down into smaller pieces. The small fragments are called sediments. Running water, ice, and gravity all transport these sediments from one place to another by **erosion**. During **sedimentation**, the sediments are laid down or deposited. In order to form a sedimentary rock, the accumulated sediment must become compacted and cemented together.

Metamorphism

When a rock is exposed to extreme heat and pressure within the Earth but does not melt, the rock becomes metamorphosed. **Metamorphism** may change the mineral composition and the texture of the rock. For that reason, a metamorphic rock may have a new mineral composition and/or texture.

LESSON SUMMARY

- Rocks are collections of minerals of various sizes and types.
- The three main rock types are igneous, sedimentary, and metamorphic.
- Crystallization, erosion and sedimentation, and metamorphism transform one rock type into another or change sediments into rock.
- The rock cycle describes the transformations of one type of rock to another.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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3.4: Identification and Classication

DIFFERENTIATE BETWEEN METAMORPHIC, IGNEOUS, AND SEDIMENTARY ROCK TYPES

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Types of Rocks
- Reading: Igneous Rocks
- Reading: Sedimentary Rocks
- Reading: Metamorphic Rocks

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3.5: Types of Rocks

IGNEOUS ROCKS

Igneous rocks form from the cooling and hardening of molten magma in many different environments. These rocks are identified by their composition and texture. More than 700 different types of igneous rocks are known.

Magma Composition

The rock beneath the Earth's surface is sometimes heated to high enough temperatures that it melts to create magma. Different magmas have different composition and contain whatever elements were in the rock that melted. Magmas also contain gases. The main elements are the same as the elements found in the crust. Table 1 lists the abundance of elements found in the Earth's crust and in magma. The remaining 1.5% is made up of many other elements that are present in tiny quantities.

Table 1. Elements in Earth's Crust and Magma

Element	Symbol	Percent
Oxygen	O	46.6%
Silicon	Si	27.7%
Aluminum	Al	8.1%
Iron	Fe	5.0%
Calcium	Ca	3.6%
Sodium	Na	2.8%
Potassium	K	2.6%
Magnesium	Mg	2.1%
Total		98.5%

Whether rock melts to create magma depends on several factors:

- Temperature: Temperature increases with depth, so melting is more likely to occur at greater depths.
- Pressure: Pressure increases with depth, but increased pressure raises the melting temperature, so melting is less likely to occur at higher pressures.
- Water: The addition of water changes the melting point of rock. As the amount of water increases, the melting point decreases.
- Rock composition: Minerals melt at different temperatures, so the temperature must be high enough to melt at least some minerals in the rock. The first mineral to melt from a rock will be quartz (if present) and the last will be olivine (if present).

The different geologic settings that produce varying conditions under which rocks melt will be discussed in the "Plate Tectonics" chapter.

As a rock heats up, the minerals that melt at the lowest temperatures will melt first.**Partial melting** occurs when the temperature on a rock is high enough to melt only some of the minerals in the rock. The minerals that will melt will be those that melt at lower temperatures. **Fractional crystallization** is the opposite of partial melting. This process describes the crystallization of different minerals as magma cools.

Bowen's Reaction Series indicates the temperatures at which minerals melt or crystallize (figure 1). An understanding of the way atoms join together to form minerals leads to an understanding of how different igneous rocks form. Bowen's Reaction Series also explains why some minerals are always found together and some are never found together.

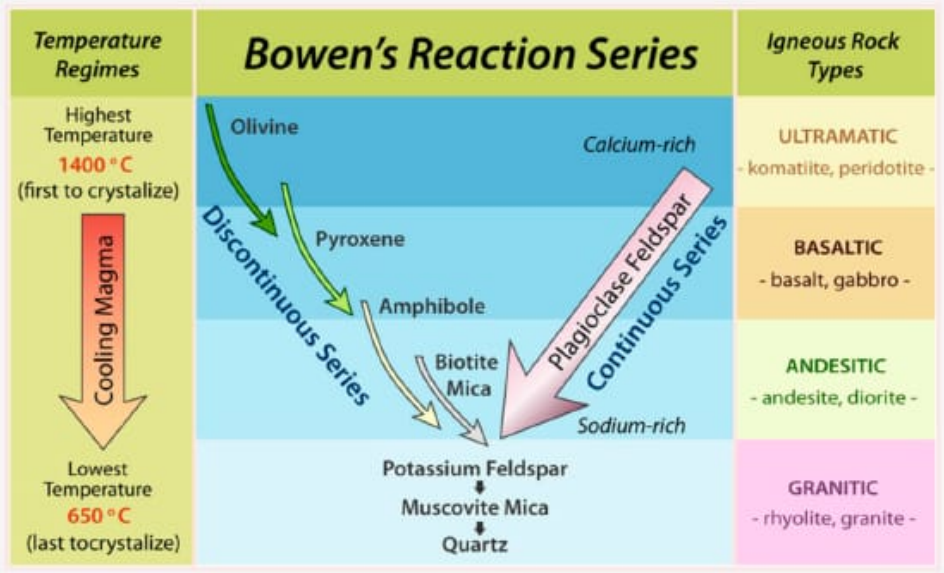


Figure 1. Bowen's Reaction Series

Follow this link to see a diagram illustrating Bowen's Reaction Series.

This excellent video that explains Bowen's Reaction Series in detail.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

If the liquid separates from the solids at any time in partial melting or fractional crystallization, the chemical composition of the liquid and solid will be different. When that liquid crystallizes, the resulting igneous rock will have a different composition from the parent rock.

Intrusive and Extrusive Igneous Rocks

Igneous rocks are called **intrusive** when they cool and solidify beneath the surface. Intrusive rocks form plutons and so are also called plutonic. A **pluton** is an igneous intrusive rock body that has cooled in the crust. When magma cools within the Earth, the cooling proceeds slowly. Slow cooling allows time for large crystals to form, so intrusive igneous rocks have visible crystals. Granite is the most common intrusive igneous rock (see figure 2 for an example).

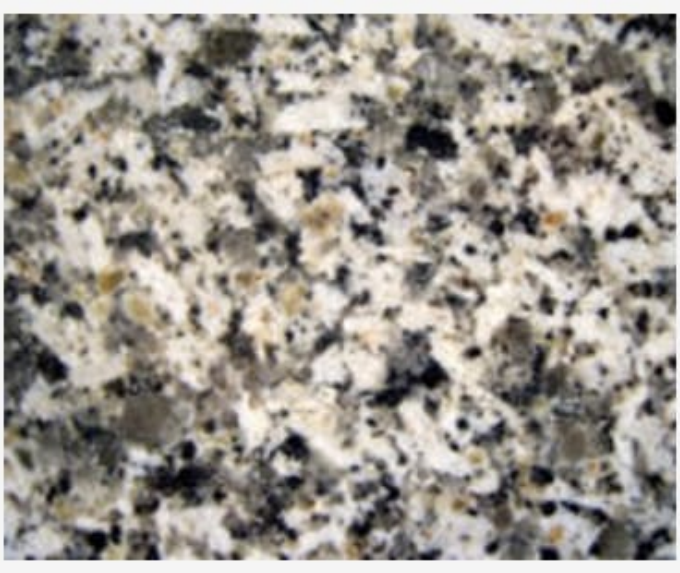


Figure 2. Granite is made of four minerals, all visible to the naked eye: feldspar (white), quartz (translucent), hornblende (black), and biotite (black, platy).

Igneous rocks make up most of the rocks on Earth. Most igneous rocks are buried below the surface and covered with sedimentary rock, or are buried beneath the ocean water. In some places, geological processes have brought igneous rocks to the surface. Figure 3 below shows a landscape in California's Sierra Nevada made of granite that has been raised to create mountains.



Figure 3. California's Sierra Nevada is intrusive igneous rock exposed at Earth's surface.

Igneous rocks are called **extrusive** when they cool and solidify above the surface. These rocks usually form from a volcano, so they are also called **volcanic rocks** (figure 4).



Figure 4. Extrusive igneous rocks form after lava cools above the surface.

Extrusive igneous rocks cool much more rapidly than intrusive rocks. There is little time for crystals to form, so extrusive igneous rocks have tiny crystals (figure 5).



Figure 5. Cooled lava forms basalt with no visible crystals. Why are there no visible crystals?

Some volcanic rocks have a mixed texture. A rock such as an andesite may have large crystals set within a matrix of tiny crystals. In this case, the magma cooled enough to form some crystals before erupting. Once erupted, the rest of the lava cooled rapidly. This is called **porphyritic** texture.

Cooling rate and gas content create other textures (see figure 6 for examples of different textures). Lavas that cool extremely rapidly may have a glassy texture. Those with many holes from gas bubbles have a **vesicular** texture.

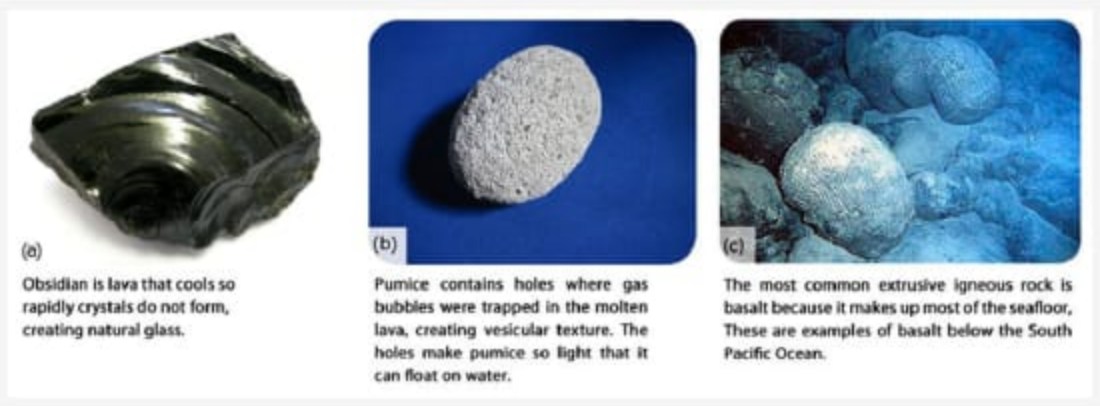


Figure 6. Different cooling rate and gas content resulted in these different textures.

Igneous Rock Classification

Igneous rocks are classified by their composition, from felsic to ultramafic. The characteristics and example minerals in each type are included in table 2.

Table 2. Properties of Igneous Rock Compositions

Composition	Color	Density	Minerals
Felsic	Light	Low	Quartz, orthoclase feldspar
Intermediate	Intermediate	Intermediate	Plagioclase feldspar, biotite, amphibole
Mafic	Dark	High	Olivine, pyroxene
Ultramafic	Very dark	Very high	Olivine

Table 3. Silica Composition and Texture of Major Igneous Rocks

Type	Amount of Silica	Extrusive	Intrusive
Ultramafic	<45%	Komatiite	Peridotite
Mafic	45-52%	Basalt	Gabbro
Intermediate	52-63%	Andesite	Diorite
Intermediate-Felsic	63-69%	Dacite	Granodiorite
Felsic	>69% SiO_2	Rhyolite	Granite

Some of the rocks in the table 3 were pictured earlier in this chapter. Look back at them and, using what you know about the size of crystals in extrusive and intrusive rocks and the composition of felsic and mafic rocks, identify the rocks in the following photos in figure 7:

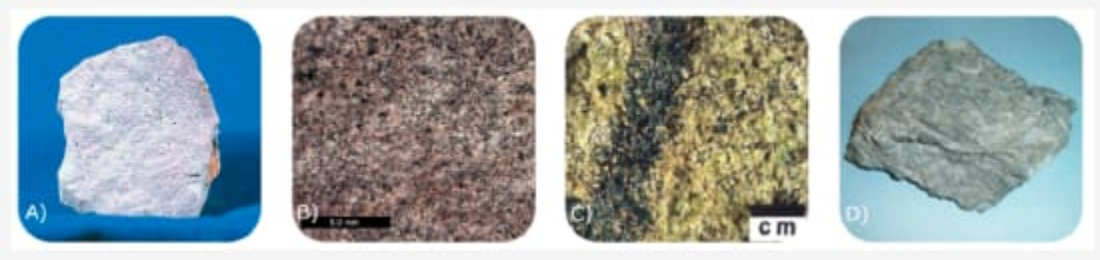


Figure 7. These are photos of A) rhyolite, B) gabbro, C) peridotite, and D) komatiite.

Uses of Igneous Rocks

Igneous rocks have a wide variety of uses. One important use is as stone for buildings and statues. Granite is used for both of these purposes and is popular for kitchen countertops (figure 8).



Figure 8. Granite is an igneous rock used commonly in statues and building materials.

Pumice is commonly used as an abrasive. Pumice is used to smooth skin or scrape up grime around the house. When pumice is placed into giant washing machines with newly manufactured jeans and tumbled, the result is “stone-washed” jeans. Ground up pumice stone is sometimes added to toothpaste to act as an abrasive material to scrub teeth.

Peridotite is sometimes mined for peridot, a type of olivine that is used in jewelry. Diorite was used extensively by ancient civilizations for vases and other decorative artwork and is still used for art today (Figure 9).

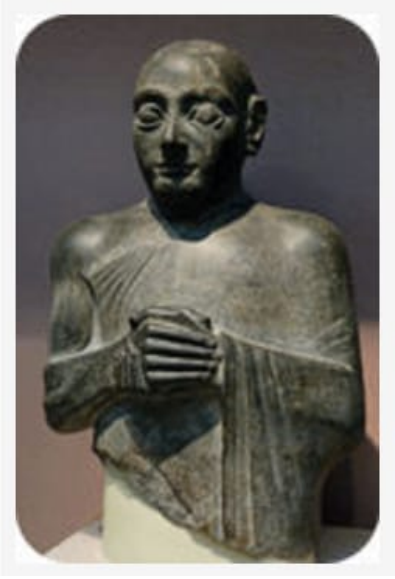


Figure 9. This diorite statue was made in approximately 2120 BC.

SEDIMENTARY ROCKS



Figure 10. The White House of the USA is made of a sedimentary rock called sandstone.

The White House (shown in the figure 10) is the official home and workplace of the President of the United States of America. Why do you think the White House is white? If you answered, “Because it is made of white rock,” you would be only partially correct. Construction for the White House began in 1792. Its outside walls are made of the sedimentary rock sandstone. This sandstone is very porous and is easily penetrated by rainwater. Water damage was common in the early days of construction for the building. To stop the water damage, workers covered the sandstone in a mixture of salt, rice, and glue, which help to give the White House its distinctive white color.

Sediments

Sandstone is one of the common types of sedimentary rocks that form from sediments. There are many other types. Sediments may include:

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

Rocks at the surface undergo mechanical and chemical weathering. These physical and chemical processes break rock into smaller pieces. Physical weathering simply breaks the rocks apart. Chemical weathering dissolves the less stable minerals. These original elements of the minerals end up in solution and new minerals may form. Sediments are removed and transported by water, wind, ice, or gravity in a process called erosion (figure 11). Much more information about weathering can be found in the “Weathering and Formation of Soil” chapter. Erosion is described in detail in the “Erosion and Deposition” chapter.

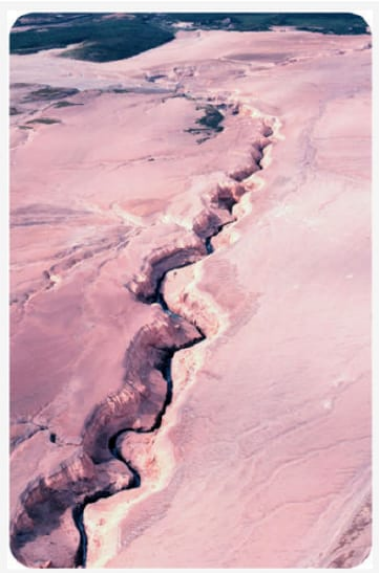


Figure 11. Water erodes the land surface in Alaska's Valley of Ten Thousand Smokes.

Streams carry huge amounts of sediment (figure 12). The more energy the water has, the larger the particle it can carry. A rushing river on a steep slope might be able to carry boulders. As this stream slows down, it no longer has the energy to carry large sediments and will drop them. A slower moving stream will only carry smaller particles.



Figure 12. A river dumps sediments along its bed and on its banks.

Sediments are deposited on beaches and deserts, at the bottom of oceans, and in lakes, ponds, rivers, marshes, and swamps. Avalanches drop large piles of sediment. Glaciers leave large piles of sediments, too. Wind can only transport sand and smaller particles. The type of sediment that is deposited will determine the type of sedimentary rock that can form. Different colors of sedimentary rock are determined by the environment where they are deposited. Red rocks form where oxygen is present. Darker sediments form when the environment is oxygen poor.

Sedimentary Rock Formation

Accumulated sediments harden into rock by **lithification**, as illustrated in figure 13. Two important steps are needed for sediments to lithify.

1. Sediments are squeezed together by the weight of overlying sediments on top of them. This is called **compaction**. Cemented,

non-organic sediments become **clastic** rocks. If organic material is included, they are **bioclastic** rocks.
2. Fluids fill in the spaces between the loose particles of sediment and crystallize to create a rock by **cementation.**



Figure 13. This cliff is made of sandstone. Sands were deposited and then lithified.

The sediment size in clastic sedimentary rocks varies greatly (see table 4).

Table 4. Sedimentary rock sizes and features

Rock	Sediment Size	Other Features
Conglomerate	Large	Rounded
Breccia	Large	Angular
Sandstone	Sand-sized	
Slitstone	Silt-sized, smaller than sand	
Shale	Clay-sized, smallest	

When sediments settle out of calmer water, they form horizontal layers. One layer is deposited first, and another layer is deposited on top of it. So each layer is younger than the layer beneath it. When the sediments harden, the layers are preserved. Sedimentary rocks formed by the crystallization of chemical precipitates are called **chemical sedimentary rocks**. As discussed in the “Earth’s Minerals” chapter, dissolved ions in fluids precipitate out of the fluid and settle out, just like the halite in figure 14.



Figure 14. The evaporite, halite, on a cobble from the Dead Sea, Israel.

Biochemical sedimentary rocks form in the ocean or a salt lake. Living creatures remove ions, such as calcium, magnesium, and potassium, from the water to make shells or soft tissue. When the organism dies, it sinks to the ocean floor to become a biochemical sediment, which may then become compacted and cemented into solid rock (figure 15).



Figure 15. Fossils in a biochemical rock, limestone, in the Carmel Formation in Utah.

Table 5 shows some common types of sedimentary rocks.

Table 5. Common Sedimentary Rocks

Picture	Rock Name	Type of Sedimentary Rock

Table 5. Common Sedimentary Rocks		
	Conglomerate	Clastic (fragments of non-organic sediments)
	Breccia	Clastic
	Sandstone	Clastic

Table 5. Common Sedimentary Rocks

	Siltstone	Clastic
	Shale	Clastic

Table 5. Common Sedimentary Rocks		
	Rock Salt	Chemical precipitate
	Gypsum	Chemical precipitate

Table 5. Common Sedimentary Rocks		
	Dolostone	Chemical precipitate
	Limestone	Bioclastic (sediments from organic materials, or plant or animal remains)

Table 5. Common Sedimentary Rocks		
	Coal	Organic

Uses of Sedimentary Rocks

Sedimentary rocks are used as building stones, although they are not as hard as igneous or metamorphic rocks. Sedimentary rocks are used in construction. Sand and gravel are used to make concrete; they are also used in asphalt. Many economically valuable resources come from sedimentary rocks. Iron ore and aluminum are two examples.

METAMORPHIC ROCKS

In the large outcrop of metamorphic rocks in figure 16, the rocks' platy appearance is a result of the process metamorphism. Metamorphism is the addition of heat and/or pressure to existing rocks, which causes them to change physically and/or chemically so that they become a new rock. Metamorphic rocks may change so much that they may not resemble the original rock.



Figure 16. The platy layers in this large outcrop of metamorphic rock show the effects of pressure on rocks during metamorphism.

Metamorphism

Any type of rock—igneous, sedimentary, or metamorphic—can become a metamorphic rock. All that is needed is enough heat and/or pressure to alter the existing rock's physical or chemical makeup without melting the rock entirely. Rocks change during metamorphism because the minerals need to be stable under the new temperature and pressure conditions. The need for stability may cause the structure of minerals to rearrange and form new minerals. Ions may move between minerals to create minerals of different chemical composition. Hornfels, with its alternating bands of dark and light crystals, is a good example of how minerals rearrange themselves during metamorphism. Hornfels is shown in table 6.



Figure 17. A foliated metamorphic rock.

Extreme pressure may also lead to **foliation**, the flat layers that form in rocks as the rocks are squeezed by pressure (figure 17). Foliation normally forms when pressure is exerted in only one direction. Metamorphic rocks may also be non-foliated. Quartzite and limestone, shown in table 6, are nonfoliated.

The two main types of metamorphism are both related to heat within Earth:

1. **Regional metamorphism:** Changes in enormous quantities of rock over a wide area caused by the extreme pressure from overlying rock or from compression caused by geologic processes. Deep burial exposes the rock to high temperatures.
2. **Contact metamorphism:** Changes in a rock that is in contact with magma because of the magma's extreme heat.

Table 6 shows some common metamorphic rocks and their original parent rock.

Table 6.

Picture	Rock Name	Type of Metamorphic Rock	Comment

Table 6.

	Slate	Foliated	Metamorp of shale
	Phyllite	Foliated	Metamorp of slate, bu under grea heat and pressure t slate

Table 6.

	Schist	Foliated	Often deri from metamorp of claysto shale; metamorp under mo heat and pressure t phyllite
	Gneiss	Foliated	Metamorp of various different r under extr conditions heat and pressure

Table 6.

	Hornfels	Non-foliated	Contact metamorp of various different r types
	Quartzite	Non-foliated	Metamorp of sandsto

Table 6.

	Marble	Non-foliated	Metamorp of limesto
	Metaconglomerate	Non-foliated	Metamorp of conglor

Uses of Metamorphic Rocks

Quartzite and marble are commonly used for building materials and artwork. Marble is beautiful for statues and decorative items such as vases (see an example in figure 18). Ground up marble is also a component of toothpaste, plastics, and paper.



Figure 18. Marble is used for decorative items and in art.

Quartzite is very hard and is often crushed and used in building railroad tracks (see figure 19). Schist and slate are sometimes used as building and landscape materials. Graphite, the “lead” in pencils, is a mineral commonly found in metamorphic rocks.



Figure 19. Crushed quartzite is sometimes placed under railroad tracks because it is very hard and durable.

LESSON SUMMARY

- Igneous rocks form either when they cool very slowly deep within the Earth (intrusive) or when magma cools rapidly at the Earth’s surface (extrusive).
- Rock may melt to create magma if temperature increases, pressure decreases, or water is added. Different minerals melt at different temperatures.
- Igneous rocks are classified on their composition and grain size, which indicates whether they are intrusive or extrusive.
- Weathering and erosion produce sediments. Sediments are transported by water, wind, ice, or gravity.
- After sediments are deposited, they undergo compaction and/or cementation to become sedimentary rocks.
- Biochemical sedimentary rocks form when living creatures using ions in water to create shells, bones, or soft tissue die and fall to the bottom as sediments.
- Metamorphic rocks form when heat and pressure transform an existing rock into a new rock.
- Contact metamorphism occurs when hot magma transforms the rock that it contacts.

- Regional metamorphism transforms large areas of existing rocks under the tremendous heat and pressure created by geologic processes.

REFLECTION QUESTIONS

- What skill does this content help you develop?
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3.6: Igneous Rocks

INTRODUCTION

Magma is molten rock inside the earth. It is the source of all igneous rock. Because the earth was largely molten at its origin, magma may be considered the beginning of the rock cycle. Igneous rocks contain information about how they originate. By carefully analyzing igneous rocks and interpreting the information they contain, we can deduce processes that take place within the earth and we can understand volcanic processes that take place on the earth's surface.

The study of igneous rocks enables us to understand the igneous part of geologic history. For example, at the end of the Triassic period, 245 million years ago, the greatest mass extinction ever known took place, wiping out more life forms on earth than the mass extinction that led to the demise of dinosaurs 65 million years ago at the end of the Cretaceous. At the end of the Triassic, a huge amount of basalt erupted onto the earth. Many geologists think that the gases and particles released into the atmosphere by those eruptions may have been a major factor in the end of Triassic mass extinction. Those scientists are studying the information contained in the basalts of that age to further test their hypotheses.

Igneous rocks contain three essential sources of information: their minerals, their overall chemical composition, and their igneous texture. Igneous rock names are based on specific combinations of these features. Igneous rocks also contain isotopic information that is used in determining absoloute ages and in further characterizing the origin of the magma. Special equipment and expertise is required to conduct isotopic and precise chemical analyses. Fortunately, with some basic training and practice anyone can learn to identify the minerals, composition and texture of an igneous rock; name the rock; and interpret key information about its origins.

All igneous rocks, other than pure volcanic glass, contain minerals. The minerals provide details on the chemical composition of the rock, and on the conditions in which the magma originated, cooled, and solidified. Geologists conduct chemical analyses of minerals to determine the temperatures and pressures at which they formed and to identify the dissolved gases and chemical elements that were present in the magma.

Most magmas are predominantly silicate liquids, composed largely of silica tetrahedra that have not yet bonded together to become silicate minerals. The chemical composition of an igneous rock tells us about the origin of the magma, beginning with which type of rock melted within the earth to form the magma in the first place, and how deep in the earth the melting occurred. Once magma has formed inside the earth, its composition may be modified. Minerals can grow from the magma and separate from it, changing the chemistry of the remaining liquid. Or, one body of magma can mix with another that has a different composition.

Magmas come in a range of compositions, from rich in silica and poor and iron and magnesium (felsic) to moderate in silica and high in iron and magnesium (mafic). Felsic igneous rocks, as a whole rock, tend to have light colors or shades: white, pink, light brown, light gray. Mafic igneous rocks, on the whole, tend to be dark colored, commonly black or dark gray. Most mafic magma originates by melting of rocks in the mantle that are extremely rich in iron and magnesium. Felsic magma usually originates in the crust or by the shedding of mafic minerals as magma rises through the crust.

The igneous texture tells us how the magma cooled and solidified. Magma can solidify into igneous rock in several different ways, each way resulting in a different igneous texture. Magma may stay within the earth, far below ground level, and crystallize into plutonic igneous rock (also known as intrusive igneous rock). Or, magma may flow out onto surface of the earth as a lava flow. Another way that igneous rock forms is by magma erupting explosively into the air and falling to earth in pieces known as pyroclastic material, also called tephra. Lava flows and pyroclastic material are volcanic igneous rock (also known as extrusive igneous rock).

The igneous texture of a rock is not how it feels in your hand, not whether it is rough or smooth. The igneous texture describes whether the rock has mineral crystals or is glassy, the size of the mineral grains, and the rock's porosity (empty spaces).

This basics page focuses on igneous rocks and gives you the background needed to understand the terms used in the igneous rock classification table.

HOW ARE IGNEOUS ROCKS CLASSIFIED?

There are two main types of igneous rocks: (1) plutonic (intrusive) rocks, which form by solidification of molten rock deep within the earth, and (2) volcanic (extrusive) rocks, which solidify from molten rock erupted to the surface. Volcanic rocks break down into two more categories: (a) lava flows and (b) tephra (pyroclastic material).

Igneous rocks are classified on the basis of their composition and their texture. Magma, and the igneous rock it becomes, has a range of chemical compositions.For example, basalt is a mafic lava flow rock which originates from melting of the upper mantle. The way that magma turns into a solid rock gives it a distinctive igneous texture. For example, magma that becomes a pluton by slowly crystallizing (growing minerals) within the crust will develop a very different texture from magma that becomes an ash flow tuff as a result of semi-molten volcanic ash spewing across a landscape and then settling down and welding itself together into solid rock.

Igneous Rock Textures

The texture of an igneous rock results from the cooling, crystallization, and solidification history of the magma that formed it. Once you know the texture of an igneous rock, you can usually deduce from the texture whether it was intrusive or extrusive, lava flow or pyroclastic.

Texture in this context is not whether the rock feels rough or smooth to the touch. Igneous texture terms have objective definitions that refer only to igneous rocks.

Volcanic Rocks

Let us start with textures associated with rocks formed by lava flows. Magmas that erupt as lava onto the earth's surface cool and solidify rapidly. Rapid cooling results in an aphanitic igneous texture, in which few or none of the individual minerals are big enough to see with the naked eye. This is sometimes referred to as a fine-grained igneous texture.

Some lava flows, however, are not purely fine-grained. If some mineral crystals start growing while the magma is still underground and cooling slowly, those crystals grow to a large enough size to be easily seen, and the magma then erupts as a lava flow, the resulting texture will consist of coarse-grained crystals embedded in a fine-grained matrix. This texture is called porphyritic.

If lava has bubbles of gas escaping from it as it solidifies, it will end up with "frozen bubble holes" in it. These "frozen bubble holes" are called vesicles, and the texture of a rock containing them is said to be vesicular.

If so many bubbles are escaping from lava that it ends up containing more bubble holes than solid rock, the resulting texture is said to be frothy. Pumice is the name of a type of volcanic rock with a frothy texture.

If lava cools extremely quickly, and has very little water dissolved in it, it may freeze into glass, with no minerals (glass by definition is not a mineral, because it does not have a crystal lattice). Such a rock is said to have a glassy texture. Obsidian is the common rock that has a glassy texture, and is essentially volcanic glass. Obsidian is usually black.

Now let us briefly consider textures of tephra or pyroclastic rocks. Like lava flow rocks, these are also extrusive igneous rocks. However, instead of originating from lava that flowed on the earth's surface, tephra is volcanic material that was hurled through the air during a volcanic eruption.

A pyroclastic rock made of fine-grained volcanic ash may be said to have a fine-grained, fragmental texture. Volcanic ash consists mainly of fine shards of volcanic glass. It may be white, gray, pink, brown, beige, or black in color, and it may have some other fine crystals and rock debris mixed in. The term "fine-grained, fragmental" is easy to confuse with the term fine-grained (aphanitic). An equivalent term that is less ambiguous is tuffaceous. Rocks made of volcanic ash are called tuff.

A pyroclastic rock with many big chunks of material in it that were caught up in the explosive eruption is said to have a coarse-grained, fragmental texture. However, a better word that will avoid confusion is to say it has a brecciated texture, and the rock is usually called a volcanic breccia. The bigger chunks of material in a volcanic breccia are more than 1 cm (5/8 inch) across, and sometimes are much bigger.

Plutonic Rocks

When magma cools slowly underground and solidifies there, it usually grows crystals big enough to be seen easily with the naked eye. These visible crystals comprise the whole rock, not just part of it as in a porphyritic, fine-grained igneous rock. The texture of an igneous rock made up entirely of crystals big enough to be easily seen with the naked eye is phaneritic. Phaneritic texture is sometimes referred to as coarse-grained igneous texture. Granite, the most well known example of an intrusive igneous rock, has a phaneritic texture.

Sometimes an intrusion of magma that is crystallizing slowly underground releases large amounts of hot water. The water is released from the magma as extremely hot fluid with lots of chemical elements dissolved in it. This hydrothermal fluid gets into cracks and voids in the earth's crust, and as it cools it may grow very large minerals from the dissolved chemical elements. A rock consisting of such large minerals is said to have a pegmatitic texture, which means the average mineral size is greater than 1 cm in diameter (and sometimes is much larger). The name of an igneous rock with a pegmatitic texture is pegmatite. Pegmatites are commonly found in or near the margins of bodies of granite.

Igneous Rock Compositions

The most common igneous compositions can be summarized in three words: mafic (basaltic), intermediate (andesitic), and felsic (granitic).

Felsic composition is higher in silica (SiO_2) and low in iron (Fe) and magnesium (Mg). Mafic composition is higher in iron and magnesium and lower in silica. Intermediate compositions contain silica, iron, and magnesium in amounts that are intermediate to felsic and mafic compositions.

Composition and Color

Composition influences the color of igneous rocks. Felsic rocks tend to be light in color (white, pink, tan, light brown, light gray). Mafic rocks tend to be dark in color (black, very dark brown, very dark gray, dark green mixed with black). The color distinction comes from the differences in iron and magnesium content. Iron and, to a lessor extent, magnesium give minerals a darker color. Intermediate igneous rocks tend to have intermediate shades or colors (green, gray, brown).

The association between color and composition is useful because before you can name and interpret an igneous rock you need to determine both its texture AND its composition. If you have an aphanitic igneous rock, which has no crystals big enough to see without a microscope, you can estimate its composition based on its color: pink or nearly white, felsic; medium gray, intermediate; very dark or black, mafic.

This color rule works most of the time but there are two problems that you need to keep in mind. First, the rule does not work for glassy igneous rocks. Obsidian, which is volcanic glass, is usually black, even though it has a felsic composition. That is because a tiny amount of iron, too little to color minerals very darkly, can color glass darkly.

The second problem is that when igneous rocks have been exposed to air and water for a long time, they start to weather, which changes their color. Geologists working in the field carry a rock hammer, so they can break off the weathered, outer parts of rocks to see the "fresh," unweathered rock inside.

If you can see and identify the minerals in an igneous rock, you can gain further information about the igneous composition. Igneous rocks with quartz in them are usually felsic. Igneous rocks with olivine in them are usually mafic. Igneous rocks with neither quartz nor olivine in them are most commonly intermediate.

ORIGINS OF IGNEOUS ROCKS

Once you have determined the texture and composition of an igneous rock, you can name it and you can also say something important about how it formed. For example, a coarse-grained, felsic igneous rock is not only a granite, it is an intrusive igneous rock that formed from slow cooling and crystallization of a body of magma within the earth's crust. The intrusion of large bodies of granite – batholiths – is usually part of the origin of a mountain range. Similarly, a fine-grained, mafic igneous rock is not only a basalt, it is an extrusive igneous rock that formed from rapid cooling and crystallization of a lava flow at earth's surface.

HOW TO IDENTIFY IGNEOUS ROCKS

Igneous rocks can be distinguished from sedimentary rocks by the lack of beds, lack of fossils, and lack of rounded grains in igneous rocks, and the presence of igneous textures. A granite, for example, can be distinguished from a sandstone because rather than being a mixture of weathered, rounded grains compressed and cemented together, granite consists of a small number of minerals in shiny black, white, or pink colors, with excellent crystal forms, grown together into a completely interlocking pattern. Sandstones, by contrast, have sedimentary bedding (layers) and consist of rounded grains with some spaces between the grains, which you can see with a hand lens or magnifying glass.

Igneous rocks can be distinguished from most regional metamorphic rocks by the lack of foliation (layering) in igneous rocks. Unfoliated metamorphic rocks lack igneous textures and usually contain minerals not found in igneous rocks.

Granite may look like gneiss at first glance, but granite has no layering, no preferred orientation of the minerals. The minerals in a granite grow randomly in all directions, rather than tending to grow parallel to each other.

Igneous rocks are classified on the basis of their texture and their composition. See the previous sections for descriptions of the different igneous textures and compositions.

The igneous rock classification tables that accompany this section are arranged on the basis of igneous textures first, and further broken down on the basis of igneous composition. Remember that igneous composition is estimated on the basis of color: light = felsic composition, medium = intermediate composition, and dark = mafic composition.

Igneous Rock Classification

Pegmatitic Texture (Extremely Coarse-Grained) ***Originates from water-rich intrusions, which cool and crystallize underground***		
Composition	**Most Common Minerals**	**Rock Name**
felsic	Na-plagioclase, orthoclase, quartz, biotite, amphibole, muscovite	pegmatite
Phanertitic Texture (Coarse-Grained) ***Originates in deep intrusions, which cool and crystallize slowly underground***		
Composition	**Most Common Minerals**	**Rock Name**
felsic	Na-plagioclase, orthoclase, quartz, biotite, amphibole, muscovite	granite
intermediate	Na-plagioclase, quartz, orthoclase, amphibole, biotite	granodiorite
	Na-plagioclase, amphibole, pyroxene, biotite	diorite
mafic	Ca-plagioclase, pyroxene, olivine, amphibole	gabbro
Aphanitic Texture (Fine-Grained) ***Originates in lava flows (or very shallow intrusions), which cool rapidly***		
Composition	**Most Common Minerals**	**Rock Name**
felsic	Na-plagioclase, orthoclase, quartz, biotite, amphibole, muscovite	rhyolite
intermediate	Na-plagioclase, quartz, orthoclase, amphibole, biotite	dacite
	Na-plagioclase, amphibole, pyroxene, biotite	andesite
mafic	Ca-plagioclase, pyroxene, olivine, amphibole	basalt
Frothy Texture (Porous, Pumiceous) ***Originates in gas-charged volcanic eruptions, commonly pyroclastic***		
Composition	**Most Common Minerals**	**Rock Name**
felsic	glass (may contain a few minerals typical of felsic rocks)	pumice
mafic	glass (may contain a few mineral typical of mafic rocks)	scoria

Note: Basalt with fewer holes, known as vesicles, is called vesicular basalt. *Scoria has more holes and may be black or red in color.*		
Glassy Texture ***Originates from cooling too rapid to allow crystal lattices to form***		
Composition	**Most Common Minerals**	**Rock Name**
felsic to mafic	glass (no minerals)	obsidian
Note: Obsidian that is transparent at thin edges and has good conchoidal fracture is probably felsic.		
Fragmental Texture—Coarse (Contains Large Rock Fragments) ***Originates from pyroclastic (explosive) eruptions***		
Composition	**Most Common Minerals**	**Rock Name**
felsic to mafic	variable (depending on rock fragments and ash content)	volcanic breccia
Fragmental Texture—Fine (Mainly Volcanic Ash) ***Originates from pyroclastic (explosive) eruptions***		
Composition	**Most Common Minerals**	**Rock Name**
felsic	may contain a few minerals typical of felsic rocks	rhyolitic tuff
medium	may contain a few minerals typical of intermediate rocks	andesitic tuff
mafic	may contain a few minerals typical of mafic rocks	andesitic tuff

REFLECTION QUESTIONS

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3.7: Sedimentary Rocks

INTRODUCTION

This basics page focuses on sedimentary rocks, which are sediments that were turned into solid rock by geologic processes. Sedimentary rocks contain information about what was occurring on earth's surface at the place and time the sediments were deposited. In some cases sedimentary rocks contain fossils, which provide information about what was living at a certain place and time on earth.

There are two main groups of sedimentary rocks: chemical and clastic. Clastic is sometimes called detrital. Each type of sedimentary rock is formed when sediments lithify (turn into rock). Chemical sediments are sediments that precipitate from solution, for example salt crystals that grow at the bottom of an evaporating body of water. Clastic sediments are solid pieces of weathered and eroded rocks or minerals, for example sand on a beach.

This page provides the background needed to understand the terms used in the sedimentary rock classification table at the end of this page.

LITHIFICATION—SEDIMENTS TO SEDIMENTARY ROCKS

Sedimentary rocks are rocks made of lithified sediment. Sediments are grains of rocks, minerals, or mineraloids deposited on the surface of the earth. Reflect on the rock cycle for an indication of the relationships between the rocks that erode to become sediments and sedimentary rocks. For sediment to become sedimentary rock, it usually undergoes burial, compaction, and cementation.

Clastic sedimentary rocks are the result of weathering and erosion of source rocks, which turns them into pieces—clasts—of rocks and minerals. Once they become pieces, these clasts are free to move away from their source rock and they usually do. They are most often transported by water and deposited as layers of sediment.

The burial stage of lithification involves the deposition of more sediment layers top of those that had been deposited earlier. In a sedimentary basin where sediment is being deposited, it is common for subsidence (lowering) of the basin to be taking place, either because the crust and lithosphere beneath it are subsiding into the mantle to some extent, or because the surrounding uplands are undergoing uplift relative to the basin, or both. This allows thousands of feet of burial, in some cases tens of thousands of feet of burial, to occur.

As sediments are buried, the weight of overlying material exerts pressure, causing compaction of the sediments. The pressure, known as lithostatic pressure, "squeezes" the sediments from all sides into a smaller volume. Lithostatic pressure packs the sediment grains closer together and reduces the porosity – space between the sediment grains.

Some chemical sedimentary rocks are rock as soon as the sediments have been deposited by crystallization of minerals from substances dissolved in water, at the earth's surface. Examples include rock salt and other evaporite deposits. These sediments of salt crystals and other minerals form sedimentary rock without having to undergo burial and compaction.

During burial and compaction, sediments will undergo some amount of cementation. Cementation refers to the growth of new minerals between the sediment grains. These new minerals bind the sediment grains together. One form of cementation is growth of quartz rims on the surfaces of pre-existing quartz grains in the sediment. This new mineral growth is a result of water in the pore spaces that dissolves and precipiates quartz. A second common cementing mineral is hematite, a red or rust-colored iron oxide mineral, which precipitates onto the sediment grains from a combination of dissolved iron and oxygen from water in the pore spaces. A third common cementing mineral is calcite, which also precipitates from ions dissolved in the water in the pore spaces during lithification. Although there are other cementing minerals, quartz, hematite, and calcite are common cementing minerals that grow between or on the surfaces of the original sedimentary grains.

Generalized steps from source to sedimentary rock:
weathering >> erosion >> transport >> deposition >> burial >> compaction >> cementation >> sedimentary rock

MINERALS AND SEDIMENTARY ROCKS

Any type of rock containing any type of mineral will undergo weathering and erosion at the earth's surface. However, some minerals are more stable than others in earth's surface environments and are more likely to be found in sedimentary rocks.

Grains of clastic sediment, which are called clasts are winnowed and modified during the weathering-to-deposition process. Weathering of minerals will gradually eliminate the physically weaker and chemically more reactive minerals, increasing the relative abundance of more resistant minerals. Quartz tends to become increasingly abundant during the process, due to its common occurrence in the source rocks combined with its hardness and lack of cleavage, which makes it resistant to breaking down physically. Quartz is not easily dissolved or chemically altered, so it is resistant to breakdown by chemical reactions as well. That is why beach sand is often more rich in quartz than any other mineral. Sediments rich in quartz are considered mineralogically "mature" because they have been subjected to a longer interval of physical and chemical modification during the erosion-to-deposition process. Mature sediments are deposited farther from their source rocks in space and/or time than immature sediments.

Feldspars are the most common type of mineral in earth's crust and are also abundant in many clastic sediments and sedimentary rocks. Although feldspar is a fairly hard mineral, it does cleave (split apart) and is chemically reactive, especially in the presence of water. The most abundant product of chemical reaction of feldspar and water is clay minerals. During the erosion-to-deposition process, clastic sediments lose feldspar and gain a larger proportion of clay. Other minerals such as amphiboles, micas, and carbonates are relatively soft and chemically reactive and tend to be scarce or absent as sediment grains in mature clastic sediments, although calcite may be present in clastic sedimentary rocks as a secondary, cementing mineral that grew during lithification.

Minerals in chemical sedimentary rocks precipitate from water and usually remain in place or are not transported far before lithification. Such mineral sediments are subjected to little, if any, erosion and transportation. Therefore, the minerals in chemical sedimentary rocks are not winnowed during the weathering-to-deposition process as are the minerals in clastic sedimentary rocks. In some cases, during the formation of chemical sediments, the minerals may change as a result of chemical reactions. For example, dolostone is a chemical sedimentary rock that forms in certain coastal environments by alteration of precipitated calcite to dolomite.

Besides minerals, mineraloid solids occur in some chemical sedimentary rocks. For example, the carbonaceous material in coal is an organic mineraloid rather than a mineral. Another example, opal, is a chemical sedimentary rock that does not have a fully developed crystal lattice and therefore is a mineraloid.

SEDIMENTARY ROCK TEXTURES

In clastic sediments the sedimentary texture includes the grain size, rounding, and sorting of the grains, all of which are related to what happened to the sediment during the weathering-to-deposition process.Because the processes that lead to the formation of chemical sedimentary rocks do not involve the weather-to-deposition process, there is no widely agreed-upon texture scheme that applies to chemical sedimentary rocks.

Clastic Textures

Clastic sedimentary textures are described in terms of the size of the sediment grains, how round they are, and how well they are sorted.

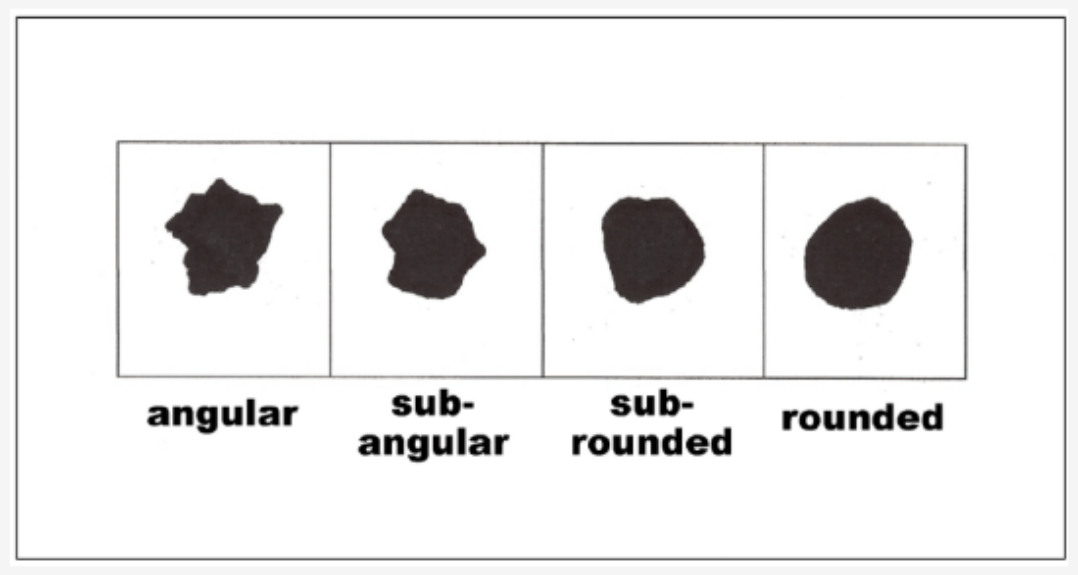
Grain Size

The diameter or width of a clastic sediment grain determines its grain size. Specific ranges of grain size have specific names.

- Gravel is an overall name for large sediment grain size, which includes boulder, cobble, and pebble.
- Sand includes sediment grains ranging in size from 2mm to 0.625 mm.
- Silt is the name of a sediment grain that range in size from 0.625 mm to 0.0039 mm.
- Mud is the smallest grain size and is also known as clay. It is important to distinguish the grain size called clay from the mineral called clay. Clay sized grains are too small to see individually without the aid of a microscope.

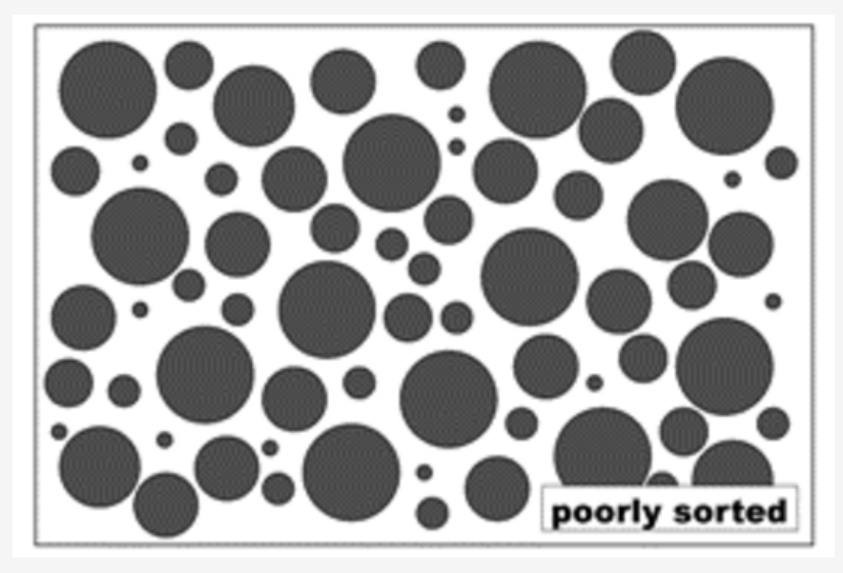
Rounding

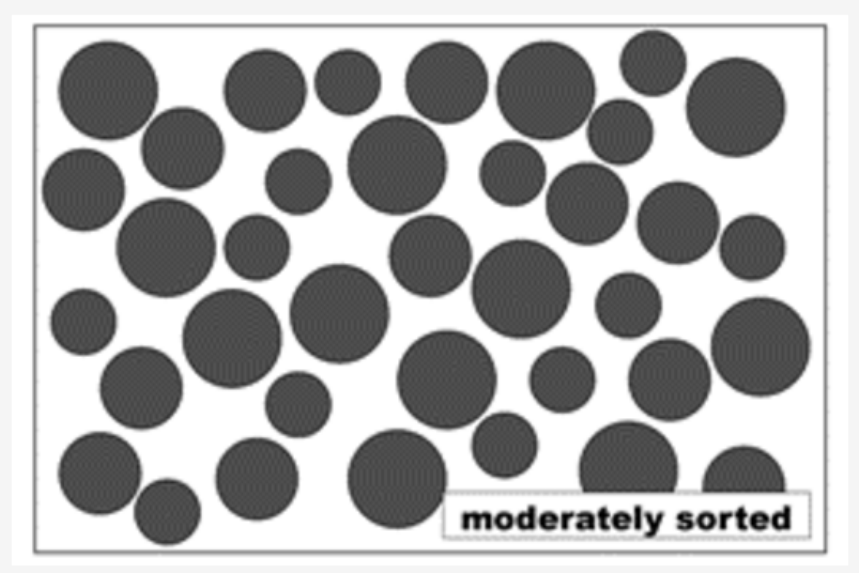
Clastic sediment grains can be round, angular, or in-between (subangular or subrounded). Breccia is a clastic sedimentary rock that by definition consists largely of angular grains of pebble size or larger. Conglomerate, another sedimentary rock, consists largely of rounded grains of pebble size or larger. The schematic diagram below shows classes of rounding, from the left: angular, subangular, subrounded, rounded. Not shown are very angular and well-rounded, which are less common.

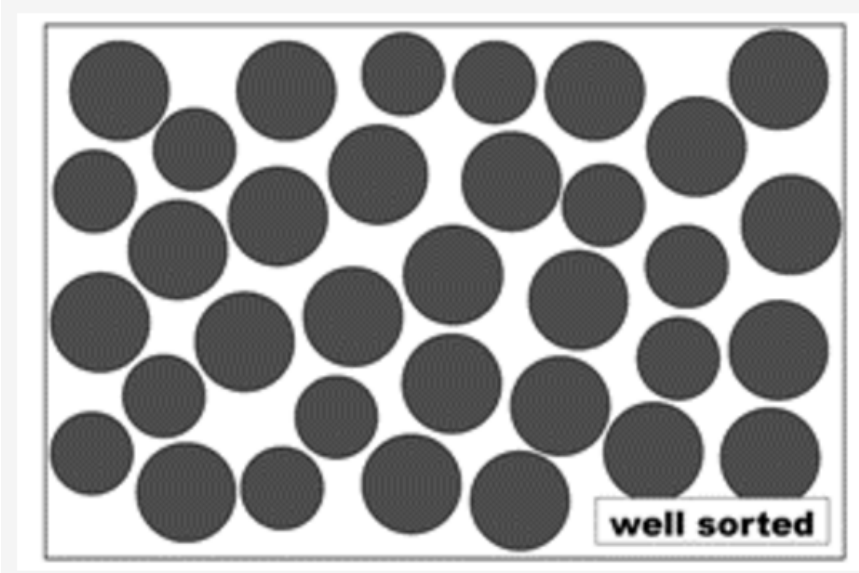


Sorting

The extent to which all the grains are the same size is known as sorting. If all the grains are the same size, they are well sorted. Some sandstones are well sorted, and some are not. Most conglomerates are poorly sorted, and consist of a mixture of grain sizes ranging from sand to pebble. The schematic diagrams below represent poorly-sorted, moderately-sorted, and well-sorted sediments.







Other Aspects of Texture

Other aspects of clastic sedimentary texture include the packing of the grains, the porosity of the rock, and the hardness of the rock as a whole.

The packing of the grains applies only to poorly sorted sediments in which the finer clasts form a matrix around the coarser clasts. If the large grains are touching each other, the packing is said to be clast-supported. If the coarse grains are separate and not touching each other, with the finer-grained sediment between them, the packing is said to be matrix-supported.

The porosity of a rock or sediment is the amount of empty space between the grains of sediment.

The hardness of the rock refers to how easily it breaks apart. Shale is harder than claystone, for example.

HOW TO IDENTIFY SEDIMENTARY ROCKS

Clastic

The common names of clastic sedimentary rocks—conglomerate, sandstone, siltstone, and shale—are based solely on grain size. However, there are more precise names within these broader categories that are based on clastic sediment features other than grain size. Breccia is a clastic sedimentary rock distinguished from conglomerate by the angularity of its clasts.

A clastic sedimentary rock simply made of sand-sized grains qualifies as sandstone, regardless of what minerals the grains are made of. More complete names for various sandstones are based on their mineral composition. Some sandstones are made almost entirely of quartz. Sandstone made virtually entirely of quartz is called arenite. Other sandstones have lots of feldspar mixed with quartz. Such sandstones are called arkose. Other sandstones are a mixture of feldspar, quartz, clay, and small fragments of "lithics," dark-appearing minerals and rock fragments, which represent mineralogically immature sediments. Such sandstones are technically known as lithic wackes, although geologists often call them by their old name, graywackes, and the rocks are sometimes informally described as "dirty sandstones."

In using the sedimentary rock classification table that accompanies this section, you will see that the clastic sedimentary rocks are classified on the basis of grain size. Sandstones are rocks made of sand-size grains. Shale is layered sedimentary rock made of fine mud-size grains too small to see with the naked eye.

Chemical

The key to naming chemical sedimentary rocks is the minerals from which they are made. For example, all limestones consist mostly of the mineral calcite. Coal is made of carbon. Rock salt is made of salt minerals such as halite. Gypsum rock is made of the mineral gypsum. Chalcedony is made of microcrystalline quartz, quartz grains so tiny that they cannot be distinguished even with a standard optical microscope.

SETTINGS FOR THE ORIGIN OF SEDIMENTARY ROCKS

The minerals, textures, structures, and fossils in sedimentary rocks are used to infer what was happening on earth biologically, chemically, physically—in sum geologically—at the time and place the sediments were originally deposited.

SEDIMENTARY ROCK CLASSIFICATION

Clastic Sedimentary Rocks			
Grain Size	**Rounding**	**Sorting**	**Rock Name**
gravel coarse (> 2 mm)	angular	poorly	breccia
	rounded	poorly	conglomerate
sand medium (0.0625–2 mm)	variable	variable	sandstone
	rounded to subangular	well to moderately	quartz arenite— >90% quartz
	subrounded to angular	well to moderately	arkose— >25% feldspar
	subangular to angular	moderately to poorly	graywacke—high % lithics, clay matrix
silt fine (0.004–0.0625 mm)	variable	well	siltstone
clay extra fine (< 0.004 mm)	not visible	well	shale—breaks along bedding planes

			mudstone—lacks bedding planes
			claystone—pure mineral clay, very soft
Chemical Sedimentary Rocks			
Mineral	**Distinguishing Characteristics**	**Rock Name**	**Common Depositional Environment**
calcite	softer than glass, reacts to HCl	limestone	warm shallow ocean
calcite	visible fossils, softer than glass, reacts to HCl	fossiliferous limestone	warm shallow ocean
dolomite	white to pink, softer than glass, reacts to HCl only when powdered	dolostone	saline lagoon
calcite	gray or brown, porous, reacts to HCl	travertine	evaporated spring or cave water
calcite	white, powdery, reacts to HCl	chalk	warm shallow ocean
microscopic quartz	conchoidal fracture	chert	deep ocean floor
microscopic quartz	red, conchoidal fracture	jasper	deep ocean floor
microscopic quartz	black, conchoidal fracture	flint	nodules in limestone
microscopic quartz	translucent, layered, conchoidal fracture	agate	nodules in volcanic rocks
microscopic quartz	white, powdery	diatomite	lakes in volcanic environments
carbon	black, soft, low density	coal	heavily vegetated swamp
halite	tastes like salt, cubic crystals and cleavage	rock salt	evaporating water body
gypsum	softer than fingernail	gypsum rock	evaporating water body

REFLECTION QUESTIONS

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3.8: Metamorphic Rocks

INTRODUCTION

A metamorphic rock used to be some other type of rock, but it was changed inside the Earth to become a new type of rock. The word metamorphism comes from ancient Greek words for “change” (meta) and “form” (morph). The type of rock that a metamorphic rock used to be, prior to metamorphism, is called the protolith. During metamorphism the mineral content and texture of the protolith are changed due to changes in the physical and chemical environment of the rock. Metamorphism can be caused by burial, tectonic stress, heating by magma, or alteration by fluids. At advanced stages of metamorphism, it is common for a metamorphic rock to develop such a different set of minerals and such a thoroughly changed texture that it is difficult to recognize what the protolith was.

A rock undergoing metamorphism remains a solid rock during the process. Rocks do not melt during most conditions of metamorphism. At the highest grade of metamorphism, rocks begin to partially melt, at which point the boundary of metamorphic conditions is surpassed and the igneous part of the rock cycle is entered.

Even though rocks remain solid during metamorphism, fluid is generally present in the microscopic spaces between the minerals. This fluid phase may play a major role in the chemical reactions that are an important part of how metamorphism occurs. The fluid usually consists largely of water.

Metamorphic rocks provide a record of the processes that occurred inside Earth as the rock was subjected to changing physical and chemical conditions. This gives the geologist literally “inside information” on what occurs within the Earth during such processes as the formation of new mountain ranges, the collision of continents, the subduction of oceanic plates, and the circulation of sea water into hot oceanic crust. Metamorphic rocks are like probes that have gone down into the Earth and come back, bringing an record of the conditions they encountered on their journey in the depths of the Earth.

FACTORS THAT CONTROL METAMORPHISM

The reason rocks undergo metamorphism is that the minerals in a rock are only stable under a limited range of pressure, temperature, and chemical conditions. When rocks are subjected to large enough changes in these factors, the minerals will undergo chemical reactions that result in their replacement by new minerals, minerals that are stable in the new conditions.

Chemical Composition of the Protolith

The type of rock undergoes metamorphism is a major factor in determing what type of metamorphic rock it becomes. In short the identify of the protolith plays a big role the identity of the metamorphic rock. A fluid phase may introduce or remove chemical substances into or out of the rock during metamorphism, but in most metamorphic rock, most of the atoms in the protolith are be present in the metamorphic rock after metamorphism; the atoms will likely be rearranged into new mineral forms within the rock. Therefore, not only does the protolith determine the initial chemistry of the metamorphic rock, most metamorphic rocks do not change their bulk (overall) chemical compositions very much during metamorphism. The fact that most metamorphic rocks retain most of their original atoms means that even if the rock was so thoroughly metamorphosed that it no longer looks at all like the protolith, the rock can be analyzed in terms of its bulk chemical composition to determine what type of rock the protolith was.

If the protolith is an arenite, made mostly of the mineral quartz (SiO_2), metamorphism cannot turn the rock into a marble, which is made of the mineral calcite ($CaCO_3$). In fact, as a result of metamorphism, a pure quartz arenite will become quartzite. It is still made of quartz, but the quartz has recrystallized during metamorphism, filling in most of the pore space of the arenite with new quartz growth and becoming a denser, harder rock. The reason pure arenite becomes quartzite is that the mineral quartz is stable over a wide range of pressures and temperatures. Under most metamorphic conditions quartz will simply recrystallize, overgrow the existing quartz grains with more quartz, and reorient its quartz crystals to become a new rock type made of quartz.

Many protoliths have chemical compositions consisting of more than three chemical elements, and most protoliths are made of minerals that do not remain stable in the conditions encountered during metamorphism. Such protoliths undergo chemical reactions during metamorphism that replace the protolith minerals with new metamorphic minerals, made of the atoms from the protolith minerals rearranged into new mineral structures.

Temperature

Temperature is another major factor of metamorphism. There are two ways to think about how the temperature of a rock can be increased as a result of geologic processes.

If rocks are buried within the Earth, the deeper they go, the higher the temperatures they experience. This is because temperature inside the Earth increases along what is called the geothermal gradient, or geotherm for short. Therefore, if rocks are simply buried deep enough enough sediment, they will experience temperatures high enough to cause metamorphism. This temperature is about 200°C (approximately 400°F).

Tectonic processes are another way rocks can be moved deeper along the geotherm. Faulting and folding the rocks of the crust, can move rocks to much greater depth than simple burial can.

Yet another way a rock in the Earth's crust can have its temperature greatly increased is by the intrusion of magma nearby. Magma intrusion subjects nearby rock to higher temperature with no increase in depth or pressure.

The upper limit of metamorphism, beyond which igneous conditions occur, is the temperature and pressure at which partial melting of the rocks begins. This limit varies greatly, depending on the pressure, the chemical composition of the rocks, and the presence of a fluid phase. With water present in the fluid, some types of rock begin melting, if the pressure is high enough, at temperatures of about 600 °C (approximately 1100 °F) at the low end. Other types of rock, if there is no fluid in the rock to lower the melting temperature, will remain solid and continue undergoing metamorphism to over 1000 °C (approximately 1800 °F).

Pressure

Pressure is a measure of the stress, the physical force, being applied to the surface of a material. It is defined as the force per unit area acting on the surface, in a direction perpendicular to the surface.

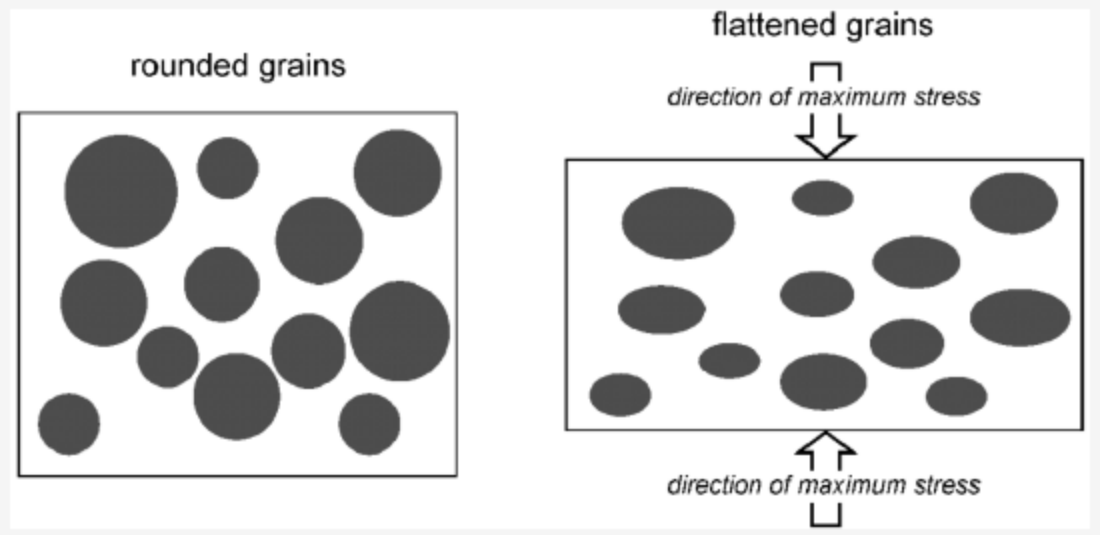
Lithostatic pressure is the pressure exerted on a rock by all the surrounding rock. The source of the pressure is the weight of all the rocks above. Lithostatic pressure increases as depth within the Earth increases and is a *uniform stress*—the pressure applies equally in all directions on the rock.

If pressure does not apply equally in all directions, differential stress occurs. There are two types of *differential stress*.

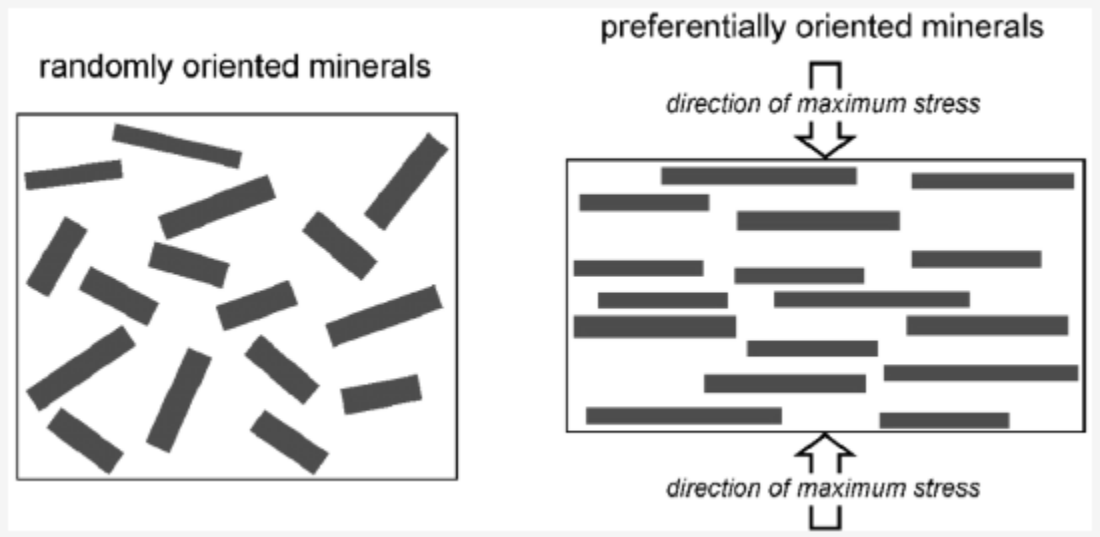
Normal stress compresses (pushes together) rock in one direction, the direction of maximum stress. At the same time, in a perpendicular direction, the rock undergoes tension (stretching), in the direction of minimum stress.

Shear stress pushes one side of the rock in a direction parallel to the side, while at the same time, the other side of the rock is being pushed in the opposite direction.

Differential stress has a major influence on the the appearance of a metamorphic rock. Differential stress can flatten pre-existing grains in the rock, as shown in the diagram below.



Metamorphic minerals that grow under differential stress will have a preferred orientation if the minerals have atomic structures that tend to make them form either flat or elongate crystals. This will be especially apparent for micas or other sheet silicates that grow during metamorphism, such as biotite, muscovite, chlorite, talc, or serpentine. If any of these flat minerals are growing under normal stress, they will grow with their sheets oriented perpendicular to the direction of maximum compression. This results in a rock that can be easily broken along the parallel mineral sheets. Such a rock is said to be foliated, or to have foliation.



Fluids

Any open space between the mineral grains in a rock, however microscopic, may contain a fluid phase. Most commonly, if there is a fluid phase in a rock during metamorphism, it will be a hydrous fluid, consisting of water and things dissolved in the water. Less commonly, it may be a carbon dioxide fluid or some other fluid. The presence of a fluid phase is a major factor during metamorphism because it helps determine which metamorphic reactions will occur and how fast they will occur. The fluid phase can also influence the rate at which mineral crystals deform or change shape. Most of this influence is due to the dissolved ions that pass in and out of the fluid phase. If during metamorphism enough ions are introduced to or removed from the rock via the fluid to change the bulk chemical composition of the rock, the rock is said to have undergone metasomatism. However, most metamorphic rocks do not undergo sufficient change in their bulk chemistry to be considered metasomatic rocks.

Time

Most metamorphism of rocks takes place slowly inside the Earth. Regional metamorphism takes place on a timescale of millions

of years. Metamorphism usually involves slow changes to rocks in the solid state, as atoms or ions diffuse out of unstable minerals that are breaking down in the given pressure and temperature conditions and migrate into new minerals that are stable in those conditions. This type of chemical reaction takes a long time.

GRADES OF METAMORPHISM

Metamorphic grade refers to the general temperature and pressure conditions that prevailed during metamorphism. As the pressure and temperature increase, rocks undergo metamorphism at higher metamorphic grade. Rocks changing from one type of metamorphic rock to another as they encounter higher grades of metamorphism are said to be undergoing prograde metamorphism.

Low-grade metamorphism takes place at approximately 200–320 °C and relatively low pressure. This is not far beyond the conditions in which sediments get lithified into sedimentary rocks, and it is common for a low-grade metamorphic rock to look somewhat like its protolith. Low grade metamorphic rocks tend to characterized by an abundance of hydrous minerals, minerals that contain water within their crystal structure. Examples of low grade hydrous minerals include clay, serpentine, and chlorite. Under low grade metamorphism many of the metamorphic minerals will not grow large enough to be seen without a microscope.

Medium-grade metamorphism takes place at approximately at 320–450 °C and at moderate pressures. Low grade hydrous minerals are replaced by micas such as biotite and muscovite, and non-hydrous minerals such as garnet may grow. Garnet is an example of a mineral which may form porphyroblasts, metamorphic mineral grains that are larger in size and more equant in shape (about the same diameter in all directions), thus standing out among the smaller, flatter, or more elongate minerals.

High-grade metamorphism takes place at temperatures above about 450 °C. Micas tend to break down. New minerals such as hornblende will form, which is stable at higher temperatures. However, as metamorphic grade increases to even higher grade, all hydrous minerals, which includes hornblende, may break down and be replaced by other, higher-temperature, non-hydrous minerals such as pyroxene.

During high-grade metamorphism the minerals tend to grow larger. Some varieties of valuable gemstones, such as rubies, emeralds, and jade, come from high grade metamorphic rocks. At the highest metamorphic grade, if the temperature gets high enough, the rock will start to melt, entering the next stage of the rock cycle, the igneous stage. The temperature at which melting begins ranges from about 600 °C to over 1000 °C depending on the rock and fluids in the rock.

INDEX MINERALS

Index minerals, which are indicators of metamorphic grade. In a given rock type, which starts with a particular chemical composition, lower-grade index minerals are replaced by higher-grade index minerals in a sequence of chemical reactions that proceeds as the rock undergoes prograde metamorphism. For example, in rocks made of metamorphosed shale, metamorphism may prograde through the following index minerals:

- chlorite characterizes the lowest regional metamorphic grade
- biotite replaces chlorite at the next metamorphic grade, which could be considered medium-low grade
- garnet appears at the next metamorphic grade, medium grade
- staurolite marks the next metamorphic grade, which is medium-high grade
- sillimanite is a characteristic mineral of high grade metamorphic rocks

Index minerals are used by geologists to map metamorphic grade in regions of metamorphic rock. A geologist maps and collects rock samples across the region and marks the geologic map with the location of each rock sample and the type of index mineral it contains. By drawing lines around the areas where each type of index mineral occurs, the geologist delineates the zones of different metamorphic grades in the region. The lines are known as isograds.

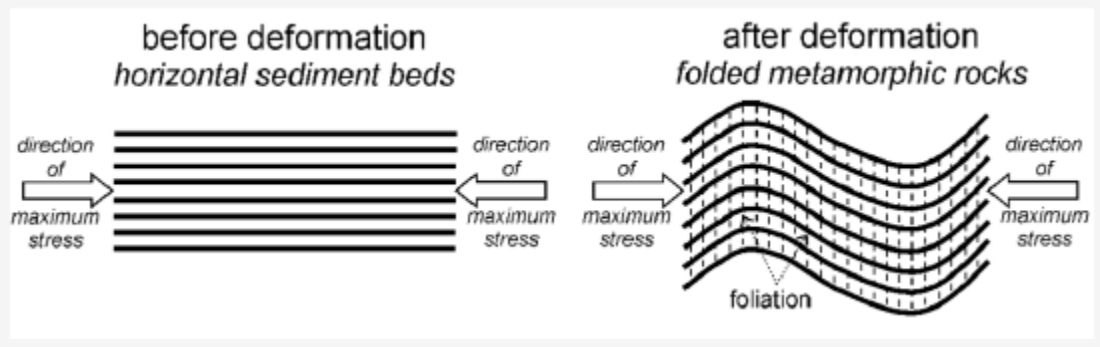
TYPES OF METAMORPHISM

Regional Metamorphism

Regional metamorphism occurs where large areas of rock are subjected to large amounts of differential stress for long intervals of time, conditions typically associated with mountain building. Mountain building occurs at subduction zones and at continental

collision zones where two plates each bearing continental crust, converge upon each other.

Most foliated metamorphic rocks—slate, phyllite, schist, and gneiss—are formed during regional metamorphism. As the rocks become heated at depth in the Earth during regional metamorphism they become ductile, which means they are relatively soft even though they are still solid. The folding and deformation of the rock while it is ductile may greatly distort the original shapes and orientations of the rock, producing folded layers and mineral veins that have highly deformed or even convoluted shapes. The diagram below shows folds forming during an early stage of regional metamorphism, along with development of foliation, in response to normal stress.



The photograph below shows high-grade metamorphic rock that has undergone several stages of foliation development and folding during regional metamorphism, and may even have reached such a high temperature that it began to melt.



Contact Metamorphism

Contact metamorphism occurs to solid rock next to an igneous intrusion and is caused by the heat from the nearby body of magma. Because contact metamorphism is not caused by changes in pressure or by differential stress, contact metamorphic rocks do not become foliated. Where intrusions of magma occur at shallow levels of the crust, the zone of contact metamorphism around the intrusion is relatively narrow, sometimes only a few m (a few feet) thick, ranging up to contact metamorphic zones over 1000 m (over 3000 feet) across around larger intrusions that released more heat into the adjacent crust. The zone of contact metamorphism surrounding an igneous intrusion is called the metamorphic aureole. The rocks closest to the contact with the intrusion are heated to the highest temperatures, so the metamorphic grade is highest there and diminishes with increasing distance away from the contact. Because contact metamorphism occurs at shallow to moderate depths in the crust and subjects the rocks to temperatures up to the verge of igneous conditions, it is sometimes referred to as high-temperature, low-pressure metamorphism. Hornfels, which is a hard metamorphic rock formed from fine-grained clastic sedimentary rocks, is a common product of contact metamorphism.

Hydrothermal Metamorphism

Hydrothermal metamorphism is the result of extensive interaction of rock with high-temperature fluids. The difference in composition between the existing rock and the invading fluid drives the chemical reactions. The hydrothermal fluid may originate from a magma that intruded nearby and caused fluid to circulate in the nearby crust, from circulating hot groundwater, or from ocean water. If the fluid introduces substantal amounts of ions into the rock and removes substantial amounts of ions from it, the fluid has metasomatized the rock—changed its chemical composition.

Ocean water that penetrates hot, cracked oceanic crust and circulates as hydrothermal fluid in ocean floor basalts produces extensive hydrothermal metamorphism adjacent to mid-ocean spreading ridges and other ocean-floor volcanic zones. Much of the basalt subjected to this type of metamorphism turns into a type of metamorphic rock known as greenschist. Greenschist contains a set of minerals, some of them green, which may include chlorite, epidote, talc, Na-plagioclase, or actinolite. The fluids eventually escape through vents in the ocean floor known as black smokers, producing thick deposits of minerals on the ocean floor around the vents.

Burial Metamorphism

Burial metamorphism occurs to rocks buried beneath sediments to depths that exceed the conditions in which sedimentary rocks form. Because rocks undergoing burial metamorphism encounter the uniform stress of lithostatic pressure, not differential pressure, they do not develop foliation. Burial metamorphism is the lowest grade of metamorphism. The main type of mineral that usually grows during burial metamorphism is zeolite, a group of low-density silicate minerals. It usually requires a strong microscope see the small grains of zeolite minerals that form during burial metamorphism.

Dynamic Metamorphism

Dynamic metamorphism is caused mainly by high shear stress along fault zones or shear zones in the crust. The minerals of the protolith may be pulverized and crushed by the high rate of shear strain that occurs in these zones. Rocks metamorphosed in these zones usually exhibit a combination of fractured, partly disintegrated, partly recrystallized versions of the original minerals, along with new mineral growth that occured during the metamorphism. Because fault zones and shear zones are highly localized, rocks that have undergone dynamic metamorphism are not a widespread type of metamorphic rock; they are much less abundant, than regional or contact metamorphic rocks.

Subduction Zone Metamorphism

During subduction, a tectonic plate, consisting of oceanic crust and lithospheric mantle, is recycled back into the deeper mantle. In most subduction zones the subducting plate is relatively cold compared with the high temperature it had when first formed at a mid-ocean spreading ridge. Subduction takes the rocks to great depth in the Earth relatively quickly. This produces a characteristic type of metamorphism, sometimes called high-pressure, low-temperature (high-P, low-T) metamorphism, which only occurs deep in a subduction zone. In oceanic basalts that are part of a subducting plate, the high-P, low-T conditions create a distinctive set of metamorphic minerals including a type of amphibole, called glaucophane, that has a blue color. Blueschist is the name given to this type of metamorphic rock. Blueschist is generally interpreted as having been produced within a subduction zone, even if the plate boundaries have subsequently shifted and that location is no longer at a subduction zone.

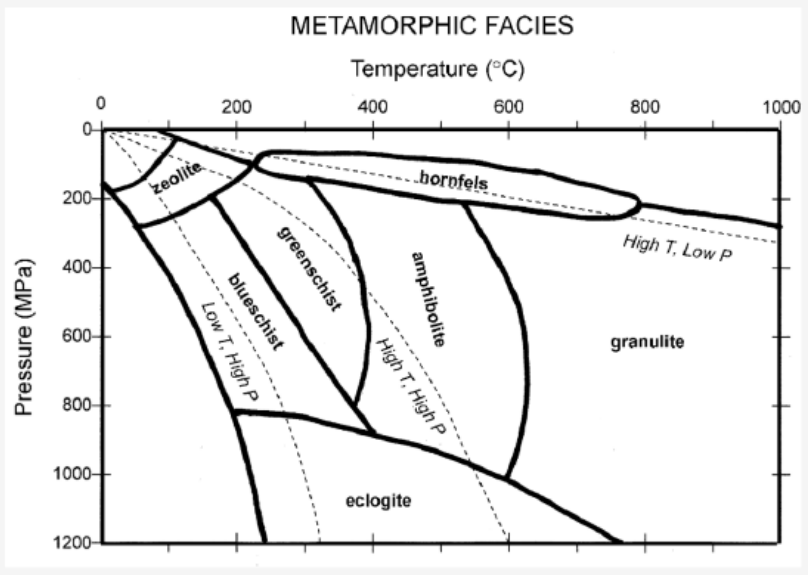
METAMORPHIC FACIES

Much as the minerals and textures of sedimentary rocks can be used as windows to see into the environment in which the sediments were deposited on the Earth's surface, the minerals and textures of metamorphic rocks provide windows through which we view the conditions of pressure, temperature, fluids, and stress that occurred inside the Earth during metamorphism. The pressure and temperature conditions under which specific types of metamorphic rocks form has been determined by a combination labratory experiments, physics-based theoretical calculations, along with evidence in the textures of the rocks and their field relations as recorded on geologic maps. The knowledge of temperatures and pressures at which particular types of metamorphic rocks form led to the concept of metamorphic facies. Each metamorphic facies is represented by a specific type of metamorphic rock that forms under a specific pressure and temperature conditions.

Even though the name of the each metamorphic facies is taken from a type of rock that forms under those conditions, that is not the only type of rock that will form in those conditions. For example, if the protolith is basalt, it will turn into greenschist

under greenschist facies conditions, and that is what facies is named for. However, if the protolith is shale, a muscovite-biotite schist, which is not green, will form instead. If it can be determined that a muscovite-biotite schist formed at around 350°C temperature and 400 MPa pressure, it can be stated that the rock formed in the greenschist facies, even though the rock is not itself a greenschist.

The diagram below shows metamorphic facies in terms of pressure and temperature condiditons inside the Earth. Earth's surface conditions are near the top left corner of the graph at about 15°C which is the average temperature at Earth's surface and 0.1 MPa (megapascals), which is about the average atmospheric pressure on the Earth's surface. Just as atmospheric pressure comes from the weight of all the air above a point on the Earth's surface, pressure inside the Earth comes from the weight of all the rock above a given depth. Rocks are much denser than air and MPa is the unit most commonly uses to express pressures inside the Earth. One MPa equals nearly 10 atmospheres. A pressure of 1000 MPa corresponds to a depth of about 35 km inside the Earth. Although pressure inside the Earth is determined by the depth, temperature depends on more than depth. Temperature depends on the heat flow, which varies from location to location. The way temperature changes with depth inside the Earth is called the geothermal gradient, geotherm for short. In the diagram below, three different geotherms are marked with dashed lines. The three geotherms represent different geological settings in the Earth.



High-pressure, low-temperature geotherms occurs in subduction zones. As the diagram shows, rocks undergoing prograde metamorphism in subduction zones will be subjected to zeolite, blueschist, and ultimately eclogite facies conditions.

High-temperature, low-pressure geotherms occur in the vicinity of igneous intrusions in the shallow crust, underlying a volcanically active area. Rocks that have their pressure and temperature conditions increased along such a geotherm will metamorphose in the hornfels facies and, if it gets hot enough, in the granulite facies.

Blueschist facies and hornfels facies are associated with unusual geothermal gradients. The most common conditions in the Earth are found along geotherms between those two extremes. Most regional metamorphic rocks are formed in conditions within this range of geothermal gradients, passing through the greenschist facies to the amphibolites facies. At the maximum pressures and temperatures the rocks may encounter within the Earth in this range of geotherms, they will enter either the granulite or eclogite facies. Regionally metamorphosed rocks that contain hydrous fluids will begin to melt before they pass beyond the amphibolite facies.

PROTOLITHS

The minerals in metamorphic rock are often a completely different set of minerals than in the protolith. But, because the mineral assemblage in the metamorphic rock reflects the overall chemical composition of the rock, the set of minerals found in the rock can give us a good idea of the type of protolith, even if the metamorphic rock no longer looks anything like its protolith.

The following terms are used to describe protoliths, and the types of metamorphic rocks they turn into, in terms of their general chemical compositions.

- pelitic—pelitic rocks are high in alumina and, as protoliths, were usually shales or mudstones. Pelitic metamorphic rocks contain alumina-rich minerals such as the micas, garnet, andalusite, kyanite, silliminate, or staurolite. Pelitic metamorphic rocks formed during regional metamorphism include many varieties of slate, phyllite, schist, and gneiss.
- mafic—mafic protoliths and the metamorphic rocks they become are high in magnesium and iron relative to silicon. Basalt is the most common mafic protolith. It can turn into mafic metamorphic rocks such as greenschist and amphibolites with chlorite, actinolite, biotite, hornblende, or plagioclase in them, depending on metamorphic grade.
- calcareous—Calcareous rocks are calcium-rich rocks. Typically, as protoliths, calcareous rocks were either limestone or dolostone, which most commonly turn into marble as metamorphic rocks.
- quartzofeldspathic—Protoliths such as granite, rhyolite, and arkose are rocks that consist mostly of a combination of quartz and feldspar are quartzofeldspathic. High-grade regional metamorphism of quartzofeldspathic rocks produces gneisses containing feldspar, quartz, biotite, and possibly hornblende.

TYPES OF METAMORPHIC ROCKS

Metamorphic rock fall into two categories, foliated and unfoliated. Most foliated metamorphic rocks originate from regional metamorphism. Some unfoliated metamorphic rocks, such as hornfels, originate only by contact metamorphism, but others can originate either by contact metamorphism or by regional metamorphism. Quartz and marble are prime examples of unfoliated that can be produced by either regional or contact metamorphism. Both rock types consist of metamorphic minerals that do not have flat or elongate shapes and thus cannot become layered even if they are produced under differential stress.

A geologist working with metamorphic rocks collects the rocks in the field and looks for the patterns the rocks form in outcrops as well as how those outcrops are related to other types of rock with which they are in contact. Field evidence is often required to know for sure whether rocks are products of regional metamorphism, contact metamorphism, or some other type of metamorphism. If only looking at rock samples in a laboratory, one can be sure of the type of metamorphism that produced a foliated metamorphic rock such as schist or gneiss, or a hornfels, which is unfoliated, but one cannot be sure of the type of metamorphism that produced an unfoliated marble or quartzite.

Foliated Metamorphic Rocks

Foliated metamorphic rocks are named for their style of foliation. However, a more complete name of each particular type of foliated metamorphic rock includes the main minerals that the rock comprises, such as biotite-garnet schist rather than just schist.

- slate—slates form at low metamorphic grade by the growth of fine-grained chlorite and clay minerals. The preferred orientation of these sheet silicates causes the rock to easily break along parallel planes, giving the rock a slaty cleavage. Some slate breaks into such extensively flat sheets of rock that it is used as the base of pool tables, beneath a layer of rubber and felt. Roof tiles are also sometimes made of slate.
- phyllite—phyllite is a low-medium grade regional metamorphic rock in which the clay minerals and chlorite have been at least partly replaced by mica mica minerals, muscovite and biotite. This gives the surfaces of phyllite a satiny luster, much brighter than the surface of a piece of slate. It is also common for the differential stresses under which phyllite forms to have produced a set of folds in the rock, making the foliation surfaces wavy or irregular, in contrast to the often perfectly flat surfaces of slaty cleavage.
- schist—the size of mineral crystals tends to grow larger with increasing metamorphic grade. Schist is a product of medium grades of metamorphism and is characterized by visibly prominent, parallel sheets of mica or similar sheet silicates, usually either muscovite or biotite, or both. In schist, the sheets of mica are usually arranged in irregular planes rather than perfectly flat planes, giving the rock a schistose foliation (or simply schistosity). Schist often contains more than just micas among its minerals, such as quartz, feldspars, and garnet.
- amphibolite—a poorly foliated to unfoliated mafic metamorphic rock, usually consisting largely of the common black amphibole known as hornblende, plus plagioclase, plus or minus biotite and possibly other minerals; it usually does not contain any quartz. Amphibolite forms at medium-high metamorphic grades. Amphibolite is also listed below in the section on unfoliated metamorphic rocks.
- gneiss—like the word schist, the word gneiss is originated from the German language; it is pronounced “nice.” As metamorphic grade continue to increase, sheet silicates become unstable and dark minerals such as hornblende or pyroxene start to grow. The dark-colored minerals tend to form separate bands or stripes in the rock, giving it a gneissic foliation of dark and light streaks. Gneiss is a high-grade metamorphic rock. Many types of gneiss look somewhat like granite, except that the gneiss has dark and light stripes whereas in granite randomly oriented and distributed minerals with no stripes or layers.

- migmatite—a combination of high-grade regional metamorphic rock – usually gneiss or schist – and granitic igneous rock. The granitic rock in migmatite probably originated from partial melting of some of the metamorphic rock, though in some migmatites the granite may have intruded the rock from deeper in the crust. In migmatite you can see metamorphic rock that has reached the limits of metamorphism and begun transitioning into the igneous stage of the rock cycle by melting to form magma.

Names of different styles of foliation come from the common rocks that exhibit such foliation:

- slate has ***slaty*** foliation
- phyllite has ***phyllitic*** foliation
- schist has ***schistose*** foliation
- gneiss has ***gneissic*** foliation (also called gneissose foliation)

Unfoliated Metamorphic Rocks

Unfoliated metamorphic rocks lack a planar (oriented) fabric, either because the minerals did not grow under differential stress, or because the minerals that grew during metamorphism are not minerals that have elongate or flat shapes. Because they lack foliation, these rocks are named entirely on the basis of their mineralogy.

- hornfels—hornfels are very hard rocks formed by contact metamorphism of shale, siltstone, or sandstone. The heat from the nearby magma “bakes” the sedimentary rocks and recrystallizes the minerals in them into a new texture that no longer breaks easily along the original sedimentary bedding planes. Depending on the composition of the rock and the temperature reached, minerals indicative of high metamorphic grade such as pyroxene may occur in some hornfels, though many hornfels have minerals indicating medium grade metamorphism.
- amphibolite—amphibolites are dark-colored rocks with amphibole, usually the common black amphibole known as hornblende, as their most abundant mineral, along with plagioclase and possibly other minerals, though usually no quartz. Amphibolites are poorly foliated to unfoliated and form at medium to medium-high grades of metamorphism from basalt or gabbro.
- quartzite—quartzite is a metamorphic rock made almost entirely of quartz, for which the protolith was quartz arenite. Because quartz is stable over a wide range of pressure and temperature, little or no new minerals form in quartzite during metamorphism. Instead, the quartz grains recrystallize into a denser, harder rock than the original sandstone. If struck by a rock hammer, quartzite will commonly break right through the quartz grains, rather than around them as when quartz arenite is broken.
- marble—marble is a metamorphic rock made up almost entirely of either calcite or dolomite, for which the protolith was either limestone or dolostone, respectively. Marbles may have bands of different colors which were deformed into convoluted folds while the rock was ductile. Such marble is often used as decorative stone in buildings. Some marble, which is considered better quality stone for carving into statues, lacks color bands.

Metamorphic Rock Classification

Foliated Metamorphic Rocks				
Crystal Size	**Mineralogy**	**Protolith**	**Metamorphism**	**Rock Name**
very fine	clay minerals	shale	low grade regional	slate
fine	clay minerals, biotite, muscovite	shale	low grade regional	phyllite
medium to coarse	biotite, muscovite, quartz, garnet, plagioclase	shale, basalt	medium grade regional	schist
medium to coarse	amphibole, plagioclase, biotite	basalt	medium grade regional	amphibolite *(Note: may be unfoliated)*
medium to coarse	plagioclase, orthoclase, quartz, biotite, amphibole, pyroxene	basalt, granite, shale	high grade regional	gneiss
Unfoliated Metamorphic Rocks				
Crystal Size	**Mineralogy**	**Protolith**	**Metamorphism**	**Rock Name**

fine to coarse	quartz	sandstone	regional or contact	quartzite
fine to coarse	calcite	limestone	regional or contact	marble
fine	pyroxene, amphibole, plagioclase	shale	contact	hornfels

Note that not all minerals listed in the mineralogy column will be present in every rock of that type and that some rocks may have minerals not listed here.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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3.9: Putting It Together

SUMMARY

In this section, you learned the following:

1. The three rock types and how they are classified
2. How each of the different rock types form
3. The techniques geologist use to identify different rocks
4. How to use these techniques to identify common rocks
5. How the rock cycle works

SYNTHESIS

The rock cycle is a continuous and dynamic cycle that has no starting or stopping point and no set progression. Rocks can move through different paths within the cycle. The rock cycle explains how each rock type forms and the processes involved. We saw how the processes within the cycle influence everything from soil formation to recording the history of the Earth to the role deformation plays in rocks. It is easy to see how the rock cycle influences our dynamic and ever changing earth.

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4: SOIL

When most people think about the resources we use, most of them will immediately think about water and air and fossil fuels. However, one resource that is absolutely vital to our existence (and other species as well) is soil. In this section, we will see how soil is formed, we will see why all soils are not the same, and we will see what the soil looks like in different biomes. You may recall from the rock cycle that soil is formed from the weathering of rocks, but this is just one piece of what goes into soil formation. If we stop and think about soil for just a minute, we can come up with an impressive resume of what soil does.

4.1: Why It Matters

4.2: Weathering and Erosion

4.3: Weathering

4.4: Soil Formation

4.5: Characteristics of Soil

4.6: Soil Profiles and Types

4.7: Soil Types

4.8: Putting It Together

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4.1: Why It Matters

EXPLAIN THE FORMATION OF SOILS AND DIFFERENT WEATHERING PROCESSES AND EROSION

When most people think about the resources we use, most of them will immediately think about water and air and fossil fuels. However, one resource that is absolutely vital to our existence (and other species as well) is soil. In this section, we will see how soil is formed, we will see why all soils are not the same, and we will see what the soil looks like in different biomes. You may recall from the rock cycle that soil is formed from the weathering of rocks, but this is just one piece of what goes into soil formation. If we stop and think about soil for just a minute, we can come up with an impressive resume of what soil does:

1. The most obvious area where soil is important is in agriculture and growing food to feed our population. But on a more personal level, do you like to garden? Do you grow your own vegetables? Imagine what would happen without this vital resource.
2. Soils are also an important part of the water cycle. They help regulate the flow and quality of water. What would happen without soil in areas that get a lot of rainfall?
3. Did you know there are more organisms in just 1 tablespoon of soil than there are people on the planet? The soil is home to billions of different species. Where would these species be without soil?

These are just a few examples of why soil is essential as a resource. So, let's see how soil forms and why there are so many different types of soil.

Learning Outcomes

- Describe and explain types and processes of weathering and erosion, and how Earth materials are altered via these processes
- Know the geologic processes involved and influences upon soil formation
- Describe and compare typical soil profiles and basic soil types

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4.2: Weathering and Erosion

DESCRIBE AND EXPLAIN TYPES AND PROCESSES OF WEATHERING AND EROSION, AND HOW EARTH MATERIALS ARE ALTERED VIA THESE PROCESSES

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Weathering

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4.3: Weathering

INTRODUCTION

The footprints that astronauts left on the Moon will be there forever. Why? This is because the Moon has no atmosphere and, as a result, has no weathering. Weathering is one of the forces on Earth that destroy rocks and landforms. Without weathering, geologic features would build up but would be less likely to break down.

WHAT IS WEATHERING?

Weathering is the process that changes solid rock into sediments. Sediments were described in the Rocks chapter. With weathering, rock is disintegrated. It breaks into pieces.

Once these sediments are separated from the rocks, erosion is the process that moves the sediments. Erosion is the next chapter's topic. The four forces of erosion are water, wind, glaciers, and gravity.

- Water is responsible for most erosion. Water can move most sizes of sediments, depending on the strength of the force.
- Wind moves sand-sized and smaller pieces of rock through the air.
- Glaciers move all sizes of sediments, from extremely large boulders to the tiniest fragments.
- Gravity moves broken pieces of rock, large or small, downslope.

While plate tectonics forces work to build huge mountains and other landscapes, the forces of weathering gradually wear those rocks and landscapes away. Together with erosion, tall mountains turn into hills and even plains. The Appalachian Mountains along the east coast of North America were once as tall as the Himalayas.



Figure 1. A once smooth road surface has cracks and fractures, plus a large pothole.

No human being can watch for millions of years as mountains are built, nor can anyone watch as those same mountains gradually are worn away. But imagine a new sidewalk or road. The new road is smooth and even. Over hundreds of years, it will completely disappear, but what happens over one year? What changes would you see (figure 1)? What forces of weathering wear down that road, or rocks or mountains over time?

Follow this link to view some animations of different types of weathering processes.

MECHANICAL WEATHERING

Mechanical weathering (also called physical weathering) breaks rock into smaller pieces. These smaller pieces are just like the bigger rock, just smaller. That means the rock has changed physically without changing its composition. The smaller pieces have the same minerals, in just the same proportions as the original rock.

There are many ways that rocks can be broken apart into smaller pieces. **Ice wedging** is the main form of mechanical weathering in any climate that regularly cycles above and below the freezing point (figure 2). Ice wedging works quickly, breaking apart rocks in areas with temperatures that cycle above and below freezing in the day and night, and also that cycle above and below freezing with the seasons.

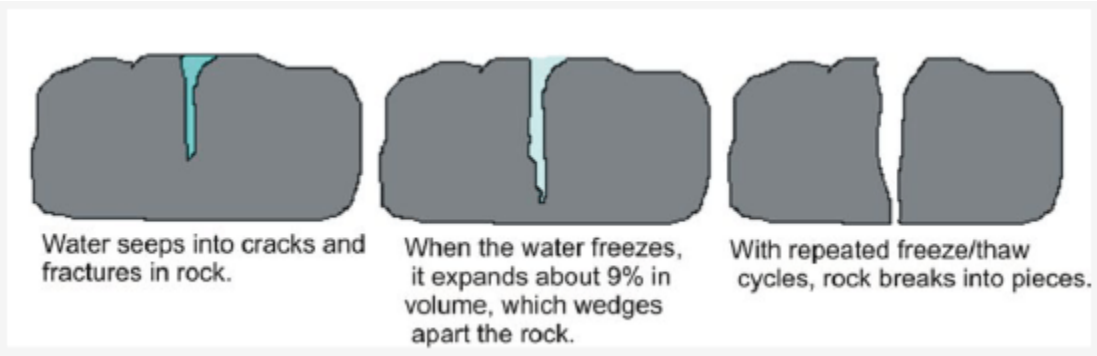


Figure 2. Ice wedging.

Ice wedging breaks apart so much rock that large piles of broken rock are seen at the base of a hillside, as rock fragments separate and tumble down. Ice wedging is common in Earth's polar regions and mid latitudes, and also at higher elevations, such as in the mountains. **Abrasion** is another form of mechanical weathering. In abrasion, one rock bumps against another rock.

- Gravity causes abrasion as a rock tumbles down a mountainside or cliff.
- Moving water causes abrasion as particles in the water collide and bump against one another.
- Strong winds carrying pieces of sand can sandblast surfaces.
- Ice in glaciers carries many bits and pieces of rock. Rocks embedded at the bottom of the glacier scrape against the rocks below.

Abrasion makes rocks with sharp or jagged edges smooth and round. If you have ever collected beach glass or cobbles from a stream, you have witnessed the work of abrasion (figure 3).



Figure 3. Rocks on a beach are worn down by abrasion as passing waves cause them to strike each other.

Now that you know what mechanical weathering is, can you think of other ways it could happen? Plants and animals can do the work of mechanical weathering (figure 4). 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.



Figure 4. (a) Human activities are responsible for enormous amounts of mechanical weathering, by digging or blasting into rock to build homes, roads, subways, or to quarry stone. (b) Salt weathering of building stone on the island of Gozo, Malta.

Mechanical weathering increases the rate of chemical weathering. As rock breaks into smaller pieces, the surface area of the pieces increases figure 5. With more surfaces exposed, there are more surfaces on which chemical weathering can occur.

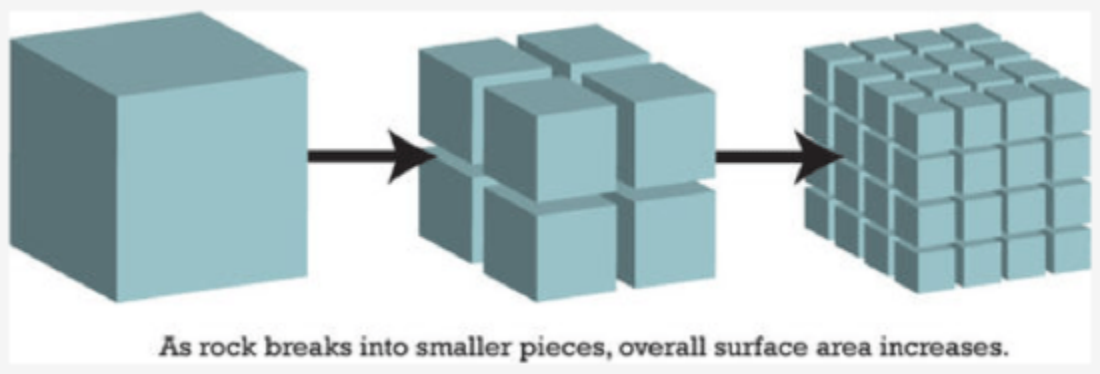


Figure 5. Mechanical weathering may increase the rate of chemical weathering.

CHEMICAL WEATHERING

Chemical weathering is the other important type of weathering. Chemical weathering is different from mechanical weathering because the rock changes, not just in size of pieces, but in composition. That is, one type of mineral changes into a different mineral. Chemical weathering works through chemical reactions that cause changes in the minerals.

Most minerals form at high pressure or high temperatures deep in the crust, or sometimes in the mantle. When these 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 and the minerals are no longer stable. In chemical weathering, minerals that were stable inside the crust must change to minerals that are stable at Earth's surface.



Figure 6. Deforestation in Brazil reveals the underlying clay-rich soil.

Remember that the most common minerals in Earth's crust are the silicate minerals. Many silicate minerals form in igneous or metamorphic rocks. The minerals that form at the highest temperatures and pressures are the least stable at the surface. Clay is stable at the surface and chemical weathering converts many minerals to clay (figure 6).

There are many types of chemical weathering because there are many agents of chemical weathering. Water is the most important agent of chemical weathering. Two other important agents of chemical weathering are carbon dioxide and oxygen.

Chemical Weathering by Water

A water molecule has a very simple chemical formula, H_2O, two hydrogen atoms bonded to one oxygen atom. But water is pretty remarkable in terms of all the things it can do. Remember from the Earth's Minerals chapter that water is a polar molecule. The positive side of the molecule attracts negative ions and the negative side attracts positive ions. So water molecules separate the ions from their compounds and surround them. Water can completely dissolve some minerals, such as salt. Follow this link to check out this animation of how water dissolves salt.

Hydrolysis is the name of the chemical reaction between a chemical compound and water. When this reaction takes place, water dissolves ions from the mineral and carries them away. These elements have undergone **leaching**. Through hydrolysis, a mineral such as potassium feldspar is leached of potassium and changed into a clay mineral. Clay minerals are more stable at the Earth's surface.

Chemical Weathering by Carbon Dioxide

Carbon dioxide (CO_2) combines with water as raindrops fall through the atmosphere. This makes a weak acid, called carbonic acid. Carbonic acid is a very common in nature where it works to dissolve rock. Pollutants, such as sulfur and nitrogen, from fossil fuel burning, create sulfuric and nitric acid. Sulfuric and nitric acids are the two main components of acid rain, which accelerate chemical weathering (figure 7). Acid rain is discussed in the Human Actions and the Atmosphere chapter.



Figure 7. This statue has been damaged by acid rain.

Chemical Weathering by Oxygen

Oxidation is a chemical reaction that takes place when oxygen reacts with another element. Oxygen is very strongly chemically reactive. The most familiar type of oxidation is when iron reacts with oxygen to create rust (figure 8). Minerals that are rich in iron break down as the iron oxidizes and forms new compounds. Iron oxide produces the red color in soils.



Figure 8. When iron rich minerals oxidize, they produce the familiar red color found in rust.

Now that you know what chemical weathering is, can you think of some other ways chemical weathering might occur? 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.

INFLUENCES ON WEATHERING

Weathering rates depend on several factors. These include the composition of the rock and the minerals it contains as well as the climate of a region.

Rock and Mineral Type

Different rock types weather at different rates. Certain types of rock are very resistant to weathering. Igneous rocks, especially intrusive igneous rocks such as granite, weather slowly because it is hard for water to penetrate them. Other types of rock, such as limestone, are easily weathered because they dissolve in weak acids.



Figure 9. Devil's Tower is the central plug of resistant lava from which the surrounding rock weathered and eroded away.

Rocks that resist weathering remain at the surface and form ridges or hills. Devil's Tower in Wyoming is an igneous rock from beneath a volcano (figure 9). As the surrounding less resistant rocks were worn away, the resistant center of the volcano remained behind.

Different minerals also weather at different rates. Some minerals in a rock might completely dissolve in water but the more resistant minerals remain. In this case, the rock's surface becomes pitted and rough. When a less resistant mineral dissolves, more resistant mineral grains are released from the rock.

Climate

A region's **climate** strongly influences weathering. Climate is determined by the temperature of a region plus the amount of precipitation it receives. Climate is weather averaged over a long period of time. Chemical weathering increases as:

- Temperature increases: Chemical reactions proceed more rapidly at higher temperatures. For each 10°C increase in average temperature, the rate of chemical reactions doubles.
- Precipitation increases: More water allows more chemical reactions. Since water participates in both mechanical and chemical weathering, more water strongly increases weathering.

So how do different climates influence weathering? A cold, dry climate will produce the lowest rate of weathering. A warm, wet climate will produce the highest rate of weathering. The warmer a climate is, the more types of vegetation it will have and the greater the rate of biological weathering (figure 10). This happens because plants and bacteria grow and multiply faster in warmer temperatures.



Figure 10. Wet, warm tropical areas have the most weathering.

Some resources are concentrated by weathering processes. 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 aluminum ore.

LESSON SUMMARY

- Mechanical weathering breaks rocks into smaller pieces without changing their composition.
- Ice wedging and abrasion are two important processes of mechanical weathering.
- Chemical weathering breaks down rocks by 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.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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4.4: Soil Formation

KNOW THE GEOLOGIC PROCESSES INVOLVED AND INFLUENCES UPON SOIL FORMATION

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Characteristics of Soil

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4.5: Characteristics of Soil

INTRODUCTION

Without mechanical and chemical weathering working to break down rock, there would not be any soil on Earth. It is unlikely that humans or most other creatures would be able to live on Earth without soil. Wood, paper, cotton, medicines, and even pure water need soil. So soil is a precious resource that must be carefully managed and cared for. Although soil is a renewable resource, its renewal takes a lot of time.

Even though soil is only a very thin layer on Earth's surface over the solid rocks below, it is the where the atmosphere, hydrosphere, biosphere, and lithosphere meet. Within the soil layer, important reactions between solid rock, liquid water, air, and living things take place. **Soil** is a complex mixture of different materials.

- About half of most soils are **inorganic** materials, such as the products of weathered rock, including pebbles, sand, silt, and clay particles.
- About half of all soils are organic materials, formed from the partial breakdown and decomposition of plants and animals. The organic materials are necessary for a soil to be fertile. The organic portion provides the nutrients, such as nitrogen, needed for strong plant growth.
- In between the solid pieces, there are tiny spaces filled with air and water.



Figure 1. Peat is so rich in organic material, it can be burned for energy.

In some soils, the organic portion could be missing, as in desert sand. Or a soil could be completely organic, such as the materials that make up peat in a bog or swamp (figure 1).



Figure 2. Earthworms and insects are important residents of soils.

Soil is an ecosystem unto itself. In the spaces of soil, there are thousands or even millions of living organisms. Those organisms could be anything from earthworms, ants, bacteria, or fungi (figure 2).

CLIMATE

Scientists know that climate is the most important factor determining soil type because given enough time, different rock types in a given climate will produce a similar soil. Even the same rock type in different climates will not produce the same type of soil. This is true because most rocks on Earth are made of the same eight elements and when the rock breaks down to become soil, those elements dominate.

The same factors that lead to increased weathering also lead to greater soil formation.

- More rain equals more chemical reactions to weather minerals and rocks. Those reactions are most efficient in the top layers of the soil where the water is fresh and has not yet reacted with other materials.
- Increased rainfall increases the amount of rock that is dissolved as well as the amount of material that is carried away by moving water. As materials are carried away, new surfaces are exposed, which also increases the rate of weathering.
- Increased temperature increases the rate of chemical reactions, which also increases soil formation.
- In warmer regions, plants and bacteria grow faster, which helps to weather material and produce soils. In tropical regions, where temperature and precipitation are consistently high, thick soils form. Arid regions have thin soils.

Soil type also influences the type of vegetation that can grow in the region. We can identify climate types by the types of plants that grow there.

ROCK TYPE

The original rock is the source of the inorganic portion of the soil. The minerals that are present in the rock determine the composition of the material that is available to make soil. Soils may form in place or from material that has been moved.

- Residual soils form in place. The underlying rock breaks down to form the layers of soil that reside above it. Only about one-third of the soils in the United States are residual.
- Transported soils have been transported in from somewhere else. Sediments can be transported into an area by glaciers, wind, water, or gravity. Soils form from the loose particles that have been transported to a new location and deposited.

SLOPE

The steeper the slope, the less likely material will be able to stay in place to form soil. Material on a steep slope is likely to go downhill. Materials will accumulate and soil will form where land areas are flat or gently undulating.

TIME

Soils thicken as the amount of time available for weathering increases. The longer the amount of time that soil remains in a particular area, the greater the degree of alteration.

BIOLOGICAL ACTIVITY

The partial decay of plant material and animal remains produces the organic material and nutrients in soil. In soil, decomposing organisms breakdown the complex organic molecules of plant matter and animal remains to form simpler inorganic molecules that are soluble in water. Decomposing organisms also create organic acids that increase the rate of weathering and soil formation. Bacteria in the soil change atmospheric nitrogen into nitrates.

The decayed remains of plant and animal life are called **humus**, which is an extremely important part of the soil. Humus coats the mineral grains. It binds them together into clumps that then hold the soil together, creating its structure. Humus increases the soil's porosity and water holding capacity and helps to buffer rapid changes in soil acidity. Humus also helps the soil to hold its nutrients, increasing its fertility. Fertile soils are rich in nitrogen, contain a high percentage of organic materials, and 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. Fertile soils are more easily cultivated.

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 and, to a lesser extent, on the original parent rock material and other factors.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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4.6: Soil Profiles and Types

DESCRIBE AND COMPARE TYPICAL SOIL PROFILES AND BASIC SOIL TYPES

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Soil Types

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4.7: Soil Types

SOIL TEXTURE AND COMPOSITION

The inorganic portion of soil is made of many different size particles, and these different size particles are present in different proportions. The combination of these two factors determines some of the properties of the soil.



Figure 1. A loam field.

- A **permeable** soil allows water to flow through it easily because the spaces between the inorganic particles are large and well connected. Sandy or silty soils are considered 'light' soils because they are permeable, water-draining types of soils.
- Soils that have lots of very small spaces are water-holding soils. For example, when clay is present in a soil, the soil is heavier, holds together more tightly, and holds water.
- When a soil contains a mixture of grain sizes, the soil is called a **loam** (figure 1).

When soil scientists want to precisely determine soil type, they measure the percentage of sand, silt, and clay. They plot this information on a triangular diagram, with each size particle at one corner (figure 2). The soil type can then be determined from the location on the diagram. At the top, a soil would be clay; at the left corner, it would be sand, and at the right corner it would be silt. Soils in the lower middle with less than 50% clay are loams.

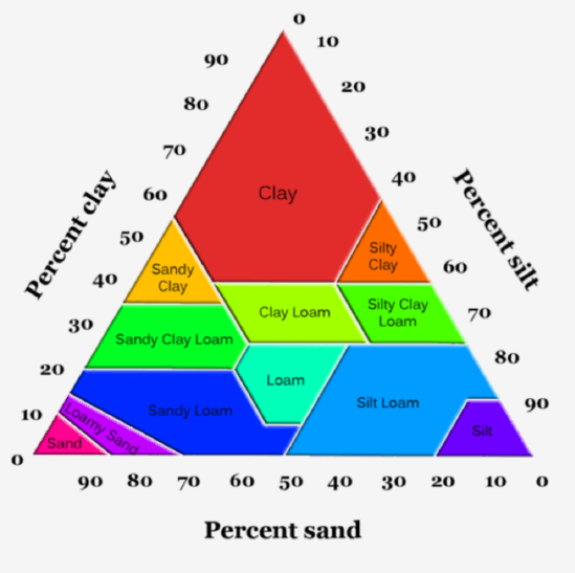


Figure 2. Soil types by particle size.

Using the chart as a guide, what is the composition of a sandy clay loam? If you would like to determine soil type by feel, here's a chart from the USDA to help you.

SOIL HORIZONS AND PROFILES

A residual soil forms over many years, as mechanical and chemical weathering slowly change solid rock into soil. The development of a residual soil may go something like this.

1. The bedrock fractures because of weathering from ice wedging or another physical process.
2. Water, oxygen, and carbon dioxide seep into the cracks to cause chemical weathering.
3. Plants, such as lichens or grasses, become established and produce biological weathering.
4. Weathered material collects until there is soil.
5. The soil develops **soil horizons**, as each layer becomes progressively altered. The greatest degree of weathering is in 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.



Figure 3. Soil is an important resource. Each soil horizon is distinctly visible in this photograph.

A cut in the side of a hillside shows each of the different layers of soil. All together, these are called a **soil profile** (figure 3).

The simplest soils have three horizons.

Topsoil

Called the A horizon, the **topsoil** is usually the darkest layer of the soil because it has the highest proportion of organic material. The topsoil is the region of most intense biological activity: insects, worms, and other animals burrow through it and plants stretch their roots down into it. Plant roots help to hold this layer of soil in place. In the topsoil, minerals may dissolve in the fresh water that moves through it to be carried to lower layers of the soil. Very small particles, such as clay, may also get carried to lower layers as water seeps down into the ground.

Subsoil

The **B horizon** or **subsoil** is where soluble minerals and clays accumulate. This layer is lighter brown and holds more water than the topsoil because of the presence of iron and clay minerals. There is less organic material. Look at figure 4.

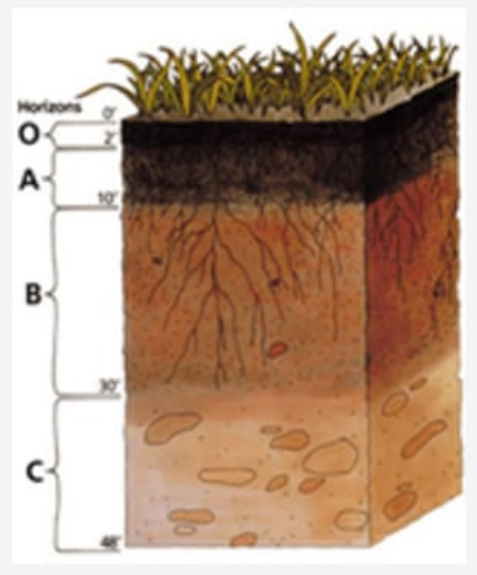


Figure 4. A soil profile is the complete set of soil layers. Each layer is called a horizon.

C Horizon

The **C horizon** is a layer of partially altered bedrock. There is some evidence of weathering in this layer, but pieces of the original rock are seen and can be identified.

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 no soils at all.

TYPES OF SOILS

Although soil scientists recognize thousands of types of soil—each with its own specific characteristics and name—let's consider just three soil types. This will help you to understand some of the basic ideas about how climate produces a certain type of soil, but there are many exceptions to what we will learn right now (figure 5).



Figure 5. Just some of the thousands of soil types.

Pedalfer

Deciduous trees, the trees that lose their leaves each winter, need at least 65 cm of rain per year. These forests produce soils called **pedalfers**, which are common in many areas of the temperate, eastern part of the United States (figure 6). The word pedalfer comes from some of the elements that are commonly found in the soil. The *Al* in ped**al**fer is the chemical symbol of the element aluminum, and the *Fe* in pedal**fe**r is the chemical symbol for iron. Pedalfers are usually a very fertile, dark brown or black soil. Not surprising, they are rich in aluminum clays and iron oxides. Because a great deal of rainfall is common in this climate, most of the soluble minerals dissolve and are carried away, leaving the less soluble clays and iron oxides behind.



Figure 6. A pedalfer is the dark, fertile type of soil that will form in a forested region.

Pedocal

Pedocal soils form in drier, temperate areas where grasslands and brush are the usual types of vegetation (figure 7). The climates that form pedocals have less than 65 cm rainfall per year, so compared to pedalfers, there is less chemical weathering and less water to dissolve away soluble minerals so more soluble minerals are present and fewer clay minerals are produced. It is a drier region with less vegetation, so the soils have lower amounts of organic material and are less fertile.



Figure 7. A pedocal is the alkaline type of soil that forms in grassland regions.

A pedocal is named for the calcite enriched layer that forms. Water begins to move down through the soil layers, but before it gets very far, it begins to evaporate. Soluble minerals, like calcium carbonate, concentrate in a layer that marks the lowest place that water was able to reach. This layer is called caliche.

Laterite

In tropical rainforests where it rains literally every day, **laterite** soils form (figure 8). In these hot, wet, tropical regions, intense chemical weathering strips the soils of their nutrients. There is practically no humus. All soluble minerals are removed from the soil and all plant nutrients are carried away. All that is left behind are the least soluble materials, like aluminum and iron oxides. These soils are often red in color from the iron oxides. Laterite soils bake as hard as a brick if they are exposed to the sun.



Figure 8. A laterite is the type of thick, nutrient poor soil that forms in the rainforest.

Many climates types have not been mentioned here. Each produces a distinctive soil type 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. Soil development takes a very long time, it may take hundreds or even thousands of years for a good fertile topsoil to form. Soil scientists estimate that in the very best soil-forming conditions, soil forms at a rate of about 1mm/year. In poor conditions, soil formation may take thousands of years!

SOIL CONSERVATION

Soil is only a renewable resource if it is carefully managed. Drought, insect plagues, or outbreaks of disease are natural cycles of events that can negatively impact ecosystems and the soil, but there are also many ways in which humans neglect or abuse this important resource.



Figure 9. Organic material can be added to soil to help increase its fertility.

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. Land is also deliberately cleared or deforested for wood. The loose soils then 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. There are many practices that can protect and preserve soil resources. Adding organic material to the soil in the form of plant or animal waste, such as compost or manure, increases the fertility of the soil and improves its ability to hold onto water and nutrients (figure 9). Inorganic fertilizer can also temporarily increase the fertility of a soil and may be less expensive or time consuming, but it does not provide the same long-term improvements as organic materials.



Figure 10. Steep slopes can be terraced to make level planting areas and decrease surface water runoff and erosion.

Agricultural practices such as 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 10). No-till or low-tillage farming helps to keep soil in place by disturbing the ground as little as possible when planting.

LESSON SUMMARY

- Soil texture and composition, plus the amount of organic material in a soil, determine a soil's qualities and fertility.
- Given enough time, rock is weathered to produce a layered soil, called a soil profile.
- Each type of climate can ultimately produce a unique type of soil.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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4.8: Putting It Together

SUMMARY

In this section, you learned the following:

1. How weathering and erosion contribute to soil formation
2. How different processes alter rocks
3. The different types of soil
4. The different types of soil profiles

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5: PLATE TECTONICS

Learning Objectives

Identify and compare common rock forming minerals, mineral structures and mineral properties.

- Describe the basic chemistry involved in mineral formation and structures.
- Identify and classify common rock forming minerals.
- Identify the most common elements in the Earth's crust and their order of abundance.

Plate tectonics is often seen as the missing piece of the puzzle for geologists. Plate tectonics explains, either directly or indirectly, just about every topic discussed in geology. It is the glue that binds everything together.

5.1: Why It Matters

5.2: Geological Development

5.3: Basics of Plate Tectonics

5.4: Continental Drift

5.5: Continental Drift

5.6: Theory of Plate Tectonics

5.7: Theory of Plate Tectonics

5.8: Plate Tectonics

5.9: Effects of Plate Tectonics

5.10: The Ring of Fire

5.11: Intraplate Deformation

5.12: Folds

5.13: Climates and Tectonics

5.14: Hot Spots

5.15: Intraplate Activity

5.16: Hot Spots

5.17: Putting It Together

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5.1: Why It Matters

RECOGNIZE THE ONGOING DEVELOPMENT OF, EVIDENCE FOR, AND LARGE SCALE PLANETARY EFFECTS OF THE THEORY OF PLATE TECTONICS.

Plate tectonics is often seen as the missing piece of the puzzle for geologists. Plate tectonics explains, either directly or indirectly, just about every topic discussed in geology. It is the glue that binds everything together. Before plate tectonics, geologists had no explanation for these (and other) questions:

1. What causes the tectonic plates to move the way they do?
2. Why is the oceanic crust younger than continental crust?
3. Why do the continents look the way they do, like puzzle pieces or are positioned as they are?
4. Why are Japan and California so prone to earthquakes and volcanoes?
5. How did the Himalayas form?
6. Why do we find evidence of aquatic species at the very top of the Himalayas and other mountainous areas?
7. How do mountains form?
8. Why do the oceans look the way they do?
9. What factors contributed to the occurrence of the ice ages?
10. Why the same species can be found on continents on opposite sides of the oceans?

As you move through this section, keep in mind all of these questions and make note of any other impacts the Theory of Plate Tectonics has had on the field of geology.

Learning Outcomes

- Describe the processes of development of continental and oceanic crusts, continents, continental rifting, supercontinents, volcanic arcs, and the formation of ocean basins in relation to plate tectonics
- Describe and compare different types of plate motions, rates of motion, and the driving mechanisms and forces involved with each
- Compare and contrast Continental Drift with Plate Tectonics
- Critique and interpret major types of evidence supporting the Theory of Plate Tectonics
- Explain how rock formations, geologic environments, mineral resources, volcanoes and their eruptions, landforms, mountain building processes, climate change, evolution, folds, faults and earthquakes relate to and are affected by plate tectonics
- Interpret and explain hot spots and how they relate to plate motion
- Categorize and differentiate between a variety of global and regional plate boundaries and interpret the geological implications and history associated with each

Ok, let's get started! [Or insert another appropriate transition statement here.]

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5.2: Geological Development

DESCRIBE THE PROCESSES OF DEVELOPMENT OF CONTINENTAL AND OCEANIC CRUSTS, CONTINENTS, CONTINENTAL RIFTING, SUPERCONTINENTS, VOLCANIC ARCS, AND THE FORMATION OF OCEAN BASINS IN RELATION TO PLATE TECTONICS

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Basics of Plate Tectonics

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5.3: Basics of Plate Tectonics

INTRODUCTION

The theory of plate tectonics revolutionized geology in the 1960s. By 1970, college geology majors were taught a set of ideas that were unheard of by most geology students prior to 1960. The foundation for the new way of comprehending earth processes is the understanding that the outer layer of the earth is the lithosphere rather than simply the crust.

THE LAYERS OF THE EARTH

The earth is layered in terms of chemical composition as follows:

1. The outer layer is the crust. Continental crust is thick (25–50 km thick), low in density, and has an intermediate average composition; oceanic crust is thin (typically 5–10 km thick), higher in density, and has a mafic average composition.
2. The mantle consists of dense, ultramafic rock.
3. The core consists of a mixture of iron and nickel.

The earth is also layered in terms of physical or mechanical behavior. In those terms, the outer layer of the earth is the lithosphere, which is a rigid layer that is broken up into tectonic plates and averages about 100 km (60 miles) thick. The layer beneath the lithosphere is the weak, soft asthenosphere, which is roughly 300 to 400 km thick. To understand plate tectonics, the different ways of classifying the layers of the earth-by composition and by mechanical behavior-must be kept in mind.

THE THEORY OF PLATE TECTONICS

Plate tectonic theory allowed geologists to understand the origins of and the relationships between: the world's volcanic arcs and deep earthquake zones; exotic terranes and thrust fault zones; and transform faults and shallow earthquake zones. Plate tectonics also enabled geologists to explain the origins of the oceanic crust and the continents.

According to plate tectonic theory, the lithosphere is divided into rigid plates that interact with one another at their boundaries. Earthquakes, faults, and folds take place at these boundaries. Voluminous igneous intrusions and frequent volcanic eruptions occur at two of the major types of plate boundaries. In sum, most (though not all) of the earthquakes and volcanic eruptions that take place in the world happen in association with plate boundaries. Much of the action in geology that gets peoples' attention—volcanic eruptions, devastating earthquakes—happens because of how plates interact with each other along their boundaries.

The Pacific Northwest lies near the boundaries of several tectonic plates. The influence of these plates and their boundary interactions underlies the major geological themes of the region, including the uplift of the Coast Ranges, the formation of the Puget-Willamette Lowland, and the volcanism of the Cascade Range. Plate boundary processes also explain how most of the land of Washington and Oregon has come to be part of North America in the last 200 million years. Prior to the addition of continent the area west of Idaho was an ocean basin.

PALEOMAGNETISM

The earth, as you know, has a magnetic field. Some types of rock, when they originate, record the magnetism of the earth at the time the rock formed. This happens because magnetic minerals in the rock orient themselves, like little compasses, in the direction of the earth's magnetic field, then are locked in place as the rock is lithified. After the rock has formed, as long as it does not get heated up to nearly its melting point—as long as it does not get above what is called the Curie point, the temperature at which the magnetism in the minerals is destroyed—it will retain that record of the earth's magnetism at the time the rock formed. This provides the basis of paleomagnetism, the study of the magnetic record of the earth preserved in the rocks. Paelomagnetism has been a key for unlocking much of our modern knowledge of the geology of earth, especially the theory of plate tectonics.

The Magnetic North Pole on earth today is in far northern Canada, only approximately in the direction of the Geographic North Pole. The Geographic North Pole, which is also called the True North Pole, is the northern end of earth's axis of rotation.

The Geographic or True North Pole is not the same thing as the Magnetic North Pole and should not be mistaken for it. The Geographic North Pole is is at 90° N latitude, at the very top of the earth. The Magnetic North Pole is currently at about 85° latitude, but it wanders up to a degree every few years.

The magnetism of earth is created by convection and other movements of earth's outer core. The outer core consists of hot, molten metal, mostly iron and nickel, in which many of the electrons move about freely among the atoms. The daily spinning around of this sea of molten metal and its virtually free electrons, combined with the convection of the molten core, creates the magnetic field of the earth. Unlike the magnetism of a bar magnet, the earth's magnetic field is not very stable. The location of the Magnetic North Pole wanders many miles every year. Even more amazing, every several hundred thousand to several million years, the magnetism produced by earth's core becomes so unstable, or "tangled up," that it ends up reversing its north and south magnetic poles. There is no regular timing to when the earth's magnetic field reverses itself. The last magnetic reversal was 780,000 years ago.

By the way, earth's magnetic field is not very powerful in terms of its direct effects on living things. If it shut down right now, you would not feel anything. If you have played with bar magnets or touched old-fashioned televisions with cathode-ray tubes—the common type of TV and computer monitor before flat screens—while they were turned on, then you have been exposed to much more powerful magnetism than the earth's magnetism, yet you did not feel that much stronger magnetism, either. As far as the geological record indicates, no species have gone extinct at any of the times when earth's magnetic field reversed itself.

These reversals of the magnetic field of earth, and how long ago they took place, have been detected and measured from many rocks in the earth that preserve a record of the earth's magnetism, including igneous rocks and sedimentary rocks from the floor of the ocean. Basalt flows are the strongest recorders of the earth's magnetism, but other types of igneous rock and certain types of sedimentary rock also record earth's magnetic field as they form. The ocean floor consists largely of basalt flows, which provide a strong enough record of earth's paleomagnetism that it can be measured from a ship passing above. The ocean floor contains many layers of sediment and sedimentary rock that are relatively easy to recover from drill cores, which also recorded the magnetic field when they originated. Igneous and sedimentary rocks from the continents have also been used, along with fossil records, to study earth's magnetic past.

Together, these various ways of studying paleomagnetism have verified and refined our knowledge of how the magnetic poles have wandered in the past, and when each reversal of earth's magnetic field has taken place. This has allowed us to construct a timeline of magnetic reversals over the course of earth's history. The accuracy and precision of the magnetic reversal timeline becomes much weaker for geologic ages more than about 200 Ma (millions of years ago). This is because nearly all older ocean floor has been subducted (recycled) back into the earth, and the paleomagnetic record from rocks on the continents is spottier—less continuous—than the paleomagnetic record derived from measurements of oceanic crust.

The paleomagnetism of rocks on the floor of the ocean was the key to unlocking the theory of sea floor spreading, an essential component of the theory of plate tectonics. As oceanic crust forms at the divergent plate boundaries and spreads away from there, it acts like a magnetic tape recorder, spreading a record of earth's magnetism across the ocean floor. The magnetic reversals recorded in rocks on the ocean floor are still called magnetic anomalies because, when they were first discovered in the 1950s, neither sea floor spreading nor the fact that earth's magnetic field has often reversed itself was yet realized. By knowing how long ago a particular magnetic reversal occurred, along with the distance of that magnetic isochron to the ridge where it originated, you can determine the rate at which the plate has been spreading away from the ridge. This is done by dividing the distance from the isochron to the ridge, by the number of years that have passed since that magnetic reversal occurred. In addition, the direction in which a plate has been moving can also be determined by analyzing the map patterns of its magnetic anomalies on the ocean floor.

Similarly, the paleomagnetism of rocks on the continents has been the key to unlocking continental drift, another building block of the theory of plate tectonics. The paleomagnetism of rocks on the continents is used to reconstruct the motions of continents across the face of the earth.

Paleomagnetism has also been one of the keys to unlocking the origins of many accreted terranes. If a part of a continent is suspected of being an accreted terrane, and it contains rocks with measurable paleomagnetism, the paleomagnetism may determine if the rocks did indeed originate far from their present-day location, on a tectonic plate separate from the continent, only to be moved in and accreted to the continent later. See also, the Basics page on Exotic Terranes.

PLATE BOUNDARIES

There are three general types of plate boundaries:

1. divergent plate boundaries, where two plates move away from each other
2. transform plate boundaries, where two plates move horizontally side-by-side in opposite directions
3. convergent plate boundaries, where two plates move toward each other and either collide with each other or one plate bends down and goes beneath the other

Divergent Plate Boundaries

Most of the world's divergent plate boundaries are on the ocean floor, in the form of mid-ocean spreading ridge. At divergent boundaries, the two plates are continually moving apart, heading in opposite directions away from each other. The divergence causes normal faults and rift valleys (grabens) to form there as a result of the tension in the crust. In other words, in response to getting pulled apart by tectonic forces, the crust cracks apart and sections of it drop down into rift valleys.

At a divergent plate boundary, the spreading crust forms channels through which magma rises from the mantle. Some of the magma erupts on the ocean floor and builds up piles of pillow basalt. Some of it solidifies within the cracks, beneath the surface of the crust, forming igneousdikes. Some of it solidifies as gabbro intrusions deeper in the crust. At the places where the magma pools within the crust, olivine and other dense minerals settle into layers at the bottom of the pools and form layered mafic and ultramafic igneous rocks.

All these eruptions and intrusions solidify and become new oceanic crust, which moves away from the mid-ocean spreading ridge and makes way for yet more magma to rise and continue the process. Creation of oceanic crust is part of a continual process that occurs at divergent plate boundaries on the ocean floor. The new oceanic crust is part of a moving tectonic plate. It continues to move as part of the ocean floor and will eventually collect layers of sediment descending from the water above.

Transform Plate Boundaries

Transform plate boundaries are strike-slip faults that separate tectonic plates which are moving parallel to each other but in opposite directions. Tectonic plates average about 100 km in thickness. As the two plates slide next to each other, trying to move in opposite directions, there is much friction and stress between them. As a result, transform plate boundaries are zones of frequent earthquakes.

Most transform plate boundaries are on the ocean floor, in the oceanic crust, connecting segments of mid-ocean spreading ridges. However, in a few places transform plate boundaries cut through continental crust. The most famous example is the San Andreas Fault in California, which is a transform plate boundary that separates the North American Plate from the Pacific Plate.

Convergent Plate Boundaries

Convergent plate boundaries are where two plates move toward each other. Subduction is a process that occurs at convergent plate boundaries. The western part of the Pacific Northwest is at a convergent plate boundary, and the effects of subduction have reached all the way across the Rocky Mountains to the edge of the Great Plains.

Depending on the type of crust that composes the upper part of each plate, there are three types of convergent plate boundaries: continent-continent, ocean-ocean, and ocean-continent.

Continent-Continent Convergent Plate Boundaries

Continental crust is too low in density to go down into the mantle and stay there. Continent-continent convergent plate boundaries are not zones of subduction in the normal sense. Instead, the two continents collide with each other, folding, thrust faulting, and building upward into a high, wide mountain range. The Himalayas in south central Asia are an example of a continent-continent convergent plate boundary.

Although large earthquakes occur in association with continent-continent convergent plate boundaries there are no volcanoes. Mountain ranges such as the Himalayas do not have volcanoes because there is no oceanic plate subducting beneath them.

Ocean-Ocean Convergent Plate Boundaries

At ocean-ocean convergent plate boundaries, as the two plates with oceanic crust converge, one goes down beneath the other

and into the mantle. This zone where a plate is diving back down into the mantle, beneath the edge of the adjacent plate, is called a subduction zone.

The outer edge of a subduction zone is an oceanic trench, which forms where the subducting plate bends and pushes downward as it enters the subduction process. Oceanic trenches at ocean-ocean subduction zones are the deepest places in the ocean. Island arcs, which are composite cone volcanoes arrayed in the form of an island chain, are also associated with ocean-ocean convergent plate boundaries. The Aleutian Islands of Alaska are an example of an island arc.

Ocean-Continent Convergent Plate Boundaries

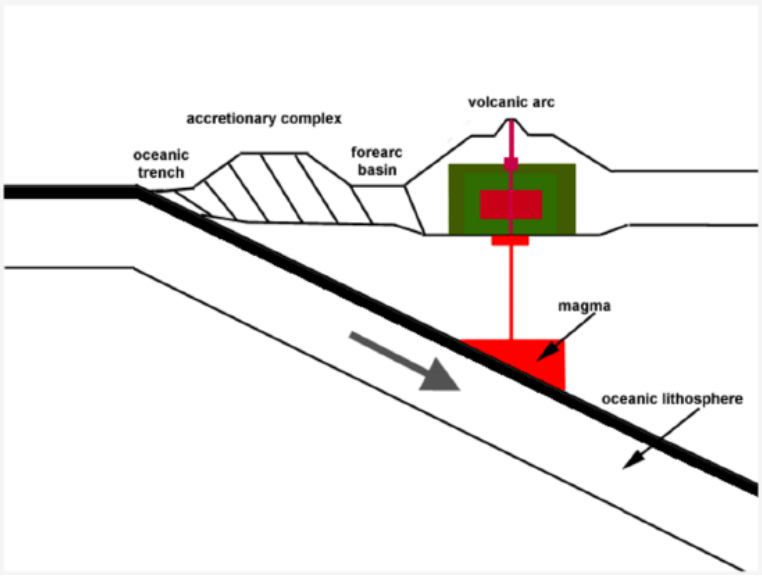
At an ocean-continent convergent plate boundary, the plate that carries oceanic crust subducts into the mantle beneath the edge of the continent. Ocean-continent convergent plate boundaries are similar to ocean-ocean subduction zones, but the much thicker continental crust leads to a greater range of geological features, including a volcanic arc that forms above the region in the crust at which the subducting plate reaches a depth of 65 to 80 miles beneath the surface and an accretionary complex.

Table: Convergent Plate Boundaries

Type	Examples	Landforms	Geologic Processes
ocean-ocean	• Aleutian Islands • West Indies • Mariana Islands	• oceanic trench • island arc (chain of composite cone islands in the ocean)	• subduction • major deep earthquakes • shallow earthquakes • volcanism • igneous intrusion
ocean-continent	• Andean subduction zone • Cascadia subduction zone	• oceanic trench • accretionary complex • forearc basin • volcanic arc (chain of composite cones on continent)	• subduction • major deep earthquakes • shallow earthquakes • volcanism • igneous intrusion • terrane accretion • orogeny
continent-continent	• Himalayas • Alps	• broad, high mountain range (no volcanoes)	• thrust faulting • shallow earthquakes • folding • mountain building

SUBDUCTION ZONES

Because the convergent plate boundary along the Northwest coast is a subduction zone, we need to examine the parts of a subduction zone in a little more detail.



The Oceanic Trench

Most subduction zones start at an oceanic trench, where the subducting plate begins the process of bending and pushing downward. The apparent lack of an oceanic trench off the Northwest coast is an anomaly. To some extent, there may be a trench that has been filled in with the abundant sediments dumped onto the continental shelf by the Columbia River and other rivers that drain to the Pacific Coast.

Deep Earthquakes (Subduction Earthquakes)

Another characteristic of subduction zones is that they have major earthquakes that occur within the subducting plate, as it forces its way down into the mantle. The most powerful earthquakes on earth are these earthquakes in subducting plates. The stress of the subduction process also causes shallower earthquakes to take place in the continental crust [GLOSS] of the overlying plate.

The Accretionary Complex

At ocean-continent subduction zones, the leading edge of the continent is the site of an accretionary complex, also called an accretionary prism or accretionary wedge. An accretionary complex is an elevated zone built up of pieces of oceanic crust or lithosphere that were accreted from the subducting plate onto the edge of the continent along reverse faults. Accretionary complexes tend to build up high enough to form coastal mountain ranges. However, unlike the main volcanic arc mountain range, accretionary complex coast ranges are not volcanic.

The Forearc Basin

Between the accretionary mountain range and the volcanic arc is the forearc basin, a low area into which rivers drain and which may contain an arm of the ocean.

The Volcanic Arc

All subduction zones have, at some distance in from the edge of the upper plate, arcs or chains of composite cone volcanoes. The subducting plate, as it goes down deep into the mantle, releases water. This changes the chemistry of the already hot rocks in the mantle and causes them to melt, forming magma. The magma is less dense than the solid rocks around it, so it rises upward, culminating in volcanic eruptions at the earth's surface.

The volcanic arc at an ocean-continent subduction zone is not only a chain of volcanoes. The stress of plate convergence compresses the crust there, causing it to thicken through a combination of folds and thrust faults. Igneous intrusions and volcanic

eruptions also thicken the crust there. Deep within the crust, the igneous intrusions solidify into batholiths of rocks such as granite, and the pre-existing rocks that are intruded by the batholiths are regionally metamorphosed into new rocks. The result is a high mountain range with granitic and metamorphic rock at its core, folded and faulted sedimentary and volcanic around its margins, and a chain of composite cone volcanoes distributed along the crest of the range.

Terrane Accretion

A large tectonic plate, such as the Pacific Plate, carries more than oceanic crust. It also carries island arcs and oceanic plateaus, which are zones of unusually thick oceanic crust. Large island complexes such as the islands of Japan, which were built by the assemblage of several island arcs, also ride on tectonic plates. Other plate passengers include ocean islands such as the Hawaiian Islands, which build from volcanic eruptions that emanate from mantle hot spots.

As the oceanic plate carrying these larger pieces of crust comes into an ocean-continent subduction zone, the island arcs, oceanic plateaus, island complexes, and oceanic islands will not go down the subduction zone. Instead, they will be plastered to the edge of the continent, becoming accreted terranes. Examples of all these types of crust, swept in and accreted to North America by a subducting oceanic plate, can be found in the Pacific Northwest.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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5.4: Continental Drift

DESCRIBE CONTINENTAL DRIFT INCLUDING SUPPORTING EVIDENCE.

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Continental Drift

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5.5: Continental Drift

INTRODUCTION

The continental drift hypothesis was developed in the early part of the 20th century, mostly by Alfred Wegener. Wegener said that continents move around on Earth's surface and that they were once joined together as a single supercontinent. 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. That's the true size and shape of a 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 (figure 1).



Figure 1. The continents fit together like pieces of a puzzle. This is how they looked 250 million years ago.

Alfred Wegener proposed that the continents were once united into a single supercontinent named Pangaea, meaning *all earth* in ancient Greek. He 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 way the continents fit together, Wegener and his supporters collected a great deal of evidence for the continental drift hypothesis.

- Identical rocks, of the same type and age, are found on both sides of the Atlantic Ocean. Wegener said the rocks had formed side-by-side and that the land had since moved apart.
- Mountain ranges with the same rock types, structures, and ages 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 (figure 2). Wegener concluded that they formed as a single mountain range that was separated as the continents drifted.



Figure 2. The similarities between the Appalachian and the eastern Greenland mountain ranges are evidences for the continental drift hypothesis.

- Ancient fossils of the same species of extinct plants and animals are found in rocks of the same age but are on continents that are now widely separated (figure 3). Wegener proposed that the organisms had lived side by side, but that the lands had moved apart after they were dead and fossilized. He suggested that the organisms would not have been able to travel across the oceans.
  - Fossils of the seed fern *Glossopteris* were too heavy to be carried so far by wind.
  - *Mesosaurus* was a swimming reptile but could only swim in fresh water.
  - *Cynognathus* and *Lystrosaurus* were land reptiles and were unable to swim

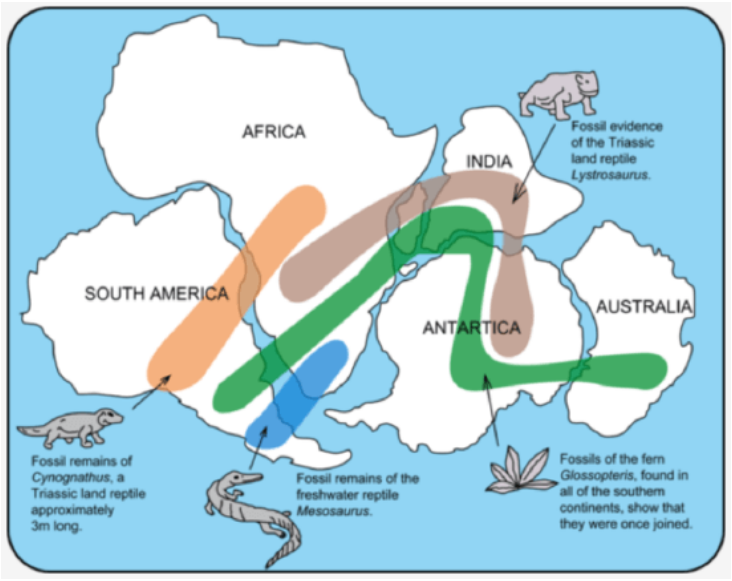


Figure 3. Wegener used fossil evidence to support his continental drift hypothesis. The fossils of these organisms are found on lands that are now far apart.

- Grooves and rock deposits left by ancient glaciers are found today on different continents very close to the equator. This would indicate that the glaciers either formed in the middle of the ocean and/or covered most of the Earth. Today glaciers only form on land and nearer the poles. Wegener thought that the glaciers were centered over the southern land mass close to the South Pole and the continents moved to their present positions later on.
- Coral reefs and coal-forming swamps are found in tropical and subtropical environments, but ancient coal seams and coral reefs are found in locations where it is much too cold today. Wegener suggested that these creatures were alive in warm climate zones and that the fossils and coal later had drifted to new locations on the continents.

Take a look at this animation showing that Earth's climate belts remain in roughly the same position while the continents move and this animation showing how the continents split up.

Although Wegener's evidence was sound, most geologists at the time rejected his hypothesis of continental drift. Why do you think they did not accept continental drift?

Scientists argued that there was no way to explain how solid continents could plow through solid oceanic crust. Wegener's idea

was nearly forgotten until technological advances presented even more evidence that the continents moved and gave scientists the tools to develop a mechanism for Wegener's drifting continents.

MAGNETIC POLARITY EVIDENCE

Puzzling new evidence came in the 1950s from studies on the Earth's magnetic history (figure 4). Scientists used **magnetometers**, devices capable of measuring the magnetic field intensity, to look at the magnetic properties of rocks in many locations.

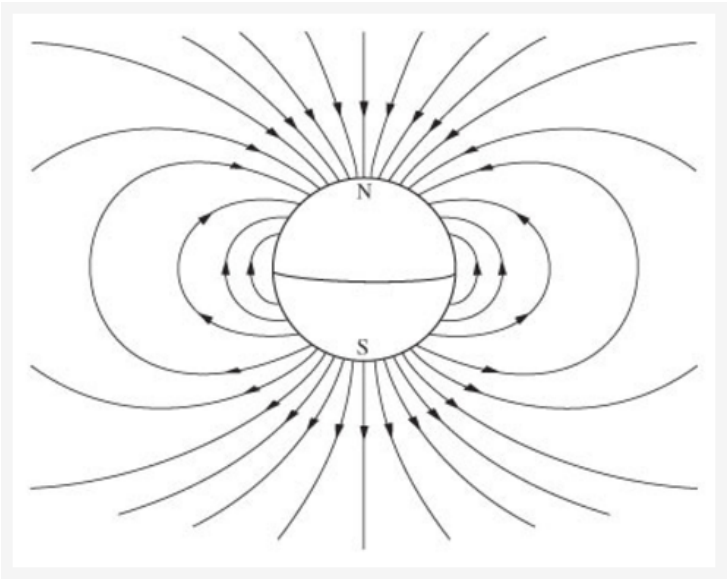


Figure 4. Earth's magnetic field is like a magnet with its north pole near the geographic North Pole and the south pole near the geographic South Pole.

Magnetite crystals are like tiny magnets that point to the north magnetic pole as they crystallize from magma. The crystals record both the direction and strength of the **magnetic field** at the time. The direction is known as the field's **magnetic polarity.**

Magnetic Polarity on the Same Continent with Rocks of Different Ages

Geologists noted important things about the magnetic polarity of different aged rocks on the same continent:

- Magnetite crystals in fresh volcanic rocks point to the current magnetic north pole (figure 5) no matter what continent or where on the continent the rocks are located.

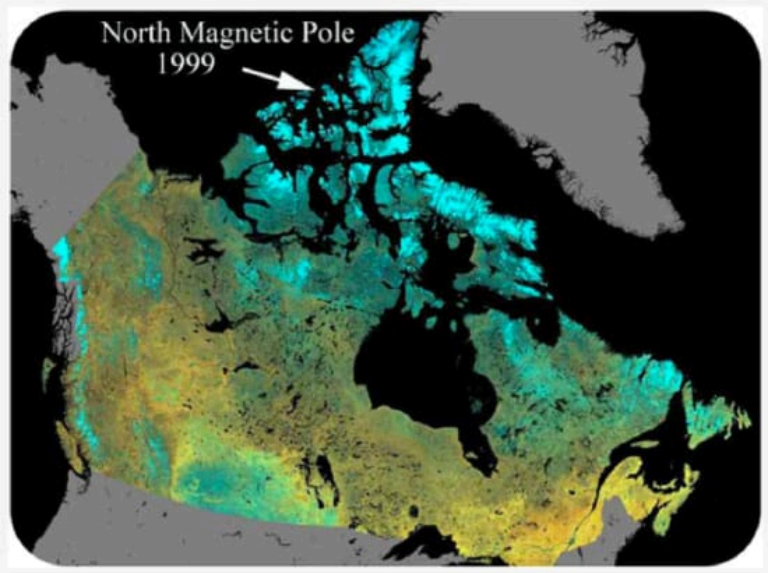


Figure 5. Earth's current north magnetic pole is in northern Canada.

- Older rocks that are the same age and are located on the same continent point to the same location, but that location is not the current north magnetic pole.
- Older rock that are of different ages do not point to the same locations or to the current magnetic north pole.

In other words, although the magnetite crystals were pointing to the magnetic north pole, the location of the pole seemed to wander. Scientists were amazed to find that the north magnetic pole changed location through time (figure 6).

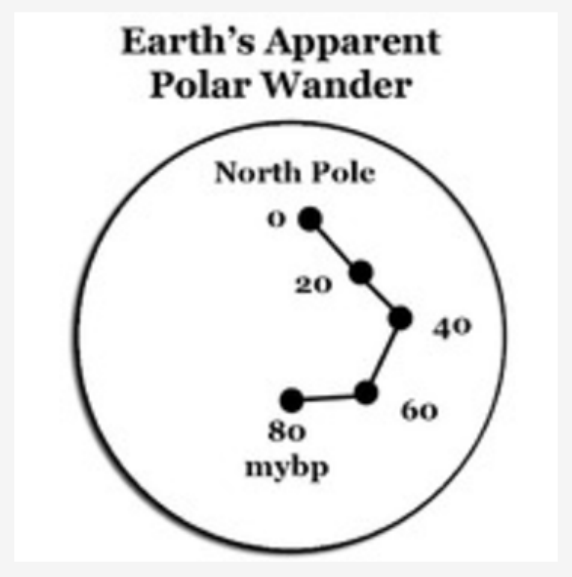


Figure 6. The location of the north magnetic north pole 80 million years before present (mybp), then 60, 40, 20, and now.

There are three possible explanations for this:

1. The continents remained fixed and the north magnetic pole moved.
2. The north magnetic pole stood still and the continents moved.
3. Both the continents and the north pole moved.

Magnetic Polarity on Different Continents with Rocks of the Same Age

Geologists noted that for rocks of the same age but on different continents, the little magnets pointed to different magnetic north

poles.

- 400-million-year-old magnetite in Europe pointed to a different north magnetic pole than the same-aged magnetite in North America.
- 250 million years ago, the north poles were also different for the two continents.

The scientists looked again at the three possible explanations. Only one can be correct. If the continents had remained fixed while the north magnetic pole moved, there must have been two separate north poles. Since there is only one north pole today, the only reasonable explanation is that the north magnetic pole has remained fixed but that the continents have moved.

To test this, geologists fitted the continents together as Wegener had done. It worked! There has only been one magnetic north pole and the continents have drifted (figure 7). They named the phenomenon of the magnetic pole that seemed to move but actually did not **apparent polar wander.**

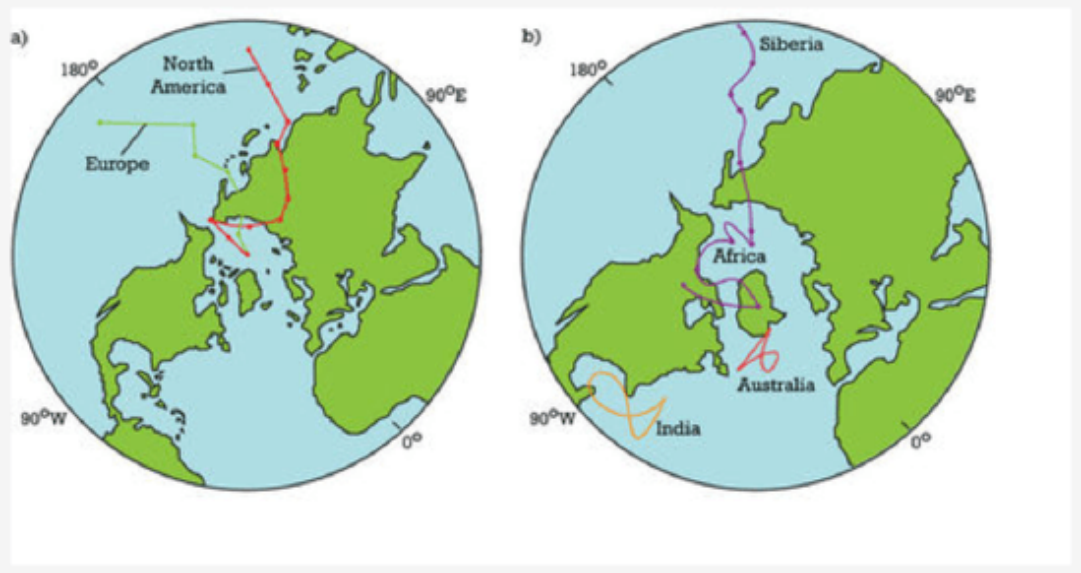


Figure 7. On the left: The apparent north pole for Europe and North America if the continents were always in their current locations. The two paths merge into one if the continents are allowed to drift.

This evidence for continental drift gave geologists renewed interest in understanding how continents could move about on the planet's surface.

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 for continental drift was extremely strong, scientists rejected the idea because no mechanism for how solid continents could move around on the solid earth was developed.
- The discovery of apparent polar wander renewed scientists interest in continental drift.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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5.6: Theory of Plate Tectonics

CRITIQUE AND INTERPRET MAJOR TYPES OF EVIDENCE SUPPORTING THE THEORY OF PLATE TECTONICS BY DESCRIBING AND COMPARING DIFFERENT TYPES OF PLATE MOTIONS, RATES OF MOTION, AND THE DRIVING MECHANISMS AND FORCES INVOLVED WITH EACH

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Theory of Plate Tectonics
- Reading: Plate Tectonics

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5.7: Theory of Plate Tectonics

When the concept of seafloor spreading came along, scientists recognized that it was the mechanism to explain how continents could move around Earth's surface. Like the scientists before us, we will now merge the ideas of continental drift and seafloor spreading into the theory of plate tectonics.

Watch this video about continental drift and the mechanism of seafloor spreading create plate tectonics.

EARTH'S TECTONIC PLATES

Seafloor and continents move around on Earth's surface, but what is actually moving? What portion of the Earth makes up the "plates" in plate tectonics? This question was also answered because of technology developed during war times – in this case, the Cold War. The **plates** are made up of the lithosphere.

During the 1950s and early 1960s, scientists set up seismograph networks to see if enemy nations were testing atomic bombs. These seismographs also recorded all of the earthquakes around the planet. The 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.

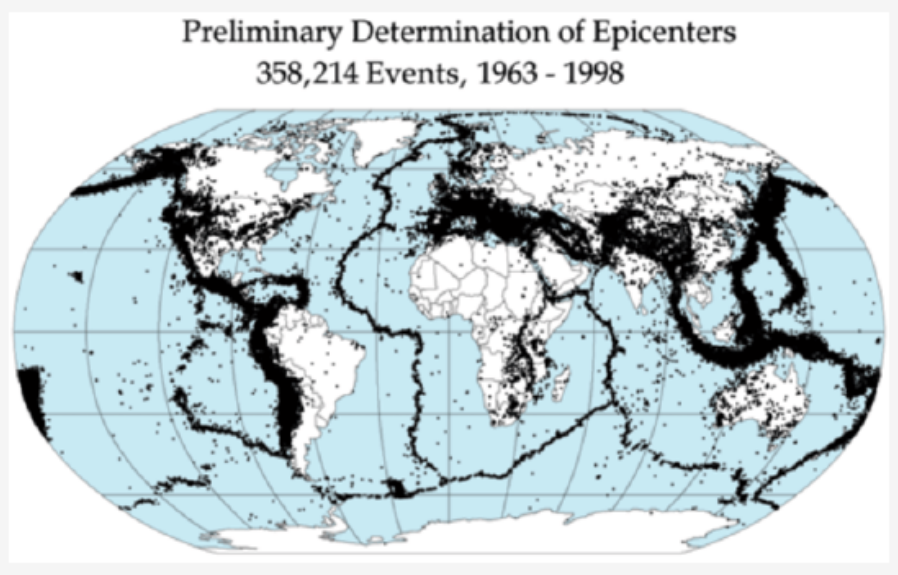


Figure 1. Earthquakes outline the plates.

Earthquake epicenters outline the plates. Mid-ocean ridges, trenches, and large faults mark the edges of the plates, and this is where earthquakes occur (figure 1).

The lithosphere is divided into a dozen major and several minor plates (figure 2). The plates' edges can be drawn by connecting the dots that mark earthquakes' epicenters. 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.

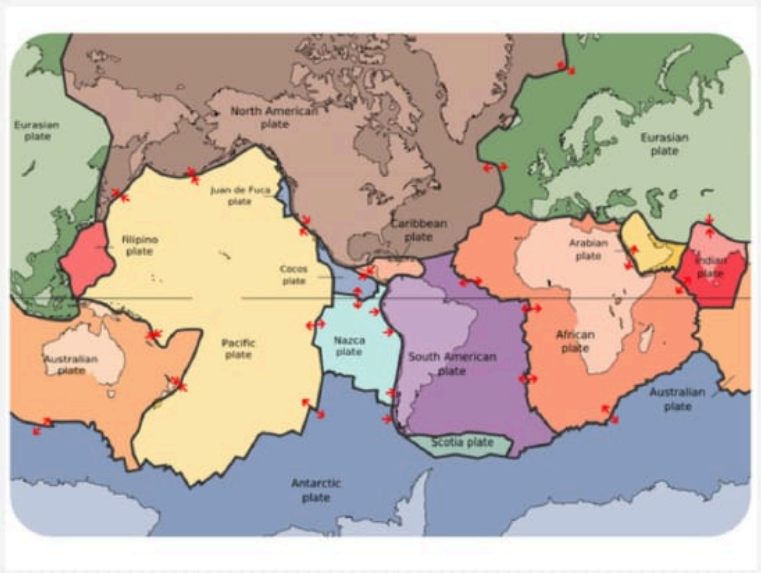


Figure 2. The lithospheric plates and their names. The arrows show whether the plates are moving apart, moving together, or sliding past each other.

Movement of the plates over Earth's surface is termed **plate tectonics**. Plates move at a rate of a few centimeters a year, about the same rate fingernails grow.

HOW PLATES MOVE

If seafloor spreading drives the plates, what drives seafloor spreading? Picture two convection cells side-by-side in the mantle, similar to the illustration in figure 3.

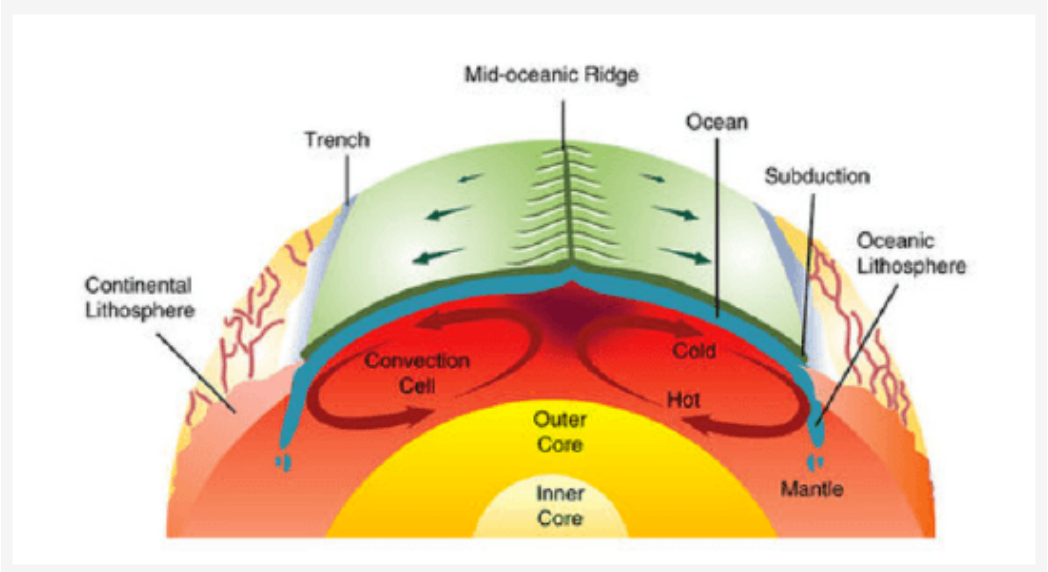


Figure 3. Mantle convection drives plate tectonics. Hot material rises at mid-ocean ridges and sinks at deep sea trenches, which keeps the plates moving along the Earth's surface.

1. Hot mantle from the two adjacent cells rises at the ridge axis, creating new ocean crust.
2. The top limb of the convection cell moves horizontally away from the ridge crest, as does the new seafloor.
3. The outer limbs of the convection cells plunge down into the deeper mantle, dragging oceanic crust as well. This takes place at the deep sea trenches.
4. The material sinks to the core and moves horizontally.
5. The material heats up and reaches the zone where it rises again.

Check out this animation of mantle convection and watch this video:

YouTube Video

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PLATE BOUNDARIES

Plate boundaries are the edges where two plates meet. Most geologic activities, including volcanoes, earthquakes, and mountain building, take place at plate boundaries. How can two plates move relative to each other?

- **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.

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.

Divergent Plate Boundaries

Plates move apart at mid-ocean ridges where new seafloor forms. Between the two plates is a rift valley. Lava flows at the surface cool rapidly to become basalt, but deeper in the crust, magma cools more slowly to form gabbro. So the entire ridge system is made up of igneous rock that is either extrusive or intrusive. Earthquakes are common at mid-ocean ridges since the movement of magma and oceanic crust results in crustal shaking. The vast majority of mid-ocean ridges are located deep below the sea (figure 4).



Figure 4. (a) Iceland is the one location where the ridge is located on land: the Mid-Atlantic Ridge separates the North American and Eurasian plates; (b) The rift valley in the Mid-Atlantic Ridge on Iceland.

Check out these animations:

- Divergent plate boundary at mid-ocean ridge
- Divergent plate boundary

Can divergent plate boundaries occur within a continent? What is the result? **Incontinental rifting** (figure 5), magma rises

beneath the continent, causing it to become thinner, break, and ultimately split apart. New ocean crust erupts in the void, creating an ocean between continents.



Figure 5. The Arabian, Indian, and African plates are rifting apart, forming the Great Rift Valley in Africa. The Dead Sea fills the rift with seawater.

Convergent Plate Boundaries

When two plates converge, the result depends on the type of lithosphere the plates are made of. No matter what, smashing two enormous slabs of lithosphere together results in magma generation and earthquakes.

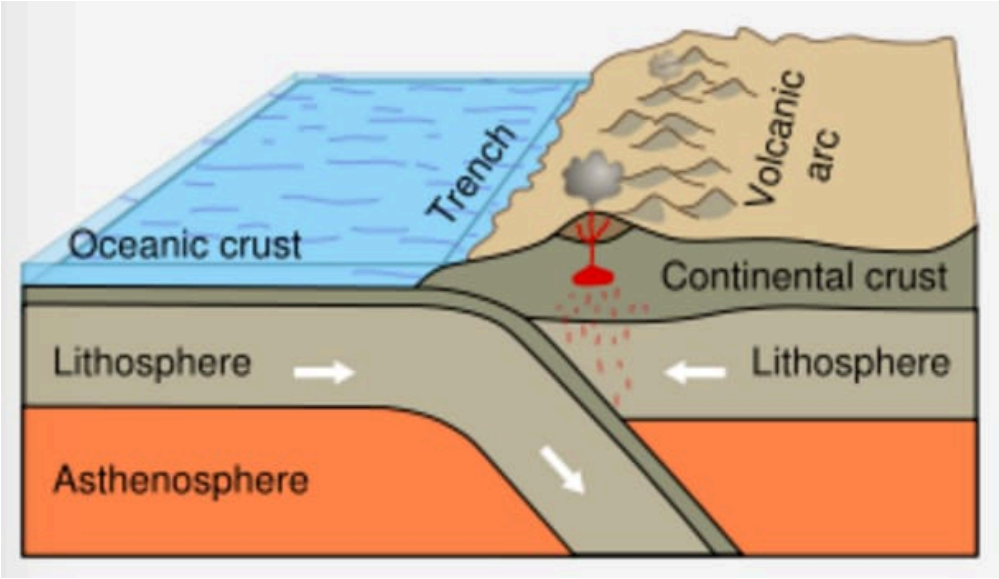


Figure 6. Subduction of an oceanic plate beneath a continental plate causes earthquakes and forms a line of volcanoes known as a continental arc.

Ocean-Continent

When oceanic crust converges with continental crust, the denser oceanic plate plunges beneath the continental plate. This process, called **subduction**, occurs at the oceanic trenches (figure 6). 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 coastal volcanic mountains are found in a line above the subducting plate (figure 7). The volcanoes are known as a **continental arc**.

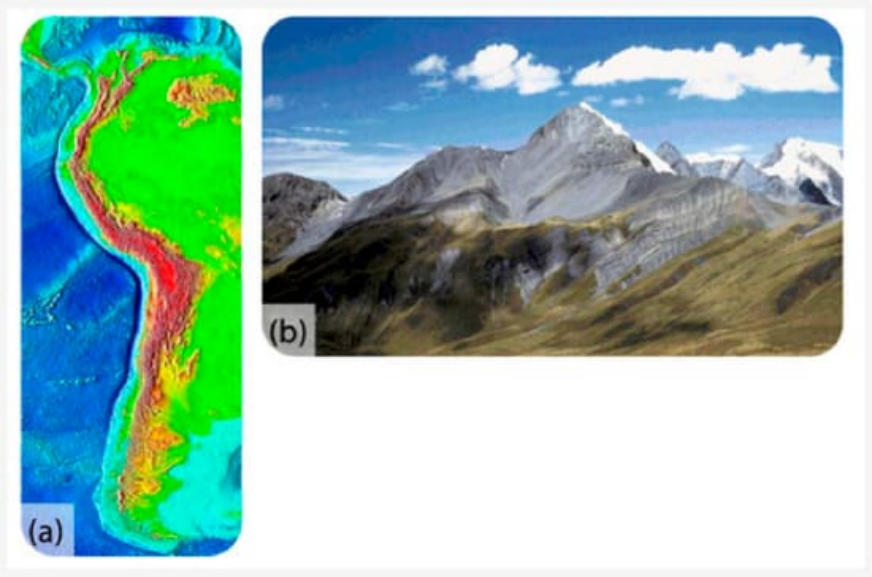


Figure 7. (a) At the trench lining the western margin of South America, the Nazca plate is subducting beneath the South American plate, resulting in the Andes Mountains (brown and red uplands); (b) Convergence has pushed up limestone in the Andes Mountains where volcanoes are common.

The movement of crust and magma causes earthquakes. Look at this map of earthquake epicenters at subduction zones. This animation shows the relationship between subduction of the lithosphere and creation of a volcanic arc.

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 8). The Juan de Fuca plate is created by seafloor spreading just offshore at the Juan de Fuca ridge.

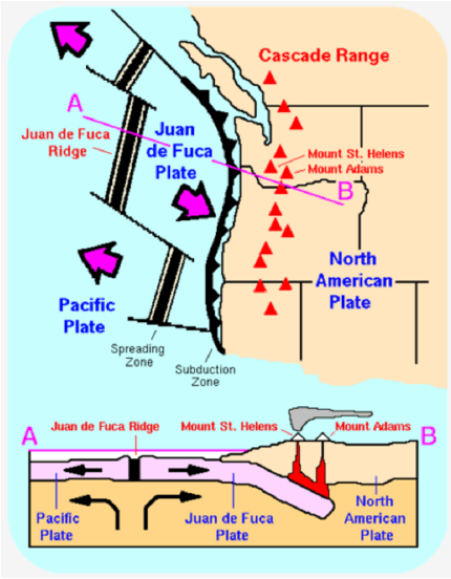


Figure 8. The Cascade Mountains of the Pacific Northwest are a continental arc.

If the magma at a continental arc is felsic, it may be too viscous (thick) to rise through the crust. The magma will cool slowly to form granite or granodiorite. These large bodies of intrusive igneous rocks are called **batholiths**, which may someday be uplifted to form a mountain range (figure 9).



Figure 9. The Sierra Nevada batholith cooled beneath a volcanic arc roughly 200 million years ago. The rock is well exposed here at Mount Whitney. Similar batholiths are likely forming beneath the Andes and Cascades today.

Ocean-Ocean

When two oceanic plates converge, the older, denser plate will subduct into the mantle. An ocean trench marks the location where the plate is pushed down into the mantle. The line of volcanoes that grows on the upper oceanic plate is an **island arc**. Do you think earthquakes are common in these regions (figure 10)?

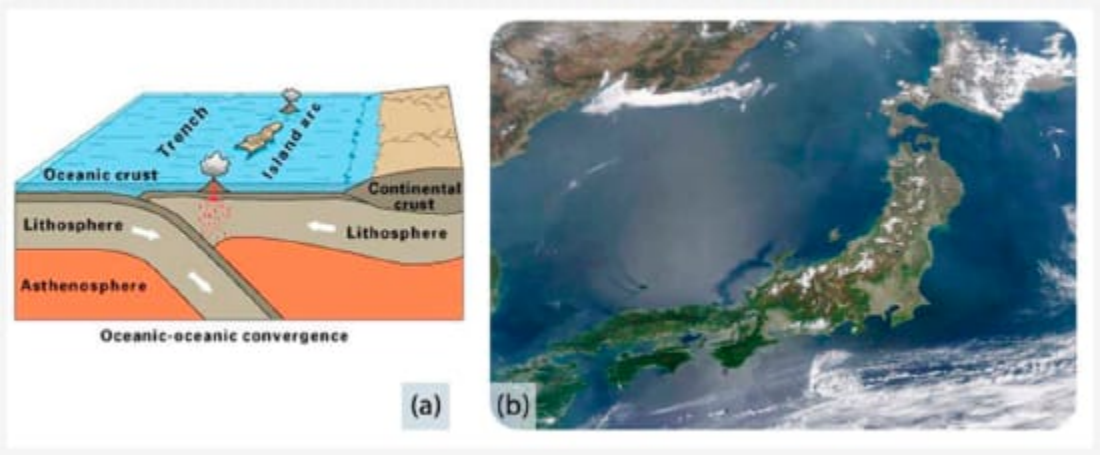


Figure 10. (a) Subduction of an ocean plate beneath an ocean plate results in a volcanic island arc, an ocean trench and many earthquakes. (b) Japan is an arc-shaped island arc composed of volcanoes off the Asian mainland, as seen in this satellite image.

Check out this animation of an ocean continent plate boundary.

Continent-Continent

Continental plates are too buoyant to subduct. What happens to continental material when it collides? Since it has nowhere to go but up, this creates some of the world's largest mountains ranges (figure 11). Magma cannot penetrate this thick crust so there are no volcanoes, although the magma stays in the crust. Metamorphic rocks are common because of the stress the continental crust experiences. With enormous slabs of crust smashing together, continent-continent collisions bring on numerous and large earthquakes.

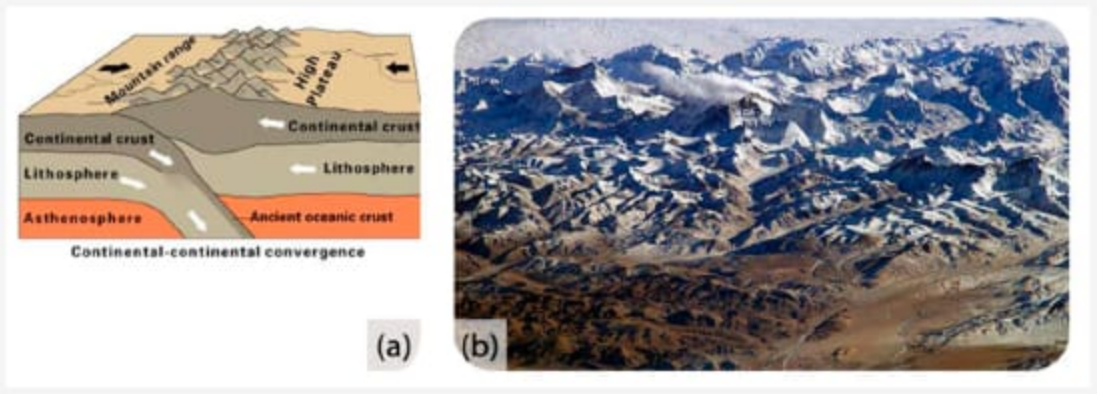


Figure 11. (a) In continent-continent convergence, the plates push upward to create a high mountain range. (b) The world's highest mountains, the Himalayas, are the result of the collision of the Indian Plate with the Eurasian Plate, seen in this photo from the International Space Station.

Check out this short animation of the Indian Plate colliding with the Eurasian Plate.

Watch this animation of the Himalaya rising.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

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**, where two plates move past each other in opposite directions. Transform faults on continents bring massive earthquakes (figure 12).

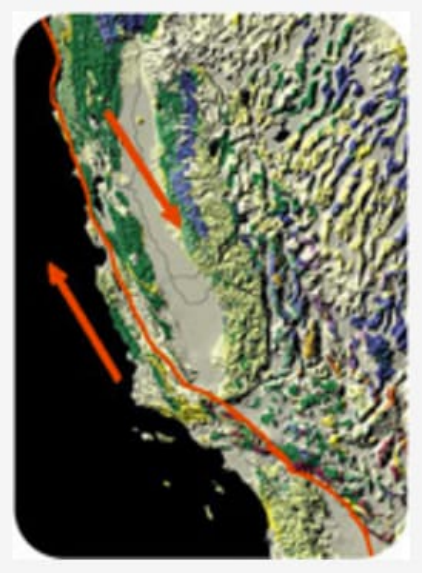


Figure 12. At the San Andreas Fault in California, the Pacific Plate is sliding northeast relative to the North American plate, which is moving southwest. At the northern end of the picture, the transform boundary turns into a subduction zone.

California is very geologically active. What are the three major plate boundaries in or near California (figure 13)?

1. A transform plate boundary between the Pacific and North American plates creates the San Andreas Fault, the world's most notorious transform fault.
2. Just offshore, a divergent plate boundary, Juan de Fuca ridge, creates the Juan de Fuca plate.
3. A convergent plate boundary between the Juan de Fuca oceanic plate and the North American continental plate creates the Cascades volcanoes.



Figure 13. This map shows the three major plate boundaries in or near California.

A brief review of the three types of plate boundaries and the structures that are found there is the subject of this wordless video.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

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EARTH'S CHANGING SURFACE

Geologists know that Wegener was right because the movements of continents explain so much about the geology we see. Most of the geologic activity that we see on the planet today is because of the interactions of the moving plates.



Figure 14. Mountain ranges of North America.

In the map of North America (figure 14), where are the mountain ranges located? Using what you have learned about plate tectonics, try to answer the following questions:

1. What is the geologic origin of the Cascades Range? The Cascades are a chain of volcanoes in the Pacific Northwest. They are not labelled on the diagram but they lie between the Sierra Nevada and the Coastal Range.
2. What is the geologic origin of the Sierra Nevada? (Hint: These mountains are made of granitic intrusions.)
3. What is the geologic origin of the Appalachian Mountains along the Eastern US?

Remember that Wegener used the similarity of the mountains on the west and east sides of the Atlantic as evidence for his continental drift hypothesis. The Appalachian mountains formed at a convergent plate boundary as Pangaea came together (figure 15).



Figure 15. About 200 million years ago, the Appalachian Mountains of eastern North America were probably once as high as the Himalaya, but they have been weathered and eroded significantly since the breakup of Pangaea.

Before Pangaea came together, the continents were separated by an ocean where the Atlantic is now. The proto-Atlantic ocean shrank as the Pacific ocean grew. Currently, the Pacific is shrinking as the Atlantic is growing. This **supercontinent cycle** is responsible for most of the geologic features that we see and many more that are long gone (figure 16).

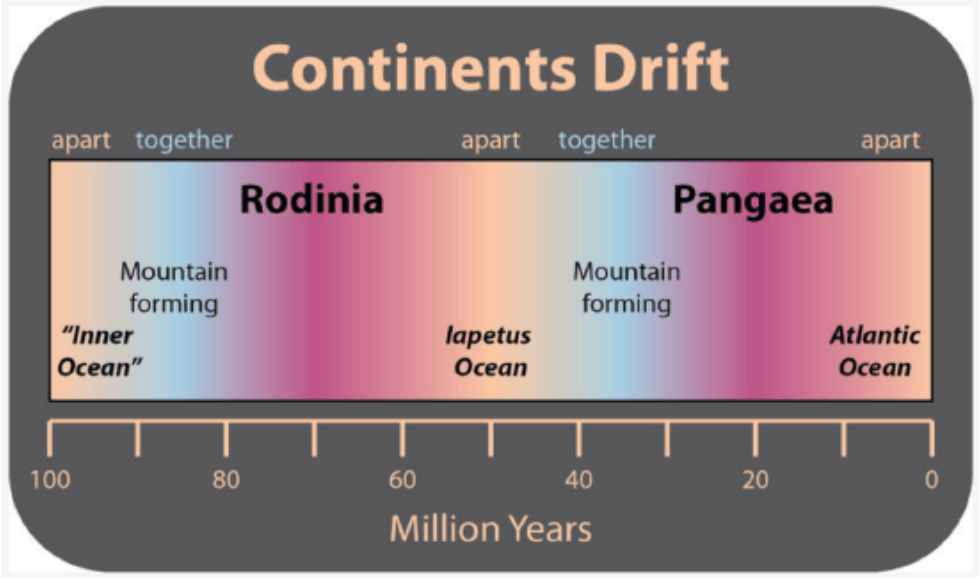


Figure 16. Scientists think that the creation and breakup of a supercontinent takes place about every 500 million years. The supercontinent before Pangaea was Rodinia. A new continent will form as the Pacific ocean disappears.

This animation shows the movement of continents over the past 600 million years beginning with the breakup of Rodinia.

LESSON SUMMARY

- Plates of lithosphere move because of convection currents in the mantle. One type of motion is produced by seafloor spreading.
- Plate boundaries can be located by outlining earthquake epicenters.
- Plates interact at three types of plate boundaries: divergent, convergent and transform.
- Most of the Earth's geologic activity takes place at plate boundaries.
- At a divergent boundary, volcanic activity produces a mid ocean ridge and small earthquakes.

- At a convergent boundary with at least one oceanic plate, an ocean trench, a chain of volcanoes develops and many earthquakes occur.
- At a convergent boundary where both plates are continental, mountain ranges grow and earthquakes are common.
- At a transform boundary, there is a transform fault and massive earthquakes occur but there are no volcanoes.
- Processes acting over long periods of time create Earth's geographic features.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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5.8: Plate Tectonics

Plate tectonics is a scientific theory that describes the large-scale motion of Earth's lithosphere. This theoretical model builds on the concept of continental drift which was developed during the first few decades of the 20th century. The geoscientific community accepted the theory after the concepts of seafloor spreading were later developed in the late 1950s and early 1960s.

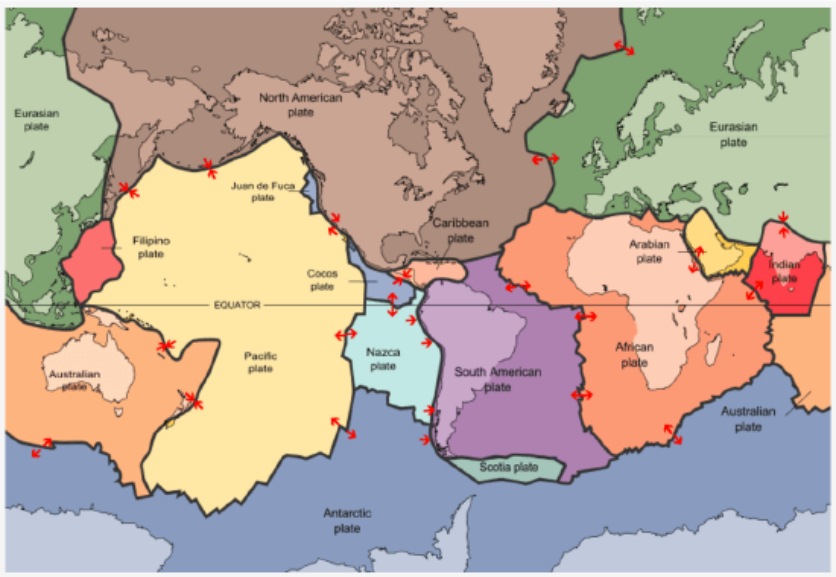


Figure 1. The tectonic plates of the world were mapped in the second half of the 20th century.

The lithosphere, which is the rigid outermost shell of a planet (on Earth, the crust and upper mantle), is broken up into tectonic plates. On Earth, there are seven or eight major plates (depending on how they are defined) and many minor plates. Where plates meet, their relative motion determines the type of boundary; convergent, divergent, or transform. Earthquakes,volcanic activity, mountain-building, and oceanic trench formation occur along these plate boundaries. The lateral relative movement of the plates typically varies from zero to 100 mm annually.

Tectonic plates are composed of oceanic lithosphere and thicker continental lithosphere, each topped by its own kind of crust. Along convergent boundaries, subduction carries plates into the mantle; the material lost is roughly balanced by the formation of new (oceanic) crust along divergent margins by seafloor spreading. In this way, the total surface of the globe remains the same. This prediction of plate tectonics is also referred to as the conveyor belt principle. Earlier theories (that still have some supporters) propose gradual shrinking (contraction) or gradual expansion of the globe.

Tectonic plates are able to move because the Earth's lithosphere has greater strength than the underlying asthenosphere. Lateral density variations in the mantle result in convection. Plate movement is thought to be driven by a combination of the motion of the seafloor away from the spreading ridge (due to variations in topography and density of the crust, which result in differences in gravitational forces) and drag, with downward suction, at the subduction zones. Another explanation lies in the different forces generated by the rotation of the globe and the tidal forces of the Sun and Moon. The relative importance of each of these factors and their relationship to each other is unclear, and still the subject of much debate.

KEY PRINCIPLES

The outer layers of the Earth are divided into the lithosphere and asthenosphere. This is based on differences inmechanical properties and in the method for the transfer of heat. Mechanically, the lithosphere is cooler and more rigid, while the asthenosphere is hotter and flows more easily. In terms of heat transfer, the lithosphere loses heat byconduction, whereas the asthenosphere also transfers heat by convection and has a nearly adiabatic temperature gradient. This division should not be confused with the *chemical* subdivision of these same layers into the mantle (comprising both the asthenosphere and the mantle portion of the lithosphere) and the crust: a given piece of mantle may be part of the lithosphere or the asthenosphere at different times depending on its temperature and pressure.

The key principle of plate tectonics is that the lithosphere exists as separate and distinct *tectonic plate*s, which ride on the fluid-like (visco-elastic solid) asthenosphere. Plate motions range up to a typical 10–40 mm/year (Mid-Atlantic Ridge; about as fast as fingernails grow), to about 160 mm/year (Nazca Plate; about as fast as hair grows). The driving mechanism behind this movement is described below.

Tectonic lithosphere plates consist of lithospheric mantle overlain by either or both of two types of crustal material:oceanic crust (in older texts called *sima* from silicon and magnesium) and continental crust (*sial* from silicon andaluminium). Average oceanic lithosphere is typically 100 km (62 mi) thick; its thickness is a function of its age: as time passes, it conductively cools and subjacent cooling mantle is added to its base. Because it is formed at mid-ocean ridges and spreads outwards, its thickness is therefore a function of its distance from the mid-ocean ridge where it was formed. For a typical distance that oceanic lithosphere must travel before being subducted, the thickness varies from about 6 km (4 mi) thick at mid-ocean ridges to greater than 100 km (62 mi) at subductionzones; for shorter or longer distances, the subduction zone (and therefore also the mean) thickness becomes smaller or larger, respectively. Continental lithosphere is typically ~200 km thick, though this varies considerably between basins, mountain ranges, and stable cratonic interiors of continents. The two types of crust also differ in thickness, with continental crust being considerably thicker than oceanic (35 km vs. 6 km).

The location where two plates meet is called a *plate boundary*. Plate boundaries are commonly associated with geological events such as earthquakes and the creation of topographic features such as mountains, volcanoes, mid-ocean ridges, and oceanic trenches. The majority of the world's active volcanoes occur along plate boundaries, with the Pacific Plate's Ring of Fire being the most active and widely known today. These boundaries are discussed in further detail below. Some volcanoes occur in the interiors of plates, and these have been variously attributed to internal plate deformation and to mantle plumes.

As explained above, tectonic plates may include continental crust or oceanic crust, and most plates contain both. For example, the African Plate includes the continent and parts of the floor of the Atlantic and Indian Oceans. The distinction between oceanic crust and continental crust is based on their modes of formation. Oceanic crust is formed at sea-floor spreading centers, and continental crust is formed through arc volcanism and accretion of terranesthrough tectonic processes, though some of these terranes may contain ophiolite sequences, which are pieces of oceanic crust considered to be part of the continent when they exit the standard cycle of formation and spreading centers and subduction beneath continents. Oceanic crust is also denser than continental crust owing to their different compositions. Oceanic crust is denser because it has less silicon and more heavier elements ("mafic") than continental crust ("felsic"). As a result of this density stratification, oceanic crust generally lies below sea level (for example most of the Pacific Plate), while continental crust buoyantly projects above sea level (see the page isostasy for explanation of this principle).

TYPES OF PLATE BOUNDARIES

Three types of plate boundaries exist, with a fourth, mixed type, characterized by the way the plates move relative to each other. They are associated with different types of surface phenomena. The different types of plate boundaries are:

1. Transform boundaries (Conservative) occur where two lithospheric plates slide, or perhaps more accurately, grind past each other along transform faults, where plates are neither created nor destroyed. The relative motion of the two plates is either sinistral (left side toward the observer) or dextral (right side toward the observer). Transform faults occur across a spreading center. Strong earthquakes can occur along a fault. TheSan Andreas Fault in California is an example of a transform boundary exhibiting dextral motion.
2. *Divergent boundaries (Constructive)* occur where two plates slide apart from each other. At zones of ocean-to-ocean rifting, divergent boundaries form by seafloor spreading, allowing for the formation of new ocean basin. As the continent splits, the ridge forms at the spreading center, the ocean basin expands, and finally, the plate area increases causing many small volcanoes and/or shallow earthquakes. At zones of continent-to-continent rifting, divergent boundaries may cause new ocean basin to form as the continent splits, spreads, the central rift collapses, and ocean fills the basin. Active zones of Mid-ocean ridges (e.g., Mid-Atlantic Ridge and East Pacific Rise), and continent-to-continent rifting (such as Africa's East African Rift and Valley, Red Sea) are examples of divergent boundaries.
3. *Convergent boundaries (Destructive)* (or *active margins*) occur where two plates slide toward each other to form either a subduction zone (one plate moving underneath the other) or a continental collision. At zones of ocean-to-continent subduction (e.g., Western South America, and Cascade Mountains in Western United States), the dense oceanic lithosphere plunges beneath the less dense continent. Earthquakes then trace the path of the downward-moving plate as it descends into asthenosphere, a trench forms, and as the subducted plate partially melts, magma rises to form continental volcanoes. At zones of ocean-to-ocean subduction (e.g., the Andes mountain range in South America, Aleutian islands, Mariana islands, and the Japanese island arc), older, cooler, denser crust slips beneath less dense crust. This causes earthquakes and a deep trench to form in an arc shape. The upper mantle of the subducted plate then heats and magma rises to form curving chains

of volcanic islands. Deep marine trenches are typically associated with subduction zones, and the basins that develop along the active boundary are often called “foreland basins.” The subducting slab contains many hydrous minerals which release their water on heating. This water then causes the mantle to melt, producing volcanism. Closure of ocean basins can occur at continent-to-continent boundaries (e.g., Himalayas and Alps): collision between masses of granitic continental lithosphere; neither mass is subducted; plate edges are compressed, folded, uplifted.

4. *Plate boundary zone*s occur where the effects of the interactions are unclear, and the boundaries, usually occurring along a broad belt, are not well defined and may show various types of movements in different episodes.

DRIVING FORCES OF PLATE MOTION

Plate tectonics is basically a kinematic phenomenon. Scientists agree on the observation and deduction that the plates have moved with respect to one another but continue to debate as to how and when. A major question remains as to what geodynamic mechanism motors plate movement. Here, science diverges in different theories.

It is generally accepted that tectonic plates are able to move because of the relative density of oceanic lithosphere and the relative weakness of the asthenosphere. Dissipation of heat from the mantle is acknowledged to be the original source of the energy required to drive plate tectonics through convection or large scale upwelling and doming. The current view, though still a matter of some debate, asserts that as a consequence, a powerful source of plate motion is generated due to the excess density of the oceanic lithosphere sinking in subduction zones. When the new crust forms at mid-ocean ridges, this oceanic lithosphere is initially less dense than the underlying asthenosphere, but it becomes denser with age as it conductively cools and thickens. The greater density of old lithosphere relative to the underlying asthenosphere allows it to sink into the deep mantle at subduction zones, providing most of the driving force for plate movement. The weakness of the asthenosphere allows the tectonic plates to move easily towards a subduction zone. Although subduction is believed to be the strongest force driving plate motions, it cannot be the only force since there are plates such as the North American Plate which are moving, yet are nowhere being subducted. The same is true for the enormous Eurasian Plate. The sources of plate motion are a matter of intensive research and discussion among scientists. One of the main points is that the kinematic pattern of the movement itself should be separated clearly from the possible geodynamic mechanism that is invoked as the driving force of the observed movement, as some patterns may be explained by more than one mechanism. In short, the driving forces advocated at the moment can be divided into three categories based on the relationship to the movement: mantle dynamics related, gravity related (mostly secondary forces), and Earth rotation related.

Driving Forces Related to Mantle Dynamics

For much of the last quarter century, the leading theory of the driving force behind tectonic plate motions envisaged large scale convection currents in the upper mantle which are transmitted through the asthenosphere. This theory was launched by Arthur Holmes and some forerunners in the 1930s and was immediately recognized as the solution for the acceptance of the theory as originally discussed in the papers of Alfred Wegener in the early years of the century. However, despite its acceptance, it was long debated in the scientific community because the leading (“fixist”) theory still envisaged a static Earth without moving continents up until the major breakthroughs of the early sixties.

Two- and three-dimensional imaging of Earth’s interior (seismic tomography) shows a varying lateral density distribution throughout the mantle. Such density variations can be material (from rock chemistry), mineral (from variations in mineral structures), or thermal (through thermal expansion and contraction from heat energy). The manifestation of this varying lateral density is mantle convection from buoyancy forces.

How mantle convection directly and indirectly relates to plate motion is a matter of ongoing study and discussion in geodynamics. Somehow, this energy must be transferred to the lithosphere for tectonic plates to move. There are essentially two types of forces that are thought to influence plate motion: friction and gravity.

- Basal drag (friction): Plate motion driven by friction between the convection currents in the asthenosphere and the more rigid overlying lithosphere.
- Slab suction (gravity): Plate motion driven by local convection currents that exert a downward pull on plates in subduction zones at ocean trenches. Slab suction may occur in a geodynamic setting where basal tractions continue to act on the plate as it dives into the mantle (although perhaps to a greater extent acting on both the under and upper side of the slab).

Lately, the convection theory has been much debated as modern techniques based on 3D seismic tomography still fail to recognize these predicted large scale convection cells. Therefore, alternative views have been proposed:

In the theory of plume tectonics developed during the 1990s, a modified concept of mantle convection currents is used. It asserts that super plumes rise from the deeper mantle and are the drivers or substitutes of the major convection cells. These ideas, which find their roots in the early 1930s with the so-called "fixistic" ideas of the European and Russian Earth Science Schools, find resonance in the modern theories which envisage hot spots/mantle plumes which remain fixed and are overridden by oceanic and continental lithosphere plates over time and leave their traces in the geological record (though these phenomena are not invoked as real driving mechanisms, but rather as modulators). Modern theories that continue building on the older mantle doming concepts and see plate movements as a secondary phenomena are beyond the scope of this page and are discussed elsewhere (for example on the plume tectonics page).

Another theory is that the mantle flows neither in cells nor large plumes but rather as a series of channels just below the Earth's crust, which then provide basal friction to the lithosphere. This theory, called "surge tectonics", became quite popular in geophysics and geodynamics during the 1980s and 1990s.

Driving Forces Related to Gravity

Forces related to gravity are usually invoked as secondary phenomena within the framework of a more general driving mechanism such as the various forms of mantle dynamics described above.

Gravitational sliding away from a spreading ridge: According to many authors, plate motion is driven by the higher elevation of plates at ocean ridges. As oceanic lithosphere is formed at spreading ridges from hot mantle material, it gradually cools and thickens with age (and thus adds distance from the ridge). Cool oceanic lithosphere is significantly denser than the hot mantle material from which it is derived and so with increasing thickness it gradually subsides into the mantle to compensate the greater load. The result is a slight lateral incline with increased distance from the ridge axis.

This force is regarded as a secondary force and is often referred to as "ridge push". This is a misnomer as nothing is "pushing" horizontally and tensional features are dominant along ridges. It is more accurate to refer to this mechanism as gravitational sliding as variable topography across the totality of the plate can vary considerably and the topography of spreading ridges is only the most prominent feature. Other mechanisms generating this gravitational secondary force include flexural bulging of the lithosphere before it dives underneath an adjacent plate which produces a clear topographical feature that can offset, or at least affect, the influence of topographical ocean ridges, and mantle plumes and hot spots, which are postulated to impinge on the underside of tectonic plates.

Slab-pull: Current scientific opinion is that the asthenosphere is insufficiently competent or rigid to directly cause motion by friction along the base of the lithosphere. Slab pull is therefore most widely thought to be the greatest force acting on the plates. In this current understanding, plate motion is mostly driven by the weight of cold, dense plates sinking into the mantle at trenches. Recent models indicate that trench suction plays an important role as well. However, as the North American Plate is nowhere being subducted, yet it is in motion presents a problem. The same holds for the African, Eurasian, and Antarctic plates.

Gravitational sliding away from mantle doming: According to older theories, one of the driving mechanisms of the plates is the existence of large scale asthenosphere/mantle domes which cause the gravitational sliding of lithosphere plates away from them. This gravitational sliding represents a secondary phenomenon of this basically vertically oriented mechanism. This can act on various scales, from the small scale of one island arc up to the larger scale of an entire ocean basin.

Driving Forces Related to Earth Rotation

Alfred Wegener, being a meteorologist, had proposed tidal forces and pole flight force as the main driving mechanisms behind continental drift; however, these forces were considered far too small to cause continental motion as the concept then was of continents plowing through oceanic crust. Therefore, Wegener later changed his position and asserted that convection currents are the main driving force of plate tectonics in the last edition of his book in 1929.

However, in the plate tectonics context (accepted since the seafloor spreading proposals of Heezen, Hess, Dietz, Morley, Vine, and Matthews (see below) during the early 1960s), oceanic crust is suggested to be in motion *with* the continents which caused the proposals related to Earth rotation to be reconsidered. In more recent literature, these driving forces are:

1. Tidal drag due to the gravitational force the Moon (and the Sun) exerts on the crust of the Earth
2. Shear strain of the Earth globe due to N-S compression related to its rotation and modulations;
3. Pole flight force: equatorial drift due to rotation and centrifugal effects: tendency of the plates to move from the poles to the equator ("*Polflucht*");

4. The Coriolis effect acting on plates when they move around the globe;
5. Global deformation of the geoid due to small displacements of rotational pole with respect to the Earth's crust;
6. Other smaller deformation effects of the crust due to wobbles and spin movements of the Earth rotation on a smaller time scale.

For these mechanisms to be overall valid, systematic relationships should exist all over the globe between the orientation and kinematics of deformation and the geographical latitudinal and longitudinal grid of the Earth itself. Ironically, these systematic relations studies in the second half of the nineteenth century and the first half of the twentieth century underline exactly the opposite: that the plates had not moved in time, that the deformation grid was fixed with respect to the Earth equator and axis, and that gravitational driving forces were generally acting vertically and caused only local horizontal movements (the so-called pre-plate tectonic, "fixist theories"). Later studies (discussed below on this page), therefore, invoked many of the relationships recognized during this pre-plate tectonics period to support their theories (see the anticipations and reviews in the work of van Dijk and collaborators).

Of the many forces discussed in this paragraph, tidal force is still highly debated and defended as a possible principle driving force of plate tectonics. The other forces are only used in global geodynamic models not using plate tectonics concepts (therefore beyond the discussions treated in this section) or proposed as minor modulations within the overall plate tectonics model.

In 1973, George W. Moore of the USGS and R. C. Bostrom presented evidence for a general westward drift of the Earth's lithosphere with respect to the mantle. He concluded that tidal forces (the tidal lag or "friction") caused by the Earth's rotation and the forces acting upon it by the Moon are a driving force for plate tectonics. As the Earth spins eastward beneath the moon, the moon's gravity ever so slightly pulls the Earth's surface layer back westward, just as proposed by Alfred Wegener (see above). In a more recent 2006 study, scientists reviewed and advocated these earlier proposed ideas. It has also been suggested recently in Lovett (2006) that this observation may also explain why Venus and Mars have no plate tectonics, as Venus has no moon and Mars' moons are too small to have significant tidal effects on the planet. In a recent paper, it was suggested that, on the other hand, it can easily be observed that many plates are moving north and eastward, and that the dominantly westward motion of the Pacific ocean basins derives simply from the eastward bias of the Pacific spreading center (which is not a predicted manifestation of such lunar forces). In the same paper the authors admit, however, that relative to the lower mantle, there is a slight westward component in the motions of all the plates. They demonstrated though that the westward drift, seen only for the past 30 Ma, is attributed to the increased dominance of the steadily growing and accelerating Pacific plate. The debate is still open.

Summary

In line with other previous and contemporaneous proposals, in 1912 the meteorologist Alfred Wegener amply described what he called continental drift, expanded in his 1915 book *The Origin of Continents and Oceans* and the scientific debate started that would end up fifty years later in the theory of plate tectonics. Starting from the idea (also expressed by his forerunners) that the present continents once formed a single land mass (which was called Pangea later on) that drifted apart, thus releasing the continents from the Earth's mantle and likening them to "icebergs" of low density granite floating on a sea of denser basalt. Supporting evidence for the idea came from the dove-tailing outlines of South America's east coast and Africa's west coast, and from the matching of the rock formations along these edges. Confirmation of their previous contiguous nature also came from the fossil plants *Glossopteris* and *Gangamopteris*, and the therapsid or mammal-like reptile *Lystrosaurus*, all widely distributed over South America, Africa, Antarctica, India and Australia. The evidence for such an erstwhile joining of these continents was patent to field geologists working in the southern hemisphere. The South African Alex du Toit put together a mass of such information in his 1937 publication *Our Wandering Continents*, and went further than Wegener in recognizing the strong links between the Gondwana fragments.

But without detailed evidence and a force sufficient to drive the movement, the theory was not generally accepted: the Earth might have a solid crust and mantle and a liquid core, but there seemed to be no way that portions of the crust could move around. Distinguished scientists, such as Harold Jeffreys and Charles Schuchert, were outspoken critics of continental drift.

Despite much opposition, the view of continental drift gained support and a lively debate started between "drifters" or "mobilists" (proponents of the theory) and "fixists" (opponents). During the 1920s, 1930s and 1940s, the former reached important milestones proposing that convection currents might have driven the plate movements, and that spreading may have occurred below the sea within the oceanic crust. Concepts close to the elements now incorporated in plate tectonics were proposed by geophysicists and geologists (both fixists and mobilists) like Vening-Meinesz, Holmes, and Umbgrove.

One of the first pieces of geophysical evidence that was used to support the movement of lithospheric plates came from paleomagnetism. This is based on the fact that rocks of different ages show a variable magnetic field direction, evidenced by

studies since the mid-nineteenth century. The magnetic north and south poles reverse through time, and, especially important in paleotectonic studies, the relative position of the magnetic north pole varies through time. Initially, during the first half of the twentieth century, the latter phenomenon was explained by introducing what was called “polar wander” (see apparent polar wander), i.e., it was assumed that the north pole location had been shifting through time. An alternative explanation, though, was that the continents had moved (shifted and rotated) relative to the north pole, and each continent, in fact, shows its own “polar wander path”. During the late 1950s it was successfully shown on two occasions that these data could show the validity of continental drift: by Keith Runcorn in a paper in 1956, and by Warren Carey in a symposium held in March 1956.

The second piece of evidence in support of continental drift came during the late 1950s and early 60s from data on the bathymetry of the deep ocean floors and the nature of the oceanic crust such as magnetic properties and, more generally, with the development of marine geology which gave evidence for the association of seafloor spreading along the mid-oceanic ridges and magnetic field reversals, published between 1959 and 1963 by Heezen, Dietz, Hess, Mason, Vine & Matthews, and Morley.

Simultaneous advances in early seismic imaging techniques in and around Wadati-Benioff zones along the trenches bounding many continental margins, together with many other geophysical (e.g. gravimetric) and geological observations, showed how the oceanic crust could disappear into the mantle, providing the mechanism to balance the extension of the ocean basins with shortening along its margins.

All this evidence, both from the ocean floor and from the continental margins, made it clear around 1965 that continental drift was feasible and the theory of plate tectonics, which was defined in a series of papers between 1965 and 1967, was born, with all its extraordinary explanatory and predictive power. The theory revolutionized the Earth sciences, explaining a diverse range of geological phenomena and their implications in other studies such as paleogeography and paleobiology.

Continental Drift

In the late 19th and early 20th centuries, geologists assumed that the Earth’s major features were fixed, and that most geologic features such as basin development and mountain ranges could be explained by vertical crustal movement, described in what is called the geosynclinal theory. Generally, this was placed in the context of a contracting planet Earth due to heat loss in the course of a relatively short geological time.



Figure 2. Alfred Wegener in Greenland in the winter of 1912–13.

It was observed as early as 1596 that the opposite coasts of the Atlantic Ocean—or, more precisely, the edges of the continental shelves—have similar shapes and seem to have once fitted together.

Since that time many theories were proposed to explain this apparent complementarity, but the assumption of a solid Earth made these various proposals difficult to accept.

The discovery of radioactivity and its associated heating properties in 1895 prompted a re-examination of the apparent age of

the Earth. This had previously been estimated by its cooling rate and assumption the Earth's surface radiated like a black body. Those calculations had implied that, even if it started at red heat, the Earth would have dropped to its present temperature in a few tens of millions of years. Armed with the knowledge of a new heat source, scientists realized that the Earth would be much older, and that its core was still sufficiently hot to be liquid.

By 1915, after having published a first article in 1912, Alfred Wegener was making serious arguments for the idea of continental drift in the first edition of *The Origin of Continents and Oceans*. In that book (re-issued in four successive editions up to the final one in 1936), he noted how the east coast of South America and the west coast ofAfrica looked as if they were once attached. Wegener was not the first to note this (Abraham Ortelius, Antonio Snider-Pellegrini, Eduard Suess, Roberto Mantovani and Frank Bursley Taylor preceded him just to mention a few), but he was the first to marshal significant fossil and paleo-topographical and climatological evidence to support this simple observation (and was supported in this by researchers such as Alex du Toit). Furthermore, when the rockstrata of the margins of separate continents are very similar it suggests that these rocks were formed in the same way, implying that they were joined initially. For instance, parts of Scotland and Ireland contain rocks very similar to those found in Newfoundland and New Brunswick. Furthermore, the Caledonian Mountains of Europe and parts of the Appalachian Mountains of North America are very similar in structure and lithology.

However, his ideas were not taken seriously by many geologists, who pointed out that there was no apparent mechanism for continental drift. Specifically, they did not see how continental rock could plow through the much denser rock that makes up oceanic crust. Wegener could not explain the force that drove continental drift, and his vindication did not come until after his death in 1930.

Floating Continents, Paleomagnetism, and Seismicity Zones

As it was observed early that although granite existed on continents, seafloor seemed to be composed of denser basalt, the prevailing concept during the first half of the twentieth century was that there were two types of crust, named "sial" (continental type crust) and "sima" (oceanic type crust). Furthermore, it was supposed that a static shell of strata was present under the continents. It therefore looked apparent that a layer of basalt (sial) underlies the continental rocks.

However, based on abnormalities in plumb line deflection by theAndes in Peru, Pierre Bouguer had deduced that less-dense mountains must have a downward projection into the denser layer underneath. The concept that mountains had "roots" was confirmed by George B. Airy a hundred years later, during study of Himalayan gravitation, and seismic studies detected corresponding density variations. Therefore, by the mid-1950s, the question remained unresolved as to whether mountain roots were clenched in surrounding basalt or were floating on it like an iceberg.

During the 20th century, improvements in and greater use of seismic instruments such as seismographs enabled scientists to learn that earthquakes tend to be concentrated in specific areas, most notably along the oceanic trenches and spreading ridges. By the late 1920s, seismologists were beginning to identify several prominent earthquake zones parallel to the trenches that typically were inclined 40–60° from the horizontal and extended several hundred kilometers into the Earth. These zones later became known as Wadati-Benioff zones, or simply Benioff zones, in honor of the seismologists who first recognized them, Kiyoo Wadati of Japan and Hugo Benioff of the United States. The study of global seismicity greatly advanced in the 1960s with the establishment of the Worldwide Standardized Seismograph Network (WWSSN) to monitor the compliance of the 1963 treaty banning above-ground testing of nuclear weapons. The much improved data from the WWSSN instruments allowed seismologists to map precisely the zones of earthquake concentration world wide.

Meanwhile, debates developed around the phenomena of polar wander. Since the early debates of continental drift, scientists had discussed and used evidence that polar drift had occurred because continents seemed to have moved through different climatic zones during the past. Furthermore, paleomagnetic data had shown that the magnetic pole had also shifted during time. Reasoning in an opposite way, the continents might have shifted and rotated, while the pole remained relatively fixed. The first time the evidence of magnetic polar wander was used to support the movements of continents was in a paper by Keith Runcorn in 1956, and successive papers by him and his students Ted Irving (who was actually the first to be convinced of the fact that paleomagnetism supported continental drift) and Ken Creer.

This was immediately followed by a symposium in Tasmania in March 1956. In this symposium, the evidence was used in the theory of an expansion of the global crust. In this hypothesis the shifting of the continents can be simply explained by a large increase in size of the Earth since its formation. However, this was unsatisfactory because its supporters could offer no convincing mechanism to produce a significant expansion of the Earth. Certainly there is no evidence that the moon has expanded in the past 3 billion years; other work would soon show that the evidence was equally in support of continental drift on a globe with a stable radius.

During the thirties up to the late fifties, works by Vening-Meinesz, Holmes, Umbgrove, and numerous others outlined concepts that were close or nearly identical to modern plate tectonics theory. In particular, the English geologist Arthur Holmes proposed in 1920 that plate junctions might lie beneath the sea, and in 1928 that convection currents within the mantle might be the driving force. Often, these contributions are forgotten because:

- At the time, continental drift was not accepted.
- Some of these ideas were discussed in the context of abandoned fixistic ideas of a deforming globe without continental drift or an expanding Earth.
- They were published during an episode of extreme political and economic instability that hampered scientific communication.
- Many were published by European scientists and at first not mentioned or given little credit in the papers on sea floor spreading published by the American researchers in the 1960s.

Mid-Oceanic Ridge Spreading and Convection

In 1947, a team of scientists led by Maurice Ewing utilizing the Woods Hole Oceanographic Institution's research vessel *Atlantis* and an array of instruments, confirmed the existence of a rise in the central Atlantic Ocean, and found that the floor of the seabed beneath the layer of sediments consisted of basalt, not the granite which is the main constituent of continents. They also found that the oceanic crust was much thinner than continental crust. All these new findings raised important and intriguing questions.

The new data that had been collected on the ocean basins also showed particular characteristics regarding the bathymetry. One of the major outcomes of these datasets was that all along the globe, a system of mid-oceanic ridges was detected. An important conclusion was that along this system, new ocean floor was being created, which led to the concept of the "Great Global Rift". This was described in the crucial paper of Bruce Heezen (1960), which would trigger a real revolution in thinking. A profound consequence of seafloor spreading is that new crust was, and still is, being continually created along the oceanic ridges. Therefore, Heezen advocated the so-called "expanding Earth" hypothesis of S. Warren Carey (see above). So, still the question remained: how can new crust be continuously added along the oceanic ridges without increasing the size of the Earth? In reality, this question had been solved already by numerous scientists during the forties and the fifties, like Arthur Holmes, Vening-Meinesz, Coates and many others: The crust in excess disappeared along what were called the oceanic trenches, where so-called "subduction" occurred. Therefore, when various scientists during the early sixties started to reason on the data at their disposal regarding the ocean floor, the pieces of the theory quickly fell into place.

The question particularly intrigued Harry Hammond Hess, a Princeton University geologist and a Naval Reserve Rear Admiral, and Robert S. Dietz, a scientist with the U.S. Coast and Geodetic Survey who first coined the term *seafloor spreading*. Dietz and Hess (the former published the same idea one year earlier in *Nature*, but priority belongs to Hess who had already distributed an unpublished manuscript of his 1962 article by 1960) were among the small handful who really understood the broad implications of sea floor spreading and how it would eventually agree with the, at that time, unconventional and unaccepted ideas of continental drift and the elegant and mobilistic models proposed by previous workers like Holmes.

In the same year, Robert R. Coats of the U.S. Geological Survey described the main features of island arcsubduction in the Aleutian Islands. His paper, though little noted (and even ridiculed) at the time, has since been called "seminal" and "prescient". In reality, it actually shows that the work by the European scientists on island arcs and mountain belts performed and published during the 1930s up until the 1950s was applied and appreciated also in the United States.

If the Earth's crust was expanding along the oceanic ridges, Hess and Dietz reasoned like Holmes and others before them, it must be shrinking elsewhere. Hess followed Heezen, suggesting that new oceanic crust continuously spreads away from the ridges in a conveyor belt–like motion. And, using the mobilistic concepts developed before, he correctly concluded that many millions of years later, the oceanic crust eventually descends along the continental margins where oceanic trenches—very deep, narrow canyons—are formed, e.g. along the rim of the Pacific Ocean basin. The important step Hess made was that convection currents would be the driving force in this process, arriving at the same conclusions as Holmes had decades before with the only difference that the thinning of the ocean crust was performed using Heezen's mechanism of spreading along the ridges. Hess therefore concluded that the Atlantic Ocean was expanding while the Pacific Ocean was shrinking. As old oceanic crust is "consumed" in the trenches (like Holmes and others, he thought this was done by thickening of the continental lithosphere, not, as now understood, by underthrusting at a larger scale of the oceanic crust itself into the mantle), new magma rises and erupts along the spreading ridges to form new crust. In effect, the ocean basins are perpetually being "recycled," with the creation of new crust and the destruction of old oceanic lithosphere occurring simultaneously. Thus, the new mobilistic concepts neatly explained why the Earth does not get bigger with sea floor spreading, why there is so little sediment accumulation on the ocean floor, and why oceanic rocks are much younger than continental rocks.

Magnetic Striping

Beginning in the 1950s, scientists like Victor Vacquier, using magnetic instruments (magnetometers) adapted from airborne devices developed during World War II to detect submarines, began recognizing odd magnetic variations across the ocean floor. This finding, though unexpected, was not entirely surprising because it was known that basalt—the iron-rich, volcanic rock making up the ocean floor—contains a strongly magnetic mineral (magnetite) and can locally distort compass readings. This distortion was recognized by Icelandic mariners as early as the late 18th century. More important, because the presence of magnetite gives the basalt measurable magnetic properties, these newly discovered magnetic variations provided another means to study the deep ocean floor. When newly formed rock cools, such magnetic materials recorded the Earth's magnetic field at the time.

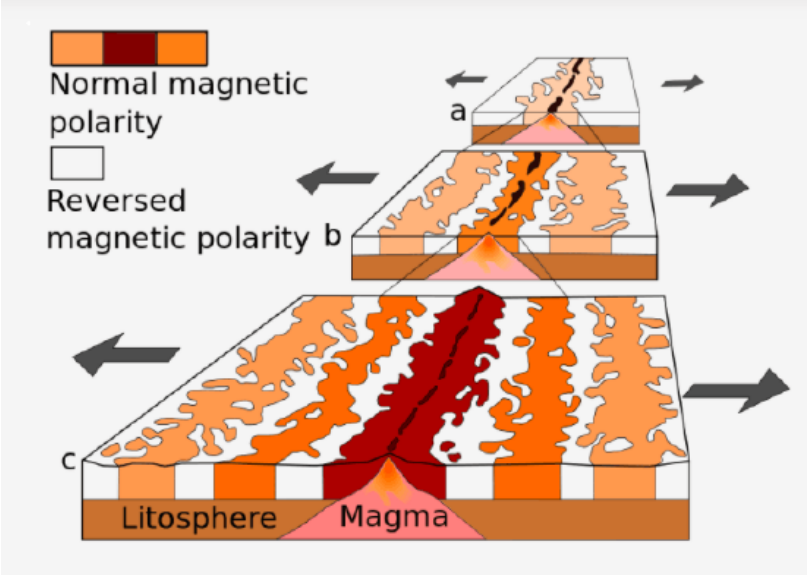


Figure 3. Seafloor magnetic striping.

As more and more of the seafloor was mapped during the 1950s, the magnetic variations turned out not to be random or isolated occurrences, but instead revealed recognizable patterns. When these magnetic patterns were mapped over a wide region, the ocean floor showed a zebra-like pattern: one stripe with normal polarity and the adjoining stripe with reversed polarity. The overall pattern, defined by these alternating bands of normally and reversely polarized rock, became known as magnetic striping, and was published by Ron G. Mason and co-workers in 1961, who did not find, though, an explanation for these data in terms of sea floor spreading, like Vine, Matthews and Morley a few years later.

The discovery of magnetic striping called for an explanation. In the early 1960s scientists such as Heezen, Hess and Dietz had begun to theorise that mid-ocean ridges mark structurally weak zones where the ocean floor was being ripped in two lengthwise along the ridge crest (see the previous paragraph). New magma from deep within the Earth rises easily through these weak zones and eventually erupts along the crest of the ridges to create new oceanic crust. This process, at first denominated the "conveyer belt hypothesis" and later called seafloor spreading, operating over many millions of years continues to form new ocean floor all across the 50,000 km-long system of mid-ocean ridges.

Only four years after the maps with the "zebra pattern" of magnetic stripes were published, the link between sea floor spreading and these patterns was correctly placed, independently by Lawrence Morley, and by Fred Vine and Drummond Matthews, in 1963, now called the Vine-Matthews-Morley hypothesis. This hypothesis linked these patterns to geomagnetic reversals and was supported by several lines of evidence:

1. the stripes are symmetrical around the crests of the mid-ocean ridges; at or near the crest of the ridge, the rocks are very young, and they become progressively older away from the ridge crest;
2. the youngest rocks at the ridge crest always have present-day (normal) polarity;
3. stripes of rock parallel to the ridge crest alternate in magnetic polarity (normal-reversed-normal, etc.), suggesting that they were formed during different epochs documenting the (already known from independent studies) normal and reversal episodes of the Earth's magnetic field.

By explaining both the zebra-like magnetic striping and the construction of the mid-ocean ridge system, the seafloor spreading

hypothesis (SFS) quickly gained converts and represented another major advance in the development of the plate-tectonics theory. Furthermore, the oceanic crust now came to be appreciated as a natural "tape recording" of the history of the geomagnetic field reversals (GMFR) of the Earth's magnetic field. Today, extensive studies are dedicated to the calibration of the normal-reversal patterns in the oceanic crust on one hand and known timescales derived from the dating of basalt layers in sedimentary sequences (magnetostratigraphy) on the other, to arrive at estimates of past spreading rates and plate reconstructions.

Defining and Refining of the Theory

After all these considerations, Plate Tectonics (or, as it was initially called "New Global Tectonics") became quickly accepted in the scientific world, and numerous papers followed that defined the concepts:

- In 1965, Tuzo Wilson who had been a promotor of the sea floor spreading hypothesis and continental drift from the very beginning added the concept of transform faults to the model, completing the classes of fault types necessary to make the mobility of the plates on the globe work out.
- A symposium on continental drift was held at the Royal Society of London in 1965 which must be regarded as the official start of the acceptance of plate tectonics by the scientific community, and which abstracts are issued asBlacket, Bullard & Runcorn (1965). In this symposium, Edward Bullard and co-workers showed with a computer calculation how the continents along both sides of the Atlantic would best fit to close the ocean, which became known as the famous "Bullard's Fit".
- In 1966 Wilson published the paper that referred to previous plate tectonic reconstructions, introducing the concept of what is now known as the "Wilson Cycle."
- In 1967, at the American Geophysical Union's meeting, W. Jason Morgan proposed that the Earth's surface consists of 12 rigid plates that move relative to each other.
- Two months later, Xavier Le Pichon published a complete model based on 6 major plates with their relative motions, which marked the final acceptance by the scientific community of plate tectonics.
- In the same year, McKenzie and Parker independently presented a model similar to Morgan's using translations and rotations on a sphere to define the plate motions.

IMPLICATIONS FOR BIOGEOGRAPHY

Continental drift theory helps biogeographers to explain the disjunct biogeographic distribution of present day life found on different continents but having similar ancestors. In particular, it explains the Gondwanan distribution of ratites and the Antarctic flora.

PLATE RECONSTRUCTION

Reconstruction is used to establish past (and future) plate configurations, helping determine the shape and make-up of ancient supercontinents and providing a basis for paleogeography.

Defining Plate Boundaries

Current plate boundaries are defined by their seismicity. Past plate boundaries within existing plates are identified from a variety of evidence, such as the presence of ophiolites that are indicative of vanished oceans.

Past Plate Motions

Tectonic motion first began around three billion years ago.

Various types of quantitative and semi-quantitative information are available to constrain past plate motions. The geometric fit between continents, such as between west Africa and South America is still an important part of plate reconstruction. Magnetic stripe patterns provide a reliable guide to relative plate motions going back into the Jurassic period. The tracks of hotspots give absolute reconstructions, but these are only available back to the Cretaceous. Older reconstructions rely mainly on paleomagnetic pole data, although these only constrain the latitude and rotation, but not the longitude. Combining poles of different ages in a particular plate to produce apparent polar wander paths provides a method for comparing the motions of different plates through time. Additional evidence comes from the distribution of certain sedimentary rock types, faunal provinces shown by particular fossil groups, and the position of orogenic belts.

Formation and Break-Up of Continents

The movement of plates has caused the formation and break-up of continents over time, including occasional formation of a supercontinent that contains most or all of the continents. The supercontinent Columbia or Nuna formed during a period of 2,000 to 1,800 million years ago and broke up about 1,500 to 1,300 million years ago. The supercontinent Rodinia is thought to have formed about 1 billion years ago and to have embodied most or all of Earth's continents, and broken up into eight continents around 600 million years ago. The eight continents later re-assembled into another supercontinent called Pangaea; Pangaea broke up into Laurasia (which became North America and Eurasia) and Gondwana (which became the remaining continents).

The Himalayas, the world's tallest mountain range, are assumed to have been formed by the collision of two major plates. Before uplift, they were covered by the Tethys Ocean.

Gallery of Past Configurations

Interpretive simulation of past continental movement and shorelines, with time given in millions of years ago (Ma). For more complete timeline of images, see Gallery of continental movement.

CURRENT PLATES

There are dozens of smaller plates, the seven largest of which are the Arabian, Caribbean, Juan de Fuca,Cocos, Nazca, Philippine Sea and Scotia.

The current motion of the tectonic plates is today determined by remote sensing satellite data sets, calibrated with ground station measurements.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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5.9: Effects of Plate Tectonics

EXPLAIN HOW ROCK FORMATIONS, GEOLOGIC ENVIRONMENTS, MINERAL RESOURCES, VOLCANOES AND THEIR ERUPTIONS, LANDFORMS, MOUNTAIN BUILDING PROCESSES, CLIMATE CHANGE, EVOLUTION, FOLDS, FAULTS AND EARTHQUAKES RELATE TO AND ARE AFFECTED BY PLATE TECTONICS

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: The Ring of Fire
- Reading: Intraplate Deformation
- Reading: Folds
- Reading: Climates and Tectonics

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5.10: The Ring of Fire

The **Ring of Fire** is an area where a large number of earthquakes and volcanic eruptions occur in the basin of the Pacific Ocean. In a 40,000 km (25,000 mi) horseshoe shape, it is associated with a nearly continuous series of oceanic trenches, volcanic arcs, and volcanic belts and/or plate movements. It has 452 volcanoes and is home to over 75% of the world's active and dormant volcanoes. It is sometimes called the **circum-Pacific belt**.

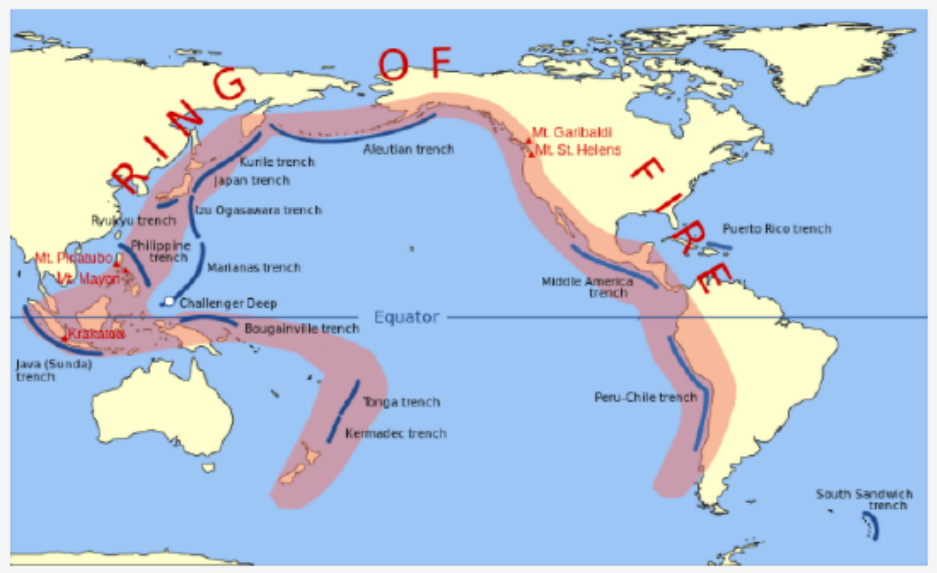


Figure 1. The Pacific Ring of Fire

About 90% of the world's earthquakes and 81% of the world's largest earthquakes occur along the Ring of Fire. The next most seismically active region (5–6% of earthquakes and 17% of the world's largest earthquakes) is the Alpide belt, which extends from Java to Sumatra through the Himalayas, theMediterranean, and out into the Atlantic. The Mid-Atlantic Ridge is the third most prominent earthquake belt.

The Ring of Fire is a direct result of plate tectonics and the movement and collisions of lithospheric plates. The eastern section of the ring is the result of the Nazca Plate and the Cocos Plate being subducted beneath the westward moving South American Plate. The Cocos Plate is being subducted beneath theCaribbean Plate, in Central America. A portion of the Pacific Plate along with the small Juan de Fuca Plate are being subducted beneath the North American Plate. Along the northern portion, the northwestward-moving Pacific plate is being subducted beneath the Aleutian Islands arc. Farther west, the Pacific plate is being subducted along the Kamchatka Peninsula arcs on south past Japan. The southern portion is more complex, with a number of smaller tectonic plates in collision with the Pacific plate from the Mariana Islands, the Philippines,Bougainville, Tonga, and New Zealand; this portion excludes Australia, since it lies in the center of its tectonic plate. Indonesia lies between the *Ring of Fire* along the northeastern islands adjacent to and including New Guinea and the *Alpide belt* along the south and west from Sumatra, Java, Bali, Flores, and Timor. The famous and very active San Andreas Fault zone of California is a transform faultwhich offsets a portion of the East Pacific Rise under southwestern United Statesand Mexico. The motion of the fault generates numerous small earthquakes, at multiple times a day, most of which are too small to be felt. The active Queen Charlotte Fault on the west coast of the Haida Gwaii, British Columbia, Canada, has generated three large earthquakes during the 20th century: a magnitude 7 event in 1929; a magnitude 8.1 in 1949 (Canada's largest recorded earthquake); and a magnitude 7.4 in 1970.

ANDES

Bolivia

The country of Bolivia hosts numerous active and extinct volcanoes across its territory. The active volcanoes are located in western Bolivia where they make up the Cordillera Occidental, the western limit of the Altiplano plateau. Many of the active

volcanoes are international mountains shared with Chile. All Cenozoic volcanoes of Bolivia are part of the Central Volcanic Zone (CVZ) of the Andean Volcanic Belt that results due to processes involved in the subduction of the Nazca Plate under the South American Plate. The Central Volcanic Zone is a major upper Cenozoic volcanic province. Apart from Andean volcanoes, the geology of Bolivia host the remnants of ancient volcanoes around the Precambrian Guaporé Shield in the eastern part of the country.

Chile

The volcanos in Chile are monitored by the National Geology and Mining Service (SERNAGEOMIN)



Figure 2. Llaima's 2008 eruption

Earthquake activity in Chile is related to subduction of the Nazca Plate to the east. Chile notably holds the record for thelargest earthquake ever recorded, the1960 Valdivia earthquake. Villarrica, one of Chile's most active volcanoes, rises above Villarrica Lake and the town of Villarrica. It is the westernmost of three large stratovolcanoes that trend perpendicular to the Andean chain. A 6-km wide caldera formed during the late Pleistocene, >0.9 million years ago.

A 2-km-wide postglacial caldera is located at the base of the presently active, dominantly basaltic-to-andesitic cone at the NW margin of the Pleistocene caldera. About 25 scoria cones dot Villarica's flanks. Plinian eruptions and pyroclastic flows have been produced during the Holocene from this dominantly basaltic volcano, but historical eruptions have consisted of largely mild-to-moderate explosive activity with occasional lava effusion. Lahars from the glacier-covered volcanoes have damaged towns on its flanks.

The Llaima Volcano is one of the largest and most active volcanoes in Chile. It is situated 82 km northeast of Temuco and 663 km southeast of Santiago, within the borders of Conguillío National Park. Llaima's activity has been documented since the 17th century, and consists of several separate episodes of moderate explosive eruptions with occasional lava flows. The last major eruption occurred in 1994.

Chile has experienced numerous volcanic eruptions from 60 volcanoes, including Llaima Volcano and the Chaitén Volcano. More recently, a M8.8 earthquake struck central Chile on February 27, 2010, the Puyehue-Cordón Caulle volcano erupted in 2011 and a M8.2 earthquake struck northern Chile on April 1, 2014. The mainshock was preceded by a number of moderate to large shocks and was followed by a large number of moderate to very large aftershocks, including a M7.6 event on 2 April.



Figure 3. Lascar erupting in 2006

Lascar Volcano is a stratovolcano, is the most active volcano of the northern Chilean Andes. The largest eruption of Lascar took place about 26,500 years ago, and following the eruption of the Tumbres scoria flow about 9,000 years ago, activity shifted back to the eastern edifice, where three overlapping craters were formed. Frequent small-to-moderate explosive eruptions have been recorded from Lascar in historical time since the mid-19th century, along with periodic larger eruptions that produced ash and tephra fall up to hundreds of kilometres away from the volcano. The largest eruption of Lascar in recent history took place in 1993, producing pyroclastic flows as far as 8.5 km (5 mi) northwest of the summit and ash fall in Buenos Aires, Argentina, more than 1,600 km (994 mi) to the southeast. The latest series of eruptions began on 18 April 2006 and were continuing as of 2011.

Chiliques is a stratovolcano located in the Antofagasta Region of Chile, immediately north of Cerro Miscanti. Laguna Lejía lies to the north of the volcano and has been dormant for at least 10,000 years, is now showing signs of life. A January 6, 2002, nighttime thermal infrared image from ASTER revealed a hot spot in the summit crater as well as several others along the upper flanks of the volcano's edifice, indicating new volcanic activity. Examination of an earlier nighttime thermal infrared image from May 24, 2000, showed no such hot spots.

Calbuco is a stratovolcano in southern Chile, located southeast of Llanquihue Lake and northwest of Chapo Lake, in the Los Lagos Region. The volcano and the surrounding area are protected within Llanquihue National Reserve. It is a very explosive andesite volcano that underwent edifice collapse in the late Pleistocene, producing a volcanic debris avalanche that reached the lake. At least 9 eruptions since 1837, with the latest one in 1972. One of the largest historical eruptions in southern Chile took place there in 1893–1894. Violent eruptions ejected 30-cm bombs to distances of 8 km from the crater, accompanied by voluminous hotlahars. Strong explosions occurred in April 1917, and a lava dome formed in the crater accompanied by hot lahars. Another short explosive eruption in January 1929 also included an apparent pyroclastic flow and a lava flow. The last major eruption of Calbuco, in 1961, sent ash columns 12–15 km high and produced plumes that dispersed mainly to the SE and two lava flows were also emitted. There was a minor, 4-hour eruption on August 26, 1972. Strong fumarolic emission from the main crater was observed on August 12, 1996.

Lonquimay Volcano is a stratovolcano of late-Pleistocene to dominantly Holocene age, with the shape of a truncated cone. The cone is largely andesitic, though basaltic and dacitic rocks are present. It is located in the La Araucanía Region of Chile, immediately SE of Tolhuaca volcano. Sierra Nevada and Llaima are their neighbors to the south. The snow-capped volcano lies within the protected area Malalcahuello-Nalcas. The volcano last erupted in 1988, the eruption ending in 1990. The VEI was 3. The eruption was from a flank vent and involved lava flows and explosive eruptions. There were fatalities.

Antuco Volcano is a stratovolcano located in the Bío Bío Region of Chile, near Sierra Velluda and on the shore of Laguna del Laja with the last eruption in 1869.

Villarrica is one of Chile's most active volcanoes, rising above the lake and town of the same name. The volcano is also known as *Rucapillán*, a Mapuche word meaning "House of the Pillán." It is the westernmost of three large stratovolcanoesthat trend perpendicular to the Andean chain along the Gastre Fault. Villarrica, along with Quetrupillán and the Chilean portion of Lanín, are protected withinVillarrica National Park. Ascents of the volcano are popular with several guided ascents reaching the top during

summer.

Villarrica, with its lava of basaltic-andesitic composition, is one of only five volcanoes worldwide known to have an active lava lake within its crater. The volcano usually generates strombolian eruptions, with ejection of incandescentpyroclasts and lava flows. Melting of snow and glacier ice as well as rainfalls often cause massive lahars (mud and debris flows), such as during the eruptions of 1964 and 1971.

Ecuador

The Geophysics Institute at the National Polytechnic School in Quito houses an international team of seismologists and volcanologists whose responsibility is to monitor Ecuadors numerous active volcanoes in the Andean Volcanic Belt and the Galapagos Islands. There are many geologists who study the eruptive activity for the volcanos in the country and observe volcanic eruptions, especially Tungurahua whose volcanic activity restarted on August 19, 1999, and is ongoing as of 2013, with several major eruptions since that period, the last starting on 1 February 2014. Tungurahua's eruptions are strombolian. They produce andesite and dacite. All historical eruptions originated from the summit crater and have been accompanied by strong explosions, pyroclastic flows and sometimes lava flows. In the last 1,300 years Tungurahua entered every 80 to 100 years into an activity phase of which the major have been the ones of 1773, 1886 and 1916–1918. In November 2014, the Geophysics Institute installed new geophysical instruments, including a new seismic and infrasound station was placed in the sector Chilma, a repeater and prospect a site for a new station between La Carolina and Lita. They also held meetings with the local authorities of the province of Carchi, and also conducted socialization map of potential volcanic hazards and training lectures for future lookouts were offered.



Figure 4. The 1999 eruption of Wawa Pichincha

Cotopaxi is a stratovolcano in the Andes Mountains, located about 50 km (31 mi) south of Quito, Ecuador, South America. It is the second highest summit in the country, reaching a height of 5,897 m (19,347 ft). Some consider it the world's highest active volcano, while others give this status to the considerably higher Llullaillaco, which most recently erupted in 1877 and is one of Ecuador's most active volcanoes. Since 1738, Cotopaxi has erupted more than 50 times, resulting in the creation of numerous valleys formed by lahars (mudflows) around the volcano.



Figure 5. Tungurahua spews hot lava and ash at night (1999).

In October 1999, Pichincha Volcano erupted in Quito and covered the city with several inches of ash. Prior to that, the last major eruptions were in 1553 and in 1660, when about 30 cm of ash fell on the city.

At 5230 meters, Sangay Volcano) is an active stratovolcano in central Ecuador and is one of the highest active volcanoes in the world and one of Ecuador's most active ones, erupting three times in recorded history. It exhibits mostly strombolianactivity; the most recent eruption, which started in 1934, is still ongoing. Geologically, Sangay marks the southern bound of the Northern Volcanic Zone, and its position straddling two major pieces of crust accounts for its high level of activity. Sangay's approximately 500,000 year old history is one of instability; two previous versions of the mountain were destroyed in massive flank collapses, evidence of which still litters its surroundings today. Sangay is one of two active volcanoes located within the namesake Sangay National Park, the other being Tungurahua to the north. As such it has been listed as a UNESCO World Heritage Site since 1983.

Reventador is an active stratovolcano which lies in the eastern Andes of Ecuador. Since 1541 it has erupted over 25 times with most recent eruption in 2009, but the largest historical eruption occurred in 2002. During that eruption the plume from the volcano reached a height of 17 km and pyroclastic flows went up to 7 km from the cone. On March 30, 2007, the mountain spewed ash again. The ash reached a height of about two miles (3 km, 11,000 ft). No injuries or damages have been reported.

Galápagos Islands, Ecuador

The Galápagos Islands are an isolated set of volcanoes, consisting of shield volcanoes and lava plateaus, located 1,200 km (746 mi) west of Ecuador. They are driven by the Galápagos hotspot, and are between approximately 4.2 million and 700,000 years of age. The largest island, Isabela Island, consists of six coalesced shield volcanoes, each delineated by a large summit caldera.Española, the oldest island, and Fernandina, the youngest, are also shield volcanoes, as are most of the other islands in the chain. The Galápagos Islands are perched on a large lava plateau known as the Galápagos Platform. This platform creates a shallow water depth of 360 to 900 m (1,181 to 2,953 ft) at the base of the islands, which stretch over a 174 mi (280 km)-long diameter. Since Charles Darwin's famous visit to the islands in 1835, there have been over 60 recorded eruptions in the islands, from six different shield volcanoes. Of the 21 emergent volcanoes, 13 are considered active.

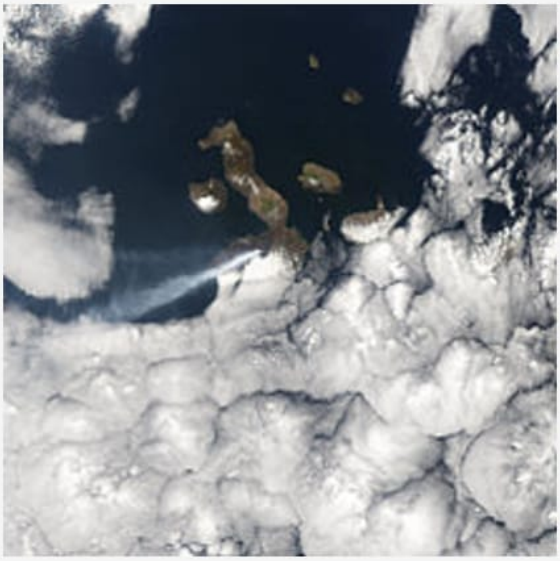


Figure 6. Photographed by NASA Earth Observatory 13227 on October 22, 2005, the Black Mountain Volcano on Isabela Island, in the Galapagos.

Blue Hill is a shield volcano on the south western part of Isabela Island in theGalápagos Islands and is one of the most active in the Galapagos, with the last eruption between May and June 2008. The Galápagos islands are geologically young for such a big chain, and the pattern of their rift zones follows one of two trends, one north-northwest, and one east-west. The composition of the lavas of the Galápagos shields are strikingly similar to those of the Hawaiian volcanoes. Curiously, they do not form the same volcanic “line” associated with most hotspots. They are not alone in this regard; the Cobb-Eickelberg Seamount chainin the North Pacific is another example of such a delineated chain. In addition, there is no clear pattern of age between the volcanoes, suggesting a complicated, irregular pattern of creation. How exactly the islands were formed remains a geological mystery, although several theories have been fronted. Black Mountain is a large shield volcano at the South eastern end of Isabela Island in the Galapagos that rises to an altitude of 1124m. It coalesces with the volcanoes Cerro Azul to the west and Alcedo to the north. The volcano is one of the most active in the Galapagos, with the last eruption starting on 22 October 2005 and lasting until 30 October 2005.

Alcedo Volcano is one of the six coalescing shield volcanoes that make up Isabela Island in the Galapagos. The remote location of the volcano has meant that even the most recent eruption in 1993 was not recorded until two years later. Alcedo, like the other volcanoes in the Galapagos, has been formed as part of the Galapagos hotspot which is a mantle plume resulting in a hotspot. The volcano is not directly on the hotspot, which is believed to be under the neighbouring island of Fernandina to the west. However, it is still active with the last eruption in 1993. Due to the remoteness of Alcedo historical eruptions are not well recorded. There was an eruption between 1946 and 1960, as determined from variation in photographs. Another eruption in 1954 is now believed to have taken place on neighbouring Sierra Negra. Even the 1993 eruption was not observed at the time and only recorded after an expedition discovered new craters in 1995.

Fernandina Island (formerly known in English as Narborough Island, after John Narborough) is the third largest, and youngest, island of the Galápagos Islands. Like the others, the island was formed by the Galápagos hotspot. The island is an active shield volcano that has been erupting since April 11, 2009. The southern flank of the volcano La Cumbre had a fissure eruption that generated flows, which subsided within hours. Isla Fernandina supports wildlife that could be threatened by the April 2009 burst of volcanic activity, according to rangers at Galapagos National Park. However, no human settlements were endangered, as the island has no human residents. Park rangers and a passing tourist boat initially observed the volcano at 10:00 p.m. local time on April 10, 2009. A sparse human population in the western reaches of the Galapagos Islands means that volcanic activity is not always observed or reported as soon as it starts. The seismic station at Puerto Ayora, on the nearby island of Santa Cruz, recorded no earthquakes associated with this eruption.

Peru

Volcanos in Peru are monitored by the Peruvian Geophysical Institute.

Sabancaya is an active 5,976-metre (19,606 ft)stratovolcano in the Andes of southern Peru, about 100 kilometres (62 mi)

northwest of Arequipa. It is the most active volcano in Peru with an ongoing eruption that started in August 2014 and is currently ongoing.



Figure 7. La Cumbre volcano, viewed from the ISS, July 2002

Ubinas is another active volcano 5,672-metre (18,609 ft) in southern Peru with an ongoing eruption. Until 2006, this stratovolcano had not erupted for about 40 years. On April 23, 2006, Peru declared a state of emergency in towns near the volcano. On April 28, 2014, Despite a recent decline in earthquakes, Ubinas Volcano erupted an ash plume on April 28, 2014.

CENTRAL AMERICA

Costa Rica

The Volcanological and Seismological Observatory of Costa Rica at the National University of Costa Rica, in Spanish Observatorio Vulcanológico y Sismológico de Costa Rica (OVSICORI) have a dedicated team that is in charge of researching and monitoring the volcanoes, earthquakes and other tectonic processes in theCentral America Volcanic Arc. In 1984, the OVSICORI-A initiates the operation of a seismographic network designed to monitor seismic and volcanic activity throughout the national territory. Currently the seismographic network has a registration system analog and one digital. The latter enables online analysis of seismic signals, allowing to expedite the analysis of signals and their study using modern computerized methods.



Figure 8. Fernandina Island during the April 2009 eruption as seen from space. Isla Isabela can also be seen to the east (right).

A powerful M7.6 earthquake shook Costa Rica and a wide swath of Central America at 8:42 a.m. (10:42 a.m. EDT; 1442 GMT) on 09/05/2012.

Poás Volcano is an active 2,708-metre (8,885 ft) stratovolcano hat is located in central Costa Rica and has erupted 39 times since 1828. The event was captured from a webcam from the Volcanological and Seismological Observatory of Costa Rica (OVSICORI) captured the moment a dark cloud exploded about 1,000 feet in the air from a massive crater of the Poás Volcano. On February 25, 2014, A webcam from the Volcanological and Seismological Observatory of Costa Rica (OVSICORI) captured the moment a dark cloud exploded about 1,000 feet in the air from a massive crater of the Poás Volcano.

Guatemala

In 1902, the Santa Maria Volcano erupted violently in Guatemala, with the largest explosions occurring over two days, ejecting an estimated 5.5 cubic kilometres (1.3 cu mi) of magma. The eruption was one of the largest of the 20th century, only slightly less in magnitude to that of Mount Pinatubo in 1991. The eruption had a volcanic explosivity index of 6. The last eruption of the Santiaguito volcano was in 2003.

NORTH AMERICAN CORDILLERA

Mexico

Volcanoes of Mexico are related to subduction of the Cocos and Rivera plates to the east, subduction which has produced large explosive eruptions. Most active volcanoes in Mexico occur in the Trans-Mexican Volcanic Belt, which extends 900 kilometres (559 mi) from west to east across central-southern Mexico. A few other active volcanoes in northern Mexico are related to extensional tectonics of the Basin and Range Province, which splits the Baja California peninsula from the mainland. Popocatépetl, lying in the eastern half of the Trans-Mexican Volcanic Belt, is the second highest peak in Mexico after thePico de Orizaba. It is one of the most active volcanoes in Mexico, having had more than 20 major eruptions since the arrival of the Spanish in 1519. The 1982 eruption of El Chichón, which killed about 2,000 people who lived near the volcano, created a 1 kilometre (1 mi) wide caldera that filled with an acidic crater lake. Prior to 2000, this relatively unknown volcano was heavily forested and of no greater height than adjacent non-volcanic peaks.



Figure 9. Santiaguito Volcano, 2003 eruption in Guatemala

United States

The United States Geological Survey and the National Earthquake Information Center (abbreviated **NEIC**) is part of the United States Geological Survey (USGS) located on the campus of the Colorado School of Mines in Golden, Colorado both monitor volcanos in the United States and are responsible for monitoring the volcanos in the United States. In the western United States lies the Cascade Volcanic Arc. It includes nearly 20 major volcanoes, among a total of over 4,000 separate volcanic vents including numerous stratovolcanoes, shield volcanoes, lava domes, and cinder cones, along with a few isolated examples of rarer volcanic forms such as tuyas. Volcanism in the arc began about 37 million years ago, however, most of the present-day Cascade volcanoes are less than 2,000,000 years old, and the highest peaks are less than 100,000 years old. The arc formed by the subductionof the Gorda and Juan de Fuca plates at the Cascadia subduction zone. This is a 680 mi (1,090 km) long fault, running 50 mi (80 km) off the west-coast of the Pacific Northwest from northern California to Vancouver Island, British Columbia. The plates move at a relative rate of over 0.4 inches (10 mm) per year at a somewhat oblique angle to the subduction zone.

Because of the very large fault area, the Cascadia subduction zone can produce very large earthquakes, magnitude 9.0 or greater, if rupture occurred over its whole area. When the “locked” zone stores energy for an earthquake, the “transition” zone, although somewhat plastic, can rupture. Thermal and deformation studies indicate that the locked zone is fully locked for 60 kilometers (about 40 miles) down-dip from the deformation front. Further down-dip, there is a transition from fully locked to aseismic sliding.

Unlike most subduction zones worldwide, there is no oceanic trench present along the continental margin in Cascadia. Instead, terranes and the accretionary wedge have been uplifted to form a series of coast ranges and exotic mountains. A high rate of sedimentation from the outflow of the three major rivers (Fraser River, Columbia River, and Klamath River) which cross the Cascade Range contributes to further obscuring the presence of a trench. However, in common with most other subduction zones, the outer margin is slowly being compressed, similar to a giant spring. When the stored energy is suddenly released by slippage across the fault at irregular intervals, the Cascadia subduction zone can create very large earthquakes such as the magnitude 9 Cascadia earthquake of 1700. Geological evidence indicates that great earthquakes may have occurred at least seven times in the last 3,500 years, suggesting a return time of 400 to 600 years. There is also evidence of accompanying tsunamis with every earthquake, as the prime reason they know of these earthquakes is through “scars” the tsunami left on the coast, and through Japanese records (tsunami waves can travel across the Pacific).

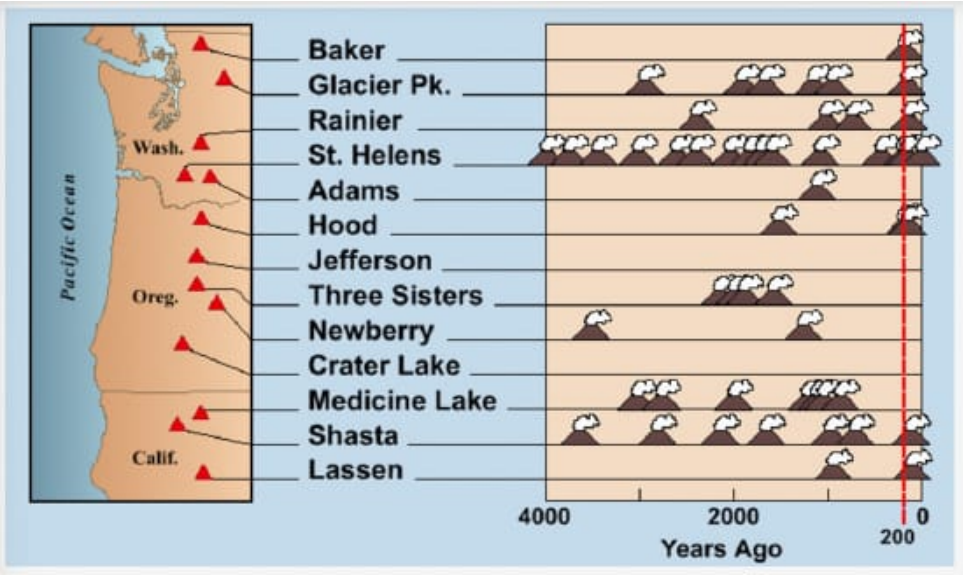


Figure 10. American Cascade Range volcano eruptions in the last 4000 years

The 1980 eruption of Mount St. Helens was the most significant to occur in the contiguous 48 U.S. states in recorded history (VEI = 5, 0.3 cu mi, 1.2 km^3 of material erupted), exceeding the destructive power and volume of material released by the 1915 eruption of California's Lassen Peak. The eruption was preceded by a two-month series of earthquakes and steam-venting episodes caused by an injection of magma at shallow depth below the mountain that created a huge bulge and a fracture system on Mount St. Helens' north slope. An earthquake at 8:32 a.m. on May 18, 1980, caused the entire weakened north face to slide away, suddenly exposing the partly molten, gas- and steam-rich rock in the volcano to lower pressure. The rock responded by exploding into a very hot mix of pulverized lava and older rock that sped toward Spirit Lake so fast that it quickly passed the avalanching north face.

Alaska is known for its seismic and volcanic activity, holding the record for the second largest earthquake in the world, the Good Friday Earthquake, and having more than 50 volcanoes which have erupted since about 1760. Volcanoes can be found not only in the mainland but also in the Aleutian Islands.

The most recent activity in the American portion of the Ring of Fire occurred in early 2009 when Mount Redoubt in Alaska became active and finally erupted late in the evening of March 22. The eruption ended in May 2009.

Canada

The Public Safety Geoscience Program at the Natural Resources Canada undertakes research to support risk reduction from the effects of space weather, earthquakes, tsunamis, volcanoes and landslides.

British Columbia and Yukon are home to a vast region of volcanoes and volcanic activity in the Pacific Ring of Fire. Several mountains that many British Columbians look at every day are dormant volcanoes. Most of them erupted during the Pleistocene and Holocene. Although none of Canada's volcanoes are currently erupting, several volcanoes,volcanic fields and volcanic centers are considered potentially active. There are hot springs at some volcanoes, while 10 volcanoes in British Columbia appear related to seismic activity since 1975, including: the Silverthrone Caldera, Mount Meager, Wells Gray-Clearwater volcanic field, Mount Garibaldi, Mount Cayley, Castle Rock, The Volcano, Mount Edziza, Hoodoo Mountain, Crow Lagoon and Nazko Cone. The volcanoes are grouped into five volcanic belts with different tectonic settings.

The Northern Cordilleran Volcanic Province (sometimes known as the Stikine Volcanic Belt) is the most active volcanic region in Canada. It formed due to extensional cracking, faulting and rifting of the North American Plate, as the Pacific Plate grinds and slides past the Queen Charlotte Fault, unlike subduction that produces the volcanoes in Japan, Philippines and Indonesia. The region hasCanada's largest volcanoes, much larger than the minor stratovolcanoes found in the Canadian portion of the Cascade Volcanic Arc. Several eruptions are known to have occurred within the last 400 years. Mount Edziza is a huge volcanic complex that erupted several times in the past several thousand years and has formed several cinder cones and lava flows. The complex comprises the Mount Edziza Plateau, a large volcanic plateau (65 kilometers long and 20 kilometers wide) made of predominantly basaltic lava flows with four large stratovolcanoesbuilt on top of the plateau. The associated lava domes and satellite cones were

constructed over the past 7.5 million years during five magmatic cycles beginning with eruption of alkali basalts and ending with felsic and basaltic eruptions as late as 1,340 years ago. The blocky lava flows still maintain their original forms.Hoodoo Mountain is a tuya in northwestern British Columbia, which has had several periods of subglacial eruptions. The oldest eruptions occurred about 100,000 years ago and the most recent about 7000 years ago. Hoodoo Mountain is also considered active and could erupt in the future. The nearby Tseax Cone and The Volcano produced some of Canada's youngest lava flows, that are about 150 years old.

Canada's worst known geophysical disaster came from the Tseax Cone during the 18th century at the southernmost end of the volcanic belt. The eruption produced a 22.5 km long lava flow, destroying the Nisga'a villages and the death of at least 2000 Nisga'a people by volcanic gases and poisonous smoke. The Nass River valley was inundated by the lava flows and contains abundant tree molds and lava tubes. The event happened at the same time with the arrival of the first European explorers to penetrate the uncharted coastal waters of northern British Columbia. Today, the basaltic lava deposits are a draw to tourists and are part of the Nisga'a Memorial Lava Beds Provincial Park.



Figure 11. Mount Edziza, a large shield volcano in northwestern British Columbia

The Garibaldi Volcanic Belt in southwestern British Columbia is the northern extension of the Cascade Volcanic Arc in the United States (which includes Mount Baker and Mount St. Helens) and contains the most explosive young volcanoes in Canada. It formed as a result of subduction of the Juan de Fuca Plate (a remnant of the much larger Farallon Plate) under the North American Plate along the Cascadia subduction zone. The Garibaldi Volcanic Belt includes the Bridge River Cones, Mount Cayley, Mount Fee, Mount Garibaldi, Mount Price, Mount Meager, the Squamish Volcanic Field and much more smaller volcanoes. The eruption styles in the belt range from effusive to explosive, with compositions frombasalt to rhyolite. Morphologically, centers include calderas, cinder cones,stratovolcanoes and small isolated lava masses. Due to repeated continental and alpine glaciations, many of the volcanic deposits in the belt reflect complex interactions between magma composition, topography, and changing ice configurations. The most recent major catastrophic eruption in the Garibaldi Volcanic Belt was the 2350 BP eruption of Mount Meager. It was similar to the 1980 eruption of Mount St. Helens, sending an ash column approximately 20 km high into the stratosphere.

The Chilcotin Group is a north-south range of volcanoes in southern British Columbia running parallel to the Garibaldi Volcanic Belt. The majority of the eruptions in this belt happened either 6–10 million years ago (Miocene) or 2–3 million years ago (Pliocene), although there have been some slightly more recent eruptions (in the Pleistocene). It is thought to have formed as a result ofback-arc extension behind the Cascadia subduction zone. Volcanoes in this belt include Mount Noel, the Clisbako Caldera Complex, Lightning Peak, Black Dome Mountain and many lava flows.

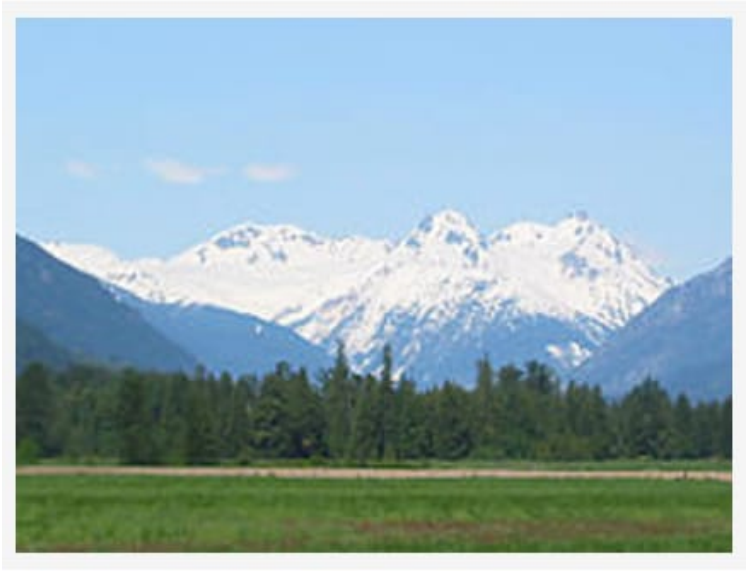


Figure 12. The Mount Meager volcanic complex as seen from the east near Pemberton, BC. Summits left to right are Capricorn Mountain, Mount Meager, and Plinth Peak

The Anahim Volcanic Belt is a line of volcanoes stretching from just north ofVancouver Island to near Quesnel, British Columbia, Canada. These volcanoes were formed 8 to 1 million years ago, and the Nazko Cone last erupted only 7,200 years ago. The volcanoes generally get younger as one moves from the coast to the interior. These volcanoes are thought to have formed as a result of theNorth American Plate sliding westward over a small hotspot, called the Anahim hotspot. The hotspot is considered similar to the one feeding the Hawaiian Islands. The belt is defined by three large shield volcanoes (Rainbow, Ilgachuzand the Itcha Ranges) and 37 Quaternary basalt centers.

Eruptions of basaltic to rhyolitic volcanoes and hypabyssal rocks of the Alert Bay Volcanic Belt in northern Vancouver Island are probably linked with the subducted margin flanked by the Explorer and Juan de Fuca plates at the Cascadia subduction zone. It appears to have been active during the Pliocene and Pleistocene time. However, no Holocene eruptions are known, and volcanic activity in the belt has likely ceased.

RUSSIA

The Kamchatka Peninsula in the Russian Far East is one of the most various and active volcanic areas in the world, with an area of 472,300 km^2. It lies between the Pacific Ocean to the east and theOkhotsk Sea to the west. Immediately offshore along the Pacific coast of the peninsula runs the 10,500 meter deepKuril-Kamchatka Trench. This is where rapid subduction of the Pacific Plate fuels the intense volcanism. Almost all types of volcanic activity are present, from stratovolcanoes and shield volcanoes to Hawaiian-style fissure eruptions.



Figure 13. Avachinsky, an active volcano on the Kamchatka Peninsula.

There are over 30 active volcanoes and hundreds of dormant and extinct volcanoes in two major volcanic belts. The most recent activity takes place in the eastern belt, starting in the north at the Shiveluch volcanic complex, which lies at the junction of the Aleutian and Kamchatka volcanic arcs. Just to the south is the famous Klyuchi volcanic group, comprising the twin volcanic cones of Kliuchevskoi and Kamen, the huge volcanic complexes of Tolbachik and Ushkovsky, and a number of other large stratovolcanoes. The only active volcano in the central belt is found west of here, the huge remote Ichinsky. Farther south, the eastern belt continues to the southern slope of Kamchatka, topped by loads ofstratovolcanoes, continuing onto the Kuril Islands, and southwards into Japan.

JAPAN

Approximately ten percent of the world's active volcanoes are found in Japan, which lies in a zone of extreme crustal instability. They are formed by subduction of the Pacific Plate and the Philippine Sea Plate. As many as 1,500 earthquakes are recorded yearly, and magnitudes of four to six on the Richter scale are not uncommon. Minor tremors occur almost daily in one part of the country or another, causing some slight shaking of buildings. Major earthquakes occur infrequently; the most famous in the twentieth century were: the Great Kantō earthquake of 1923, in which 130,000 people died; and the Great Hanshin earthquake of 17 January 1995, in which 6,434 people died. On March 11, 2011 a magnitude 9.0 Earthquake hit Japan, the country's biggest ever and the fifth largest on record, according to US Geological Survey data. Undersea earthquakes also expose the Japanese coastline to danger from tsunamis.

Mount Bandai, one of Japan's most noted volcanoes, rises above the north shore of Lake Inawashiro. Mount Bandai is formed of several overlapping stratovolcanoes, the largest of which is O-Bandai forming acomplex volcano. O-Bandai volcano was constructed within a horseshoe-shaped caldera that formed about 40,000 years when an earlier volcano collapsed, forming the Okinajima debris avalanche, which traveled to the southwest and was accompanied by a plinian eruption. Four major phreatic eruptions have occurred during the past 5,000 years, two of them in historical time, in 806 and 1888. Seen from the south, Bandai presents a conical profile, but much of the north side of the volcano is missing as a result of the collapse of Ko-Bandai volcano during the 1888 eruption, in which a debris avalanche buried several villages and formed several large lakes.



Figure 14. Mount Fuji at sunrise from Lake Kawaguchi

Nearly a century ago, the north flank of Mount Bandai collapsed during an eruption quite similar to the May 18, 1980 eruption of Mount St. Helens. After a week of seismic activity, a large earthquake on July 15, 1888, was followed by a tremendous noise and a large explosion. Eyewitnesses heard about 15 to 20 additional explosions and observed that the last one was projected almost horizontally to the north.

Mount Fuji is Japan's highest and most noted volcano. The modern postglacial stratovolcano is constructed above a group of overlapping volcanoes, remnants of which form irregularities on Fuji's profile. Growth of the younger Mount Fuji began with a period of voluminous lava flows from 11,000 to 8,000 years ago, accounting for four-fifths of the volume of the younger Mount Fuji. Minor explosive eruptions dominated activity from 8,000 to 4,500 years ago, with another period of major lava flows occurring from 4,500 to 3,000 years ago. Subsequently, intermittent major explosive eruptions occurred, with subordinate lava flows and small pyroclastic flows. Summit eruptions dominated from 3,000 to 2,000 years ago, after which flank vents were active. The extensive basaltic lava flows from the summit and some of the more than 100 flank cones and vents blocked drainages against the Tertiary Misaka Mountains on the north side of the volcano, forming the Fuji Five Lakes. The last eruption of this dominantly basaltic volcano in 1707 ejected andesitic pumice and formed a large new crater on the east flank. Scientists are saying that there may be some minor volcanic activity in the next few years.

PHILIPPINES

The 1991 eruption of Mount Pinatubo is the world's second largest terrestrial eruption of the 20th century. Successful predictions of the onset of the climactic eruption led to the evacuation of tens of thousands of people from the surrounding areas, saving many lives, but as the surrounding areas were severely damaged by pyroclastic flows, ash deposits, and later, lahars caused by rainwater remobilising earlier volcanic deposits, thousands of houses were destroyed.



Figure 15. Mayon Volcano overlooks a pastoral scene approximately five months before the volcano's violent eruption in September 1984.

Mayon Volcano is the Philippines' most active volcano. The volcano has steep upper slopes that average 35–40 degrees and is capped by a small summit crater. The historical eruptions of this basaltic-andesiticvolcano dates back to 1616 and ranges from Strombolian to basaltic Plinian eruptions. Eruptions occur predominately from the central conduit and have also produced lava flows that travel far down the flanks. Pyroclastic flows and mudflows have commonly swept down many of the approximately 40 ravines that radiate from the summit and have often devastated populated lowland areas.

Taal Volcano has had 33 recorded eruptions since 1572. A devastating eruption occurred in 1911, which claimed more than a thousand lives. The deposits of that eruption consist of a yellowish, fairly decomposed (non-juvenile) tephra with a high sulfur content. The most recent period of activity lasted from 1965 to 1977, and was characterized by the interaction of magma with the lake water, which produced violent phreatic and phreatomagmatic eruptions. Although the volcano has been dormant since 1977, it has shown signs of unrest since 1991, with strong seismic activity and ground fracturing events, as well as the formation of small mud geysers on parts of the island.



Figure 16. Map showing major volcanoes of the Philippines.

Kanlaon Volcano is the most active volcano in central Philippines and has erupted 25 times since 1866. Eruptions are typically phreatic explosions of small-to-moderate size that produce minor ashfalls near the volcano. On August 10, 1996, Kanlaon erupted without warning, killing British student Julian Green and Filipinos Noel Tragico and Neil Perez, who were among 24 mountainclimbers who were trapped near the summit.

INDONESIA

The volcanoes in Indonesia are among the most active of the Pacific Ring of Fire. They are formed due to subduction zones of three main active tectonic plates namely the Eurasian Plate, Pacific Plate, and the Indo-Australian Plate. Some of the volcanoes are notable for their eruptions, for instance, Krakatau for its global effects in 1883, Lake Toba for its supervolcanic eruption estimated to have occurred 74,000 BP, which was responsible for six years of volcanic winter, and Mount Tambora for the most violent eruption in recorded history in 1815. The eruption of Mount Tambora in 1815 caused widespread harvest failures in Northern Europe, the Northeastern United States, and eastern Canada in 1816, which was known as the Year Without a Summer.



Figure 17. Mount Merapi in Central Java

The most active volcanoes are Kelud and Mount Merapi on Java island, which have been responsible for thousands of deaths in the region. Since AD 1000, Kelud has erupted more than 30 times, of which the largest eruption was at scale 5 on the Volcanic Explosivity Index, while Merapi has erupted more than 80 times. The International Association of Volcanology and Chemistry of the Earth's Interiorhas named Merapi as a Decade Volcano since 1995 because of its high volcanic activity.

NEW ZEALAND

GNS Science was known as the Institute of Geological and Nuclear Sciences from 1992 to 2005. GNS Science was partially commercialised, and now operates as a government-owned company rather than as a government department.



Figure 18. View of Mount Taranaki from Stratford.

Originally part of the Department of Scientific and Industrial Research (DSIR), it was established as an independent organization when the Crown Research Institutes were created in 1992.

As well as undertaking basic research, and operating the national geological hazards monitoring network, GNS Science is

employed, both in New Zealand and overseas, by various private groups (notably energy companies), as well as central and local government agencies, to provide scientific advice and information.

GNS Science is based in Avalon, Lower Hutt with facilities in Dunedin and Wairakei.

New Zealand contains the world's strongest concentration of youthful rhyoliticvolcanoes, and voluminous sheets blanket much of the North Island. The earliest historically-dated eruption was at Whakaari/White Island in 1826, followed in 1886, by the country's largest historical eruption at Mount Tarawera. Much of the region north of New Zealand's North Island is made up of seamounts and smallislands, including 16 submarine volcanoes. In the last 1.6 million years, most of New Zealand's volcanism is from the Taupo Volcanic Zone.



Figure 19. Major volcanoes of New Zealand

Mount Ruapehu at the southern end of the Taupo Volcanic Zone, is one of the most active volcanoes. It began erupting at least 250,000 years ago. In recorded history, major eruptions have been about 50 years apart, in 1895, 1945 and 1995–1996. Minor eruptions are frequent, with at least 60 since 1945. Some of the minor eruptions in the 1970s generated small ash falls and lahars (mudflows) that damaged skifields. Between major eruptions, a warm acidic crater lake forms, fed by melting snow. Major eruptions may completely expel the lake water. Where a major eruption has deposited a tephra dam across the lake's outlet, the dam may collapse after the lake has refilled and risen above the level of its normal outlet, the outrush of water causing a large lahar. The most notable lahar caused the Tangiwai disaster in December 1953, when 151 people aboard a Wellington to Auckland express train were killed after the lahar destroyed the Tangiwai rail bridge just moments before the train was due. In 2000, the ERLAWS system was installed on the mountain to detect such a collapse and alert the relevant authorities.

The Auckland volcanic field on the North Island of New Zealand, has produced a diverse array of explosive craters, scoria cones, and lava flows. Currentlydormant, the field is likely to erupt again with the next "hundreds to thousands of years", a very short timeframe in geologic terms. The field contains at least 40 volcanoes, most recently active about 600 years ago at Rangitoto Island, erupting 2.3 cubic kilometers of lava.

ANTARCTICA

Mount Erebus is the second highest volcano in Antarctica (after Mount Sidley) and the southernmost active volcano on earth. It is the 6th highest ultra mountain on an island. With a summit elevation of 3,794 metres (12,448 ft), it is located on Ross Island, which is also home to three inactive volcanoes, Mount Terror, Mount Bird, and Mount Terra Nova.



Figure 20. Mount Erebus, 1972

The volcano has been observed to be continuously active since 1972 and is the site of the Mount Erebus Volcano Observatory run by the New Mexico Institute of Mining and Technology. Mount Erebus is currently the most active volcano in Antarctica and is the current eruptive zone of the Erebus hotspot.

The Lower Erebus Hut (LEH) is a permanent field facility located on Mount Erebusin Ross Island, Antarctica. The hut is the home of the Mount Erebus Volcano Observatory MEVO, run by New Mexico Institute of Mining and Technology NMT. The installation comprises two huts, one kitchen and recreation building and one working and storage building.

The Pacific Ring of Fire is completed in the south by the continent of Antarctica, which includes many large volcanoes. The makeup and structure of the volcanoes in Antarctica change largely from the other places around the ring. In contrast, the Antarctic Plate is almost completely surrounded by extensional zones, with several mid-ocean ridges which encircle it, and there is only a small subduction zone at the tip of the Antarctic Peninsula, reaching eastward to the remote South Sandwich Islands. The most well known volcano in Antarctica is Mount Erebus, which is also the world's southernmost active volcano. In many respects the geology of the Antarctic Peninsula is an extension of the Andes, hence the name sometimes used by geologists: "Antarctandes." At the opposite side of the continent, the volcanoes of Victoria Land may be seen as the 'other end' of the Antarctandes, thus completing the Pacific Ring of Fire and continuing up through the Balleny Islands to New Zealand.

The volcanoes of the Victoria Land area are the most well known in Antarctica, most likely because they are the most accessible. Much of Victoria Land is mountainous, developing the eastern section of the Transantarctic Mountains, and there are several scattered volcanoes including Mount Overlord and Mount Melbourne in the northern part.Farther south are two more well-known volcanoes, Mount Discovery and Mount Morning, which are on the coast across from Mount Erebus and Mount Terror on Ross Island. The volcanism in this area is caused by rifting along a number of rift zones increasing mainly north-south similar to the coast.

Marie Byrd Land contains the largest volcanic region in Antarctica, covering a length of almost 600 miles (970 km) along the Pacific coast. The volcanism is the result of rifting along the vast West Antarctic Rift, which extends from the base of the Antarctic Peninsula to the surrounding area of Ross Island, and the volcanoes are found along the northern edge of the rift. Protruding up through the ice are a large number of major shield volcanoes, including Mount Sidley, which is the highest volcano in Antarctica. Although a number of the volcanoes are relatively young and are potentially active (Mount Berlin, Mount Takahe,Mount Waesche, and Mount Siple), others such as Mount Andrus and Mount Hampton are over 10 million years old, yet maintain uneroded constructional forms. The desert-like surroundings of the Antarctic interior, along with a very thick and stable ice sheet which encloses and protects the bases of the volcanoes, which decreases the speed of erosion by an issue of perhaps a thousand relative to volcanoes in moist temperate or tropical climates.

LAND AREAS

- Puysegur Trench and Macquarie Ridge

- Taupo Volcanic Zone
- Kermadec Islands
- Tonga Islands
- Fiji Islands
- Bougainville and Solomon Islands
- New Hebrides Arc
- Bismarck Volcanic Arc, junction
  - Tanimbar and Kai Islands
    - Lesser Sunda Islands
    - Sunda Arc
    - Andaman and Nicobar Islands
  - Izu-Bonin-Mariana Arc
    - Mariana Islands
    - Bonin Islands
    - Izu Islands
  - Philippine Mobile Belt
    - Taiwan
    - Ryukyu Islands
- Japan, Boso Triple Junction
- Kuril Islands
- Kamchatka Peninsula
- American Cordillera
  - North American Cordillera
    - Aleutian Arc
      - Aleutian Islands
      - Aleutian Range
    - Eastern Alaska, U.S.
    - Northern Cordilleran Volcanic Province
    - Cascade Volcanic Arc and Rio Grande rift
    - Sierra Nevada (U.S.)
    - Trans-Mexican Volcanic Belt
  - Central America Volcanic Arc
  - Andes
    - North Volcanic Zone
    - Central Volcanic Zone
    - South Volcanic Zone
    - Austral Volcanic Zone
- Scotia Arc
  - South Sandwich Islands
- Antarctica
  - Antarctic Peninsula
  - Victoria Land

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5.11: Intraplate Deformation

Intraplate deformation is the folding, breaking, or flow of the Earth's crust within plates instead of at their margins. This process usually occurs in areas with especially weak crust and upper mantle, such as the Tibetan Plateau (Figure 1). Intraplate deformation brings another aspect toplate tectonic theory.



Figure 1. East Asia topographic map. The large brown area is the Tibetan plateau and the Tien Shan mountains to the northwest. Almost the whole central landmass in view is deformed from the collision of India into Asia around 50 million years ago.

CRUSTAL DEFORMATION PROCESSES

The theory of plate tectonics states that the Earth's crust is made up of rigid plates that "float" on top of the mantle and move relative to one another. As the plates move, the crust deforms dominantly along the plate margins. Intraplate deformation differs from that respect by the observation that deformation can occur anywhere the crust is weak and not just at plate margins.

Deformation is the folding, breaking, or flow of rocks. There are many different types of crustal deformation depending on whether the rocks are brittle or ductile. The aspects that determine these properties are due to certain temperatures and pressures that rocks experience within the Earth. Therefore, temperature and pressure control deformation processes. Ductile rocks tend to bend, fold, stretch, or flow due to compressional or extensional forces. Brittle rocks, on the other hand, tend to break. The zone where the crust breaks is termed a fault. There are three main types of faults: normal faults, reverse faults*, and strike slip (transform) faults.* All of these are ways the crust can deform is due to the different types of plate margins, which are: divergent boundaries, convergent boundaries, and transform boundaries.

These three boundaries do not always form perfectly and this can lead to a mixed boundary. Mixed boundaries can be a combination of a transform with convergence or a transform with divergence.

AN EXAMPLE OF INTRAPLATE DEFORMATION

Central/East Asia is possibly the best example of large-scale intraplate deformation. The formation and uplift of the Tibetan plateau and theHimalayan mountain range started in the Cenozoic era around 50 million years ago when the Indian plate collided with the Eurasian plate. The collision caused much shortening of the lithosphere, adding to increased crustal thickness and high stress in the Himalaya/Tibet region.



Figure 2. Same image as Figure 1 but without any intraplate deformation throughout Asia from the India-Asia collision.

Many geophysical observations in Tibet show a weak crustal zone and suggest that the middle to lower crust may contain fluids and be partially melted. As the Himalayan-Tibet region began to rise, lateral extrusion of the crust in the Tibetan plateau gradually became the dominant mechanism for accommodating the collision and crustal shortening. The lateral extrusion is sliding dominantly to the east and out of India's path. Eastern Tibet is traditionally interpreted as being part of a broad accommodation zone. Much of the eastern movement is due to major strike-slip faults. These strike-slip faults, along with the other faults in Tibet could still be interpreted as on a plate margin though. True intraplate deformation occurs farther north in areas such as Mongolia or the Tian Shan mountains. These areas display true intraplate deformation because there is still much faulting and folding to accommodate some of the crustal shortening from the India/Eurasia collision hundreds of kilometers away from the plate margin.

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5.12: Folds

ANTICLINES

In structural geology, an **anticline** is a fold that is convex up and has its oldest beds at its core. The term is not to be confused with *antiform*, which is a purely descriptive term for any fold that is convex up. Therefore if age relationships between various strata are unknown, the term antiform should be used.

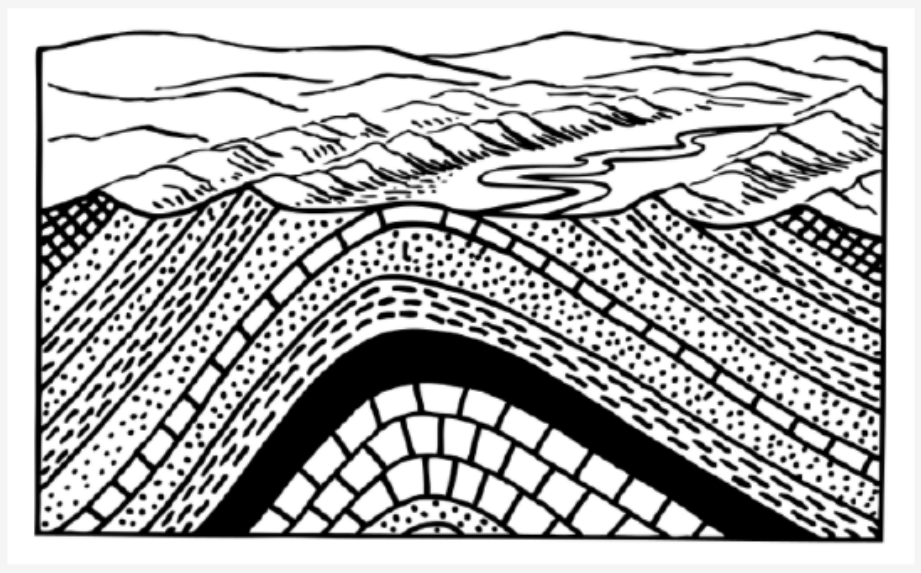


Figure 1. Diagram of an anticline.

On a geologic map, anticlines are usually recognized by a sequence of rock layers that are progressively older toward the center of the fold because the uplifted core of the fold is preferentially eroded to a deeper stratigraphic level relative to the topographically lower flanks. The strata dip away from the center, or *crest*, of the fold.

If an anticline plunges (i.e., is inclined to the Earth's surface), the surface strata will form *V*s that point in the direction of plunge. Anticlines are often flanked by synclines although faulting can complicate and obscure the relationship between the two. Folds often form during crustal deformation as the result of shortening that accompanies orogenic mountain building. In many cases anticlines are formed by movement on non-planar faults during both shortening and extension, such as *ramp anticline*s and rollover anticlines.



Figure 2. Anticline with syncline visible at far right. Note the man standing before the formation, for scale.

Terminology

Any fold whose form is **convex** upward is an antiform. Antiforms containing progressively younger rocks from their core outwards are anticlines.

An anticline or antiform has a *crest*, which is the highest point on a given stratum along the top of the fold. A *hinge* in an anticline is the locus of maximum curvature or bending in a given stratum in the fold. An *axis* is an imaginary line connecting the hinges in the different strata in a two-dimensional cross-section through the anticline. Connecting the hinges or points of maximum curvature in the different layers in three dimensions produces an *axial plane* or *axial surface*. In a symmetrical anticline, a surface trace of the axial plane coincides with the crest. With an asymmetrical anticline, the surface trace of the axial plane or axis will be offset from the crest toward the steeper flank of the fold. An*overturned* anticline is an asymmetrical anticline with a flank or limb that has been tilted beyond perpendicular so that the beds in that limb are upside-down.

A structure that plunges in all directions to form a circular or elongate structure is a dome. Domes are generally formed from one main deformation event, or via diapirism from underlying magmatic intrusions or movement of upwardly mobile, mechanically ductile material such as rock salt (salt dome) and shale (shale diapir). The Richat Structure of the Sahara is considered a dome that has been laid bare by erosion.

An anticline which plunges at both ends is termed a *doubly plunging anticline*, and may be formed from multiple deformations, or superposition of two sets of folds, or be related to the geometry of the underlying detachment fault and the varying amount of displacement along the surface of that detachment fault. The highest point on a doubly plunging anticline (or any geologic structure for that matter) is called the “culmination.”

An elongate dome which developed as the sediments were being deposited is referred to as a *pericline*.

An *anticlinorium* is a series of anticlinal folds on a regional-scale anticline. Examples include the Late Jurassic to Early Cretaceous Purcell Anticlinorium in British Columbia and the Blue Ridge anticlinorium of northern Virginia and Maryland in the Appalachians, or the Nittany Valley in central Pennsylvania.

Economic Significance

Doubly plunging or faulted anticlines, culminations, and structural domes are favored locations for oil and natural gas drilling; the low density of petroleum causes it to buoyantly migrate upward to the highest parts of the fold, until stopped by a low-permeability barrier such as an impermeable stratum or fault zone. Examples of low-permeability seals that contain the hydrocarbons, oil and gas, in the ground include shale, limestone, sandstone, and even salt domes. The actual type of stratum does not matter as long as it has low permeability.



Figure 3. Structural trap: anticlinal fold

Periclines are important focal points for pooling of hot, metal-laden formational brines, which can form manto ore deposits, Irish-type lead-zinc deposits and uranium deposits, amongst others.

Culminations in folded strata which are cut by shears and faults are favoured loci for deposition of saddle-reef style lode gold deposits.

SYNCLINES

In structural geology, a **syncline** is a fold with younger layers closer to the center of the structure. A **synclinorium** (plural **synclinoriums** or **synclinoria**) is a large syncline with superimposed smaller folds. Synclines are typically a downward fold, termed a synformal syncline (i.e. a trough); but synclines that point upwards, or perched, can be found when strata have been overturned and folded (an antiformal syncline).

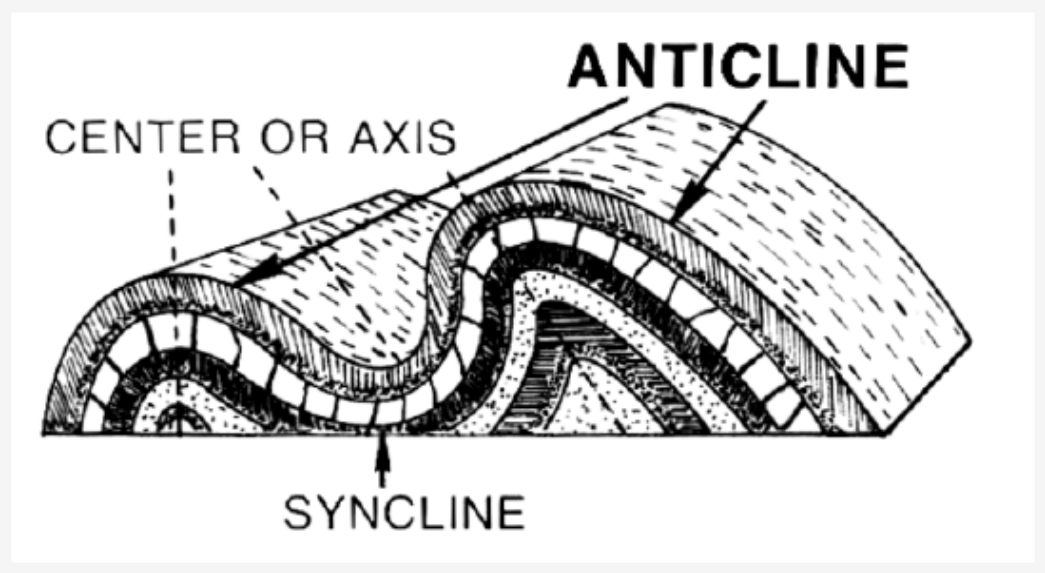


Figure 4. Diagram of a syncline and an anticline.

Characteristics

On a geologic map, synclines are recognized by a sequence of rock layers that grow progressively younger, followed by the youngest layer at the fold's center or *hinge*, and by a reverse sequence of the same rock layers on the opposite side of the hinge. If the fold pattern is circular or elongate circular the structure is a basin. Folds typically form during crustal deformation as the result of compression that accompanies orogenic mountain building.

Notable Examples

- Powder River Basin, Wyoming, USA.
- Sideling Hill roadcut along Interstate 68 in western Maryland, USA, where the Rockwell Formation and overlying Purslane Sandstone are exposed.
- Western Lake Superior, which occupies a basin created by the Midcontinent Rift System
- Saou, a commune in the Drôme department in southeastern France
- The Catlins, an area in the southeastern corner of the South Island of New Zealand

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5.13: Climates and Tectonics

Tectonic–climatic interaction refers to interrelationships between tectonic processes and the climate system. The tectonic processes in question include orogenesis,volcanism, and erosion, while relevant climatic processes include, but are not limited to,atmospheric circulation, orographic lift, monsoon circulation and the rain shadow effect. As the geological record of past climate changes over the tectonic-scale (i.e. millions of years) is sparse and poorly resolved, many questions remain unresolved regarding the nature of tectonic-climate interaction, although it is an area of active research by geologists and palaeoclimatologists.

OROGRAPHIC CONTROLS ON CLIMATE

Depending on the vertical and horizontal magnitude of a mountain range, it has the potential to have strong effects on global and regional climate patterns and processes including: deflection of atmospheric circulation, creation of orographic lift, altering monsoon circulation, and causing the rain shadow effect.

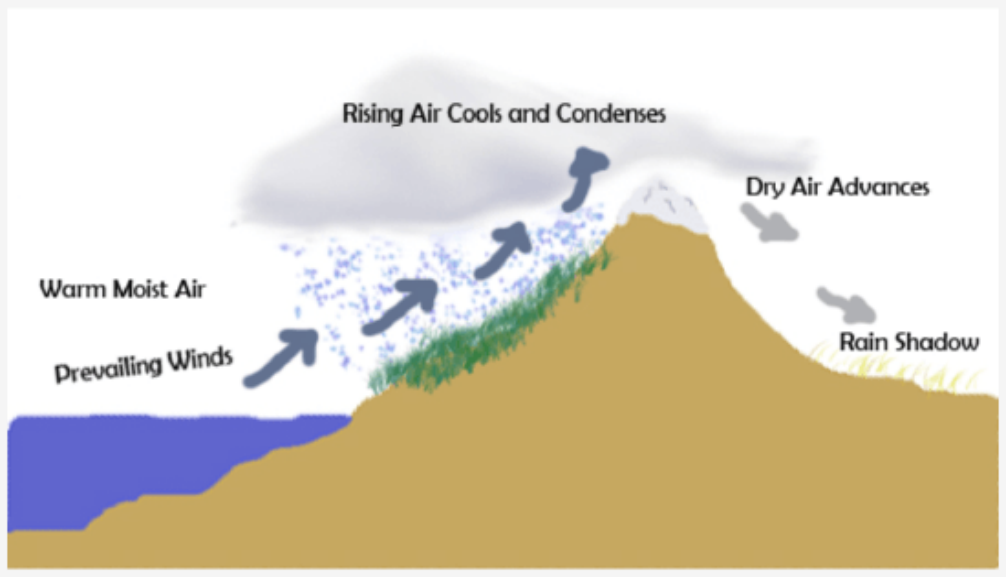


Figure 1. Simple illustration of the rain shadow effect

One well known example of an elevated terrain and its effect on climate occurs in the Southeast Asian Himalayas, the world's highest mountain system. A range of this size has the ability to influence geographic temperature, precipitation, and wind. Theories suggest that the uplift of the Tibetan Plateau has resulted in stronger deflections of the atmospheric jet stream, a heavier monsoonal circulation, increased rainfall on the front slopes, greater rates of chemical weathering, and thus lower atmospheric CO_2concentrations. It is possible that the spatial magnitude of this range is so great that it creates a regional monsoon circulation in addition to disrupting hemispheric-scale atmospheric circulation.

The monsoon season in Southeast Asia occurs due to the Asian continent becoming warmer than the surrounding oceans during the summer; as a low-pressure cell is created above the continents, a high-pressure cell forms over the cooler ocean, causing advection of moist air, creating heavy precipitation from Africa to Southeast Asia. However, the intensity of the rainfall over Southeast Asia is greater than the African monsoon, which can be attributed to the awesome size of the Asian continent compared to the African continent and the presence of a vast mountain system. This not only affects the climate of Southeast Asia, but modifies the climate in neighboring areas such as Siberia, central Asia, the Middle East, and the Mediterranean basin as well. To test this a model was created that changed only the topography of current landmasses, which resulted in correlations between the model and global fluctuations in precipitation and temperature over the past 40 Myr. interpreted by scientists.

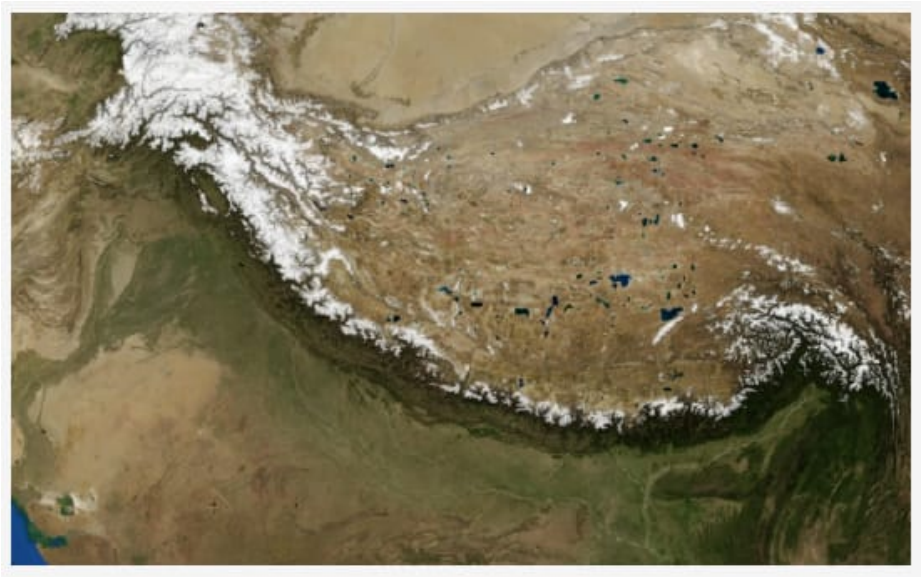


Figure 2. Example of the rain shadow effect in the Himalayas

It is commonly agreed upon that global climate fluctuations are strongly dictated by the presence or absence of greenhouse gases in the atmosphere and carbon dioxide (CO_2) is typically considered the most significant greenhouse gas. Observations infer that large uplifts of mountain ranges globally result in higher chemical erosion rates, thus lowering the volume of CO_2 in the atmosphere as well as causing global cooling. This occurs because in regions of higher elevation there are higher rates of mechanical erosion (i.e. gravity, fluvial processes) and there is constant exposure and availability of materials available for chemical weathering. The following is a simplified equation describing the consumption of CO_2 during chemical weathering of silicates: $CaSiO_3 + CO_2 \leftrightarrow CaCO_3 + SiO_2$

From this equation, it is inferred that carbon dioxide is consumed during chemical weathering and thus lower concentrations of the gas will be present in the atmosphere as long as chemical weathering rates are high enough.

CLIMATE-DRIVEN TECTONISM

There are scientists who reject that uplift is the sole cause of climate change and are in favor of uplift as a result of climate change. Some geologists theorize that a cooler and stormier climate (such as glaciations and increased precipitation) can give a landscape a younger appearance such as incision of high terrains and increased erosion rates. Glaciers are a powerful eroding agent with the ability to incise and carve deep valleys and when rapid erosion of the earth's surface occurs, especially in an area of limited relief, it is possible for isostatic rebound to occur, creating high peaks and deep valleys. A lack of glaciation or precipitation can cause an increase in erosion, but can vary between localities. It is possible to create erosion in the absence of precipitation because there would be a decrease in vegetation, which typically acts as a protective cover for the bedrock.

Models also suggest that certain topographic features of the Himalayan and Andes region is determined by an erosional/climatic interaction as opposed to tectonism. These models reveal a correlation between regional precipitation and a maximum topographic limit at the plateau margin. In the southern Andes where there is relatively low precipitation and denudation rates, there is no real extreme topography present at the plateau margin while in the north there are higher rates of precipitation and the presence of extreme topography.



Figure 3. Peaks and valleys of the Torres del Paine range of the Andes in Chile

Another interesting theory comes from an investigation of the uplift of the Andes during the Cenozoic. Some scientists hypothesize that the tectonic processes of plate subduction and mountain building are products of erosion and sedimentation. When there is an arid climate influenced by the rain shadow effect in a mountainous region, sediment supply to the trench can be reduced or even cut off. These sediments are thought to act as lubricants at the plate interface and this reduction increases the shear stress present at the interface that is large enough to support the high Andes.

VOLCANISM

Introduction

Around the world, dotting the map are volcanoes of all shapes and sizes. Lining the landmass around the Pacific Ocean are the well-known volcanoes of the Pacific Ring of Fire. From the Aleutian Islands to the Andes Mountains in Chile, these volcanoes have sculpted their local and regional environments. Aside from admiring their majestic beauty, one might wonder how these geologic wonders work and what role they play in changing the landscape and atmosphere. Principally, volcanoes are geologic features that exude magmatic material from below Earth's surface onto the surface. Upon reaching the surface, the term "magma" disappears and "lava" becomes the common nomenclature. This lava cools and forms igneous rock. By examining igneous rocks, it is possible to derive a chain of events that led from the original melt of the magma to the crystallization of the lava at Earth's surface. By examining igneous rocks, it is possible to postulate evidence for volcanic outgassing, which is known to alter atmospheric chemistry. This alteration of atmospheric chemistry changes climate cycles both globally and locally.

Fundamentals of Igneous Rock and Magmatic Gas Formation

Magmas are the starting point for the creation of a volcano. In order to understand volcanism, it is critical to understand the processes that form volcanoes. Magmas are created by keeping temperature, pressure, and composition (known as P-T-X) in the realm of melt conditions. The pressure and temperature for melts are understood by knowing the chemistry of the melt. To keep magma in a melt condition, a change in one variable will result in the change of another variable in order to maintain equilibrium (i.e. Le Chatlier's Principle). The production of magma is accomplished in multiple ways: 1) subduction of oceanic crust, 2) creation of a hot spot from a mantle plume, and 3) divergence of oceanic or continental plates. The subduction of oceanic crust produces a magmatic melt usually at great depth. Yellowstone National Park is a hot spot located within the center of a continent. Divergence of continental plates (i.e. the Atlantic Mid-Ocean ridge complex) creates magmas very near the surface of the Earth. A plume of heat from the mantle will melt rocks, creating a hot spot, which can be located at any depth in the crust. Hot spots in oceanic crust develop different magmatic plumbing systems based on plate velocities. Hawaii and the Madeira Archipelago (off the West coast of Africa) are examples of volcanic complexes with two different plumbing systems. Because islands such as Hawaii move more quickly than Madeira, the layered rocks at Hawaii have a different chemistry than those at Madeira. The layers beneath Hawaii and Madeira are different because the magma produced underground at these locations rests for different amounts of time. The

longer the amount of time magma will rest underground, the warmer the host rocks become. Fractionation of crystals from melt is partially driven by heat; therefore, the igneous rock produced will vary from an insulated host to a non-insulated host. Each of these avenues of magmatic creation develops different igneous rocks and, thus, various P-T-X histories. Definitions and other geologic explanations of igneous systems are explained in Loren A. Raymond's *Petrology* text.

In order to understand the creation of igneous rocks from a melt, it is fundamental to understand the concepts produced by Drs. Norman Bowen and Frank Tuttle from the $NaAlSiO_4$-$KAlSiO_4$-SiO_2-H_2O system. Tuttle and Bowen accomplished their work by using experimental petrologic laboratories that produce synthetic igneous materials from mixes of reagents. Observations from these experiments indicate that as a melt cools, it will produce derivative magmas and igneous rock. Following Bowen's research, the magma will crystallize a mafic igneous rock prior to a felsic igneous rock. As this crystallization process occurs in nature, pressure and temperature decrease, which changes the composition of the melt along various stages of the process. This constantly changing chemical environment alters the final composition that reaches the Earth's surface.

The evolution of magmatic gases depends on the P-T-X history of the magma. These factors include the composition of assimilated materials and composition of parent rock. Gases develop in magma through two different processes: first and second boiling. First boiling is defined as a decrease in confining pressure below the vapor pressure of the melt. Second boiling is defined as an increase in vapor pressure due to crystallization of the melt. In both cases, gas bubbles exsolve in the melt and aid the ascent of the magma towards the surface. As the magma ascends towards the surface, the temperature and confining pressure decrease. A decrease in temperature and confining pressure will allow an increase in crystallization and vapor pressure of the dissolved gas. Depending on the composition of the melt, this ascent can be either slow or fast. Felsic magmas are very viscous and travel to the surface of the Earth slower than mafic melts whose silica levels are lower. The amount of gas available to be exsolved and the concentrations of gases in the melt also control ascension of the magma. If the melt contains enough dissolved gas, the rate of exsolution will determine the magmas rate of ascension. Mafic melts contain low levels of dissolved gases whereas felsic melts contain high levels of dissolved gases. The rate of eruption for volcanoes of different compositions is not the controlling factor of gas emission into the atmosphere. The amount of gas delivered by an eruption is controlled by the origin of the magma, the crustal path the magma travels through, and several factors dealing with P-T-x at the Earth's surface. When felsic melts reach the surface of the Earth, they are generally very explosive (i.e. Mount St. Helens). Mafic melts generally flow over the surface of the Earth and form layers (i.e. Columbia River Basalt). Magma development under continental crust develops a different type of volcano than magmas that are generated under oceanic crust. Subduction zones produce volcanic island arcs (such as the Aleutian Islands, Alaska) and non-arc volcanism (such as Chile and California). Typically, arc volcanism is more explosive than non-arc volcanism due to the concentrations and amounts of gasses withheld in the magma underground.

Fluid inclusion analysis from fluids trapped in minerals can show a path of volatile evolution in volcanic rocks. Isotopic analyses and interpretation of degassing scenarios are required in order to derive the origin of magmatic volatiles. When gas bubbles accumulate in a melt that is crystallizing, they create a vesicular texture. Vesicules are created by super cooling a melt while gases are present. Because the rock crystallized very quickly while in the Earth's atmosphere, it is possible to examine some igneous rocks for fluids trapped in vesicules. By examining many different inclusions, it is possible to detect crustal assimilation and depressurization that account for volatile release.

Methods of Characterizing Igneous Rocks

The methods by which petrologists examine igneous rocks and synthetically produced materials are optical petrography, X-ray diffraction (XRD), electron probe microanalysis (EPMA), laser ablation inductively coupled mass spectrometry (LA-ICP-MS), and many others. Methods such as optical petrography aid the researcher in understanding various textures of igneous rocks and, also, the mineralogical composition of the rock. XRD methods define the mineralogical constituents of the rock being tested; therefore, composition is only known based on the mineralogical composition discovered using this method. EPMA reveals textural features of the rock on the micron level. It also reveals a composition of the rock based on elemental abundance. For information about fluids trapped in an igneous rock, LA-ICP-MS could be used. This is accomplished by finding rocks with small pockets of fluid or vapor, acquiring the fluid or vapor, and testing the fluid or vapor for various elements and isotopes.

Volcanic Emissions and Effects

While most volcanoes emit some mixture of the same few gasses, each volcano's emissions contain different ratios of those gasses. Water vapor (H_2O) is the predominant gas molecule produced, closely followed by carbon dioxide (CO_2) and sulfur dioxide (SO_2), all of which can function as greenhouse gasses. A few unique volcanoes release more unusual compounds. For example, mud volcanoes in Romania belch out much more methane gas than H_2O, CO_2, or SO_2—95–98% methane (CH_4), 1.5–2.3% CO_2, and trace amounts of hydrogen and helium gas. To measure volcanic gases directly, scientists commonly use flasks and funnels

to capture samples directly from volcanic vents or fumaroles. The advantage of direct measurement is the ability to evaluate trace levels in the gaseous composition. Volcanic gasses can be indirectly measured using Total Ozone Mapping Spectrometry (TOMS), a satellite-remote sensing tool which evaluates SO_2 clouds in the atmosphere. TOMS' disadvantage is that its high detection limit can only measure large amounts of exuded gases, such as those emitted by an eruption with an Volcanic Explosivity Index (VEI) of 3, on a logarithmic scale of 0 to 7.

Sulfur ejection from volcanoes has a tremendous impact environmental impact, and is important to consider when studying the large-scale effects of volcanism. Volcanoes are the primary source of the sulfur (in the form of SO_2) that ends up in the stratosphere, where it then reacts with OH radicals to form sulfuric acid (H_2SO_4). When the sulfuric acid molecules either spontaneously nucleate or condense on existing aerosols, they can grow large enough to form nuclei for raindrops and precipitate as acid rain. Rain containing elevated concentrations of SO_2 kills vegetation, which then reduces the ability of the area's biomass to absorb CO_2 from the air. It also creates a reducing environment in streams, lakes, and groundwater. Because of its high reactivity with other molecules, increased sulfur concentrations in the atmosphere can lead to ozone depletion and start a positive warming feedback.

Volcanoes with a felsic melt composition produce extremely explosive eruptions that can inject massive quantities of dust and aerosols high into the atmosphere. These particulate emissions are potent climate forcing agents, and can provoke a wide variety of responses including warming, cooling, and rainwater acidification. The climatic response depends on the altitude of the dust cloud as well as the size and composition of the dust. Some volcanic silicates cooled extremely quickly, created a glassy texture; their dark color and reflective nature absorb some radiation and reflect the rest. Such volcanic material injected into the stratosphere blocks solar radiation, heating that layer of the atmosphere and cooling the area beneath it. Wind patterns can distribute the dust over vast geographic regions; for example, the 1815 eruption of Tambora in Indonesia produced so much dust that a cooling of 1 degree Celsius was noted as far away as New England, and lasted for several months. Europeans and Americans called its effect "the year without a summer."

Volcanic emissions contain trace amounts of heavy metals, which can affect the hydrosphere when they are injected into the lower reaches of the atmosphere. When large quantities of these emissions are concentrated into a small area they can damage ecosystems, negatively affect agriculture, and pollute water sources.

Materials being emitted from volcanoes typically carry heavy metals in the trace level. When large quantities of these emissions are collected into a small area, the contamination effects become paramount.

> The short-term (months-to-years) impacts of volcanism on the atmosphere, climate and environment are strongly controlled by location, timing, flux, magnitude and emission height of sulfur gases. Episodic explosive eruptions represent the principal perturbation to stratospheric aerosol (though the atmospheric effects of sulfur degassing associated with continental flood basalts might well be more profound). In the troposphere, the picture is less clear but a significant part of the global tropospheric sulfate burden may be volcanogenic. Sulfate aerosol influences the Earth's radiation budget by scattering and absorption of shortwave and long-wave radiation, and by acting as cloud condensation nuclei. When they are brought to the boundary layer and Earth's surface, clouds containing volcanic sulfur in both gaseous and aerosol phases can result in profound environmental and health impacts.

Examples of the environmental and health impacts are agricultural loss due to acid rain and particulate shading, damage to ecosystems, and pollution in the hydrosphere. Intensity of a volcanic eruption is a variable controlling the altitude and effect of ejected material. Though larger eruptions occur less often than smaller eruptions, larger eruptions still deliver more particulate matter into the atmosphere. This year round behavior of emitted material yields mild effects on the atmosphere in comparison to larger eruptions. Over time, changes in the composition of smaller scale eruptions yields changes to atmospheric cycles and the global climate. Larger scale eruptions cause changes to the atmosphere immediately, which in turn leads to climatic changes in the immediate vicinity. The larger the volcanic expulsion, the higher the altitude achieved by the ejected silicate materials. Higher altitude injections are caused by larger intensity eruptions. Larger eruptions do not emit as much, on average, as smaller eruptions. This is related to the return period of the eruptions and the amount of ejected material per eruption. "The injection height of sulfur into the atmosphere represents another important determinant of climate impact. More intense eruptions, i.e., those with higher magma discharge rates, are more likely to loft the reactive sulfur gases into the stratosphere where they can generate climatically effective aerosol."

Eruption intensity of a volcano is not the only factor controlling the altitude of particles. The climate surrounding the volcano constrains the impact of the eruption. Models of eruptions that treat climatic variables as controls and hold eruption intensity constant predict particulate emissions, such as volcanic ash and other pyroclastic debris ejected into the atmosphere, in the tropics to reach higher altitudes than eruptions in arid or polar areas. Some of these climatic variables include humidity, aridity,

winds, and atmospheric stability. The observation made by the model matches what is seen in nature: volcanoes in tropical climates have greater eruption heights than those in the poles. If there were a widening of the tropics, the number of volcanoes able to produce higher altitude emissions into the atmosphere would increase. Effects on the climate from the increase in airborne silicate material would be substantial because the height of these tropical eruptions will become more prominent with a widening of the tropics leading to more risks such as cooling, pollution, and aircraft disturbances.

> The location of a volcano strongly influences the geographic distribution of atmospheric heating and the development of planetary waves that affect air circulation (especially in the northern hemisphere). Another relevant factor is that the height of the tropopause varies with latitude—at the tropics it is around 16–17 km above sea level but descends to 10–11 km at high latitudes. In general terms, an explosive eruption requires a greater intensity (magma discharge rate) to cross the tropopause in the tropics than at mid to polar latitudes. However, there are two factors that limit this effect. The first is that a high-latitude eruption will have a more limited effect than a low-latitude one because further from the tropics there is less solar energy to intercept. Secondly, atmospheric circulation works in a way to limit the effects of high latitude eruptions. A tropical eruption that pumps aerosol into the stratosphere results in localized heating. This increases the temperature difference in the middle atmosphere between the equator and high latitudes, and thereby enhances meridional air flows that spread aerosol into both hemispheres, promoting climate forcing at a worldwide scale. In contrast, volcanic aerosol injected into the stratosphere from high latitude volcanoes will tend to have the opposite effect on the temperature gradient, acting to stagnate meridional air flow. Very little, if any, of the stratospheric aerosol formed as a result of eruption of a high latitude volcano will reach the opposing hemisphere.

Interaction Between Glaciation and Volcanoes

Volcanoes do not only affect the climate, they are affected by the climate. During times of glaciation, volcanic processes slow down. Glacial growth is promoted when summer heat is weak and winter cold is enhanced and when glaciers grow larger, they get heavier. This excess weight causes a reverse effect on the magma chamber's ability to produce a volcano. Thermodynamically, magma will dissolve gases more readily when the confining pressure on the magma is greater than the vapor pressure of the dissolved components. Glacial buildup typically occurs at high elevations, which are also the home to most continental volcanoes. Buildup of ice can cause a magma chamber to fail and crystallize underground. The cause of magma chamber failure occurs when the pressure of ice pressing down on Earth is greater than the pressure being exerted on the magma chamber from heat convection in the mantle. Ice core data from glaciers provides insight into past climate. "Oxygen isotopes and the calcium ion record are essential indicators of climatic variability, while peaks in sulfate ions (SO_4) and in electrical conductivity of the ice indicate volcanic aerosol fallout." As seen in ice cores, volcanic eruptions in the tropics and southern hemisphere are not recorded in the Greenland Ice sheets. Fallout from tropical eruptions can be seen at both poles though this takes nearly two years and consists of only sulfuric precipitation. "One of the striking revelations of the ice core record is the evidence for numerous great eruptions, which have not otherwise been recognized in tephra records. One caveat to the approach is that although the dating of the ice core by counting of seasonal layers is fairly robust, it is not fail-safe. The greater the depth from which the core is retrieved, the more likely it is to have suffered deformation Prevailing winds and atmospheric chemistry play a large role in moving volcanic volatiles from their source to their final locations at the surface or in the atmosphere."

Cretaceous Climate

During the Cretaceous, Earth experienced an unusual warming trend. Two explanations for this warming are attributed to tectonic and magmatic forces. One of the theories is a magmatic super plume inducing a high level of CO_2 into the atmosphere. Carbon dioxide levels in the Cretaceous could have been as high as 3.7 to 14.7 times their present amounts today causing an average 2.8 to 7.7 degrees Celsius. Tectonically, movements of the plates and a sea level fall could cause an additional 4.8 degrees Celsius globally. The combined effect between magmatic and tectonic processes could have placed the Cretaceous Earth 7.6 to 12.5 degrees Celsius higher than today.

A second theory on the warm Cretaceous is the subduction of carbonate materials. By subducting carboniferous materials, a release of carbon dioxide would emit from volcanoes. During the Cretaceous, the Tethys Sea was rich in limestone deposits. By subducting this carboniferous platform, the resulting magma would have become more carbon dioxide rich. Because carbon dioxide dissolves into melts well, it would have remained dissolved until the confining pressure of the magma was low enough to de-gas and release massive quantities of carbon dioxide into the atmosphere causing warming.

Conclusion

Volcanoes represent powerful images and forces on Earth's landscape. Generation of a volcano depends on its location and magmatic origin. Magmas will remain a melt until pressure and temperature allow crystallization and outgassing. During outgassing, the magma chamber will rise and meet Earth's surface causing a volcano. Depending on the composition of the melted material, this volcano could contain a variety of gases. Most of the gases emitted via volcanic eruption are greenhouse gases and cause atmospheric alterations. These atmospheric alterations then force the climate, both regionally and locally, to reach a new equilibrium with the new atmosphere. These changes can reflect as cooling, warming, higher precipitation rates and many others.

REFLECTION QUESTIONS

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- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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5.14: Hot Spots

INTERPRET AND EXPLAIN HOT SPOTS AND HOW THEY RELATE TO PLATE MOTION

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Intraplate Activity
- Reading: Hot Spots

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5.15: Intraplate Activity

A small amount of geologic activity, known as **intraplate activity**, does not take place at plate boundaries but within a plate instead. Mantle plumes are pipes of hot rock that rise through the mantle. The release of pressure causes melting near the surface to form a **hotspot**. Eruptions at the hotspot create a volcano. Hotspot volcanoes are found in a line (figure 1). Can you figure out why? Hint: The youngest volcano sits above the hotspot and volcanoes become older with distance from the hotspot.

Here is an animation of the creation of a hotspot chain.

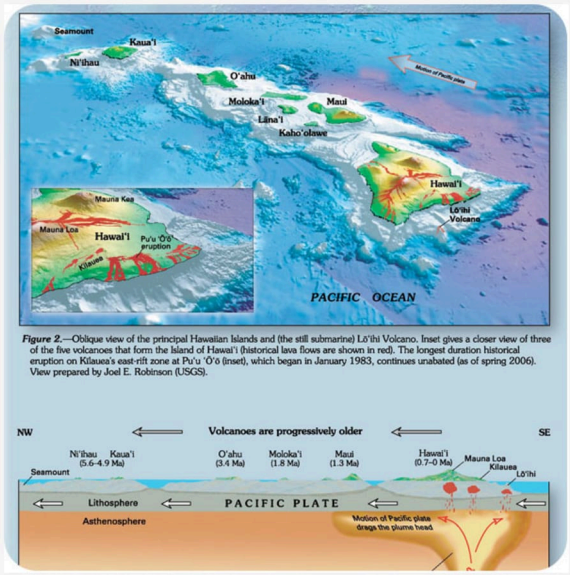


Figure 1. The Hawaiian Islands are a beautiful example of a hotspot chain. Kilauea volcano lies above the Hawaiian hotspot. Mauna Loa volcano is older than Kilauea and is still erupting, but at a lower rate. The islands get progressively older to the northwest because they are further from the hotspot. Loihi, the youngest volcano, is still below the sea surface.

Geologists use some hotspot chains to tell the direction and the speed a plate is moving (figure 2).

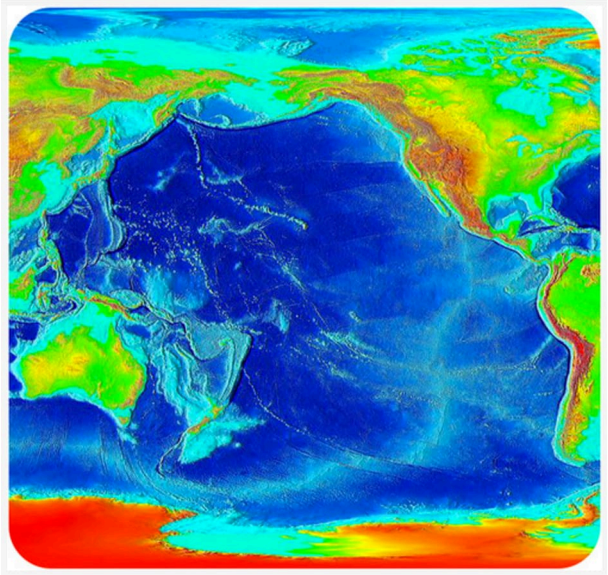


Figure 2. The Hawaiian chain continues into the Emperor Seamounts. The bend in the chain was caused by a change in the direction of the Pacific plate 43 million years ago. Using the age and distance of the bend, geologists can figure out the speed of the Pacific plate over the hotspot.

Hotspot magmas rarely penetrate through thick continental crust. One exception is the Yellowstone hotspot (figure 3).

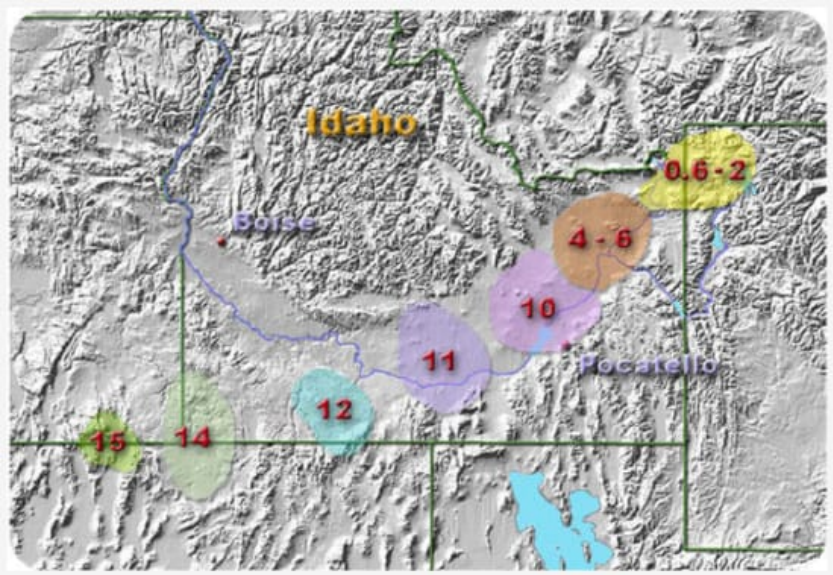


Figure 3. Volcanic activity above the Yellowstone hotspot on the North American Plate can be traced from 15 million years ago to its present location.

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5.16: Hot Spots

In geology, the places known as **hotspots** or **hot spots** are volcanic regions thought to be fed by underlying mantle that is anomalously hot compared with the surrounding mantle. They may be on, near to, or far from tectonic plate boundaries. Currently, there are two hypotheses that attempt to explain their origins. One suggests that they are due to hot mantle plumes that rise as thermal diapirs from the core-mantle boundary. An alternative hypothesis postulates that it is not high temperature that causes the volcanism, but lithospheric extension that permits the passive rising of melt from shallow depths. This hypothesis considers the term “hotspot” to be a misnomer, asserting that the mantle source beneath them is, in fact, not anomalously hot at all. Well known examples include Hawaii and Yellowstone.

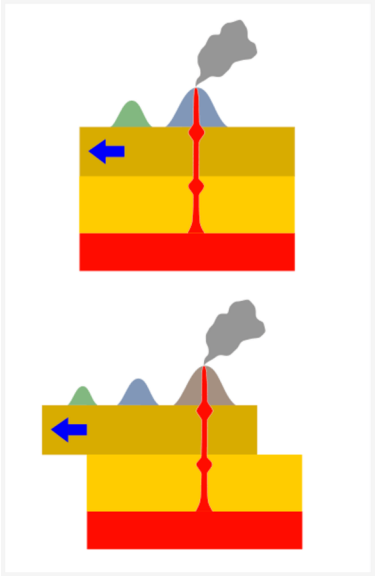


Figure 1. Diagram showing a cross section though the Earth’s lithosphere (in yellow) with magma rising from the mantle (in red)

BACKGROUND

The origins of the concept of hotspots lie in the work of J. Tuzo Wilson, who postulated in 1963 that the Hawaiian Islands result from the slow movement of a tectonic plate across a hot region beneath the surface. It was later postulated that hotspots are fed by narrow streams of hot mantle rising from the Earth’score-mantle boundary in a structure called amantle plume. Whether or not such mantle plumes exist is currently the subject of a major controversy in Earth science. Estimates for the number of hotspots postulated to be fed by mantle plumes has ranged from about 20 to several thousands, over the years, with most geologists considering a few tens to exist. Hawaii, Réunion, Yellowstone, Galápagos, and Iceland are some of the currently most active volcanic regions to which the hypothesis is applied.

Most hotspot volcanoes are basaltic (e.g., Hawaii, Tahiti). As a result, they are less explosive than subduction zone volcanoes, in which water is trapped under the overriding plate. Where hotspots occur in continental regions, basaltic magma rises through the continental crust, which melts to form rhyolites. These rhyolites can form violent eruptions. For example, the Yellowstone Caldera was formed by some of the most powerful volcanic explosions in geologic history. However, when the rhyolite is completely erupted, it may be followed by eruptions of basaltic magma rising through the same lithospheric fissures (cracks in the lithosphere). An example of this activity is the Ilgachuz Range in British Columbia, which was created by an early complex series of trachyte and rhyolite eruptions, and late extrusion of a sequence of basaltic lava flows.

The hotspot hypothesis is now closely linked to the mantle plume hypothesis.

Comparison with Island Arc Volcanoes

Hotspot volcanoes are considered to have a fundamentally different origin from island arc volcanoes. The latter form over

subduction zones, at converging plate boundaries. When one oceanic plate meets another, the denser plate is forced downward into a deep ocean trench. This plate, as it is subducted, releases water into the base of the over-riding plate, and this water mixes with the rock, thus changing its composition causing some rock to melt and rise. It is this that fuels a chain of volcanoes, such as the Aleutian Islands, near Alaska.

HOTSPOT VOLCANIC CHAINS

The joint mantle plume/hotspot hypothesis envisages the feeder structures to be fixed relative to one another, with the continents and seafloor drifting overhead. The hypothesis thus predicts that time-progressive chains of volcanoes are developed on the surface. Examples are Yellowstone, which lies at the end of a chain of extinct calderas, which become progressively older to the west. Another example is the Hawaiian archipelago, where islands become progressively older and more deeply eroded to the northwest.

Geologists have tried to use hotspot volcanic chains to track the movement of the Earth's tectonic plates. This effort has been vexed by the lack of very long chains, by the fact that many are not time-progressive (e.g. the Galápagos) and by the fact that hotspots do not appear to be fixed relative to one another (e.g., Hawaii and Iceland.)

Postulated Hotspot Volcano Chains

- Hawaiian-Emperor seamount chain (Hawaii hotspot)
- Louisville seamount chain (Louisville hotspot)
- Walvis Ridge (Gough and Tristan hotspot)
- Kodiak–Bowie Seamount chain (Bowie hotspot)
- Cobb-Eickelberg Seamount chain (Cobb hotspot)
- New England Seamount chain (New England hotspot)
- Anahim Volcanic Belt (Anahim hotspot)
- Mackenzie dike swarm (Mackenzie hotspot)
- Great Meteor hotspot track (New England hotspot)
- St. Helena Seamount Chain – Cameroon Volcanic Line (Saint Helena hotspot)
- Southern Mascarene Plateau–Chagos-Maldives-Laccadive Ridge (Réunion hotspot)
- Ninety East Ridge (Kerguelen hotspot)
- Tuamotu–Line Island chain (Easter hotspot)
- Austral–Gilbert–Marshall chain (Macdonald hotspot)
- Juan Fernández Ridge (Juan Fernández hotspot)



Figure 2. Kilauea is the most active shield volcano in the world. The volcano has erupted nonstop since 1983 and it is part of the Hawaiian-Emperor seamount chain.

List of Volcanic Regions Postulated to be Hotspots

Eurasian Plate

- Eifel hotspot
- Iceland hotspot
- Azores hotspot
- Jan Mayen hotspot
- Hainan hotspot

African Plate

- Mount Etna
- Hoggar hotspot
- Tibesti hotspot
- Jebel Marra/Darfur hotspot
- Afar hotspot
- Cameroon hotspot
- Madeira hotspot
- Canary hotspot
- New England/Great Meteor hotspot
- Cape Verde hotspot
- St. Helena hotspot
- Gough hotspot
- Tristan hotspot
- Vema hotspot (Vema Seamount)
- Discovery hotspot (Discovery Seamounts)
- Bouvet hotspot
- Shona/Meteor hotspot
- Réunion hotspot
- Comoros hotspot

Antartic Plate

- Marion hotspot
- Crozet hotspot
- Kerguelen hotspot
- Heard hotspot
- Balleny hotspot
- Erebus hotspot

South American Plate

- Trindade/Martin Vaz hotspot
- Fernando hotspot
- Ascension hotspot

North American Plate

- Bermuda hotspot
- Yellowstone hotspot
- Raton hotspot
- Anahim hotspot

Indo-Australian Plate

- Lord Howe hotspot
- Tasmanid hotspot (Gascoyne Seamount)
- East Australia hotspot

Nazca Plate

- Juan Fernández hotspot
- San Felix hotspot
- Easter hotspot
- Galápagos hotspot

Pacific Plate

- Louisville hotspot
- Foundation hotspot
- Macdonald hotspot
- North Austral/President Thiers (President Thiers Bank)
- Arago hotspot (Arago Seamount)
- Maria/Southern Cook hotspot (Îles Maria)
- Samoa hotspot
- Crough hotspot (Crough Seamount)
- Pitcairn hotspot
- Society/Tahiti hotspo
- Marquesas hotspot
- Caroline hotspot
- Hawaii hotspot
- Socorro/Revillagigedos hotspot
- Guadalupe hotspot
- Cobb hotspot
- Bowie/Pratt-Welker hotspot

FORMER HOTSPOTS

- Euterpe/Musicians hotspot (Musicians Seamounts)
- Mackenzie hotspot
- Matachewan hotspot

REFLECTION QUESTIONS

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5.17: Putting It Together

SUMMARY

In this section, you learned the following:

1. The different types of plate boundaries
2. What type of motion is associated with each boundary
3. The mechanisms that cause the plate movements
4. The geologic features associated with each boundary
5. What evidence supported Continental Drift
6. Why certain areas are prone to mountain building, earthquakes and volcanoes
7. The different types of deformation caused by plate tectonics
8. What hotspots are and how they can create new land

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6: EARTH'S INTERIOR

Geologists cannot see directly into the interior of the Earth. They have to rely on various techniques and methods to infer the appearance and physical characteristics of earth's interior. In this section, we will see how the Earth is structured, what the physical characteristics are, and just how this impacts us living on the Earth. The Earth's interior is the basis for geology. If you recall from the Plate Tectonics section, earth exists as we see it today because of plate tectonics. We also learned how plate tectonics is important in the formation of rock, mountains, volcanoes and earthquakes. Studying the interior of the Earth helps learn about all of these and the processes that helped create the Earth and currently drive plate tectonics.



- Topic hierarchy

6.1: Why It Matters

6.2: The Geosphere

6.3: Inside the Earth

6.4: Inside the Earth

6.5: Beyond Simple Layers

6.6: The Interior of the Earth

6.7: Putting It Together

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6.1: Why It Matters

DESCRIBE EARTH INCLUDING THE CHARACTERISTICS OF THE VARIOUS LAYERS; LEARN THE IMPLICATION OF THE DIFFERENT LAYERS

Introduction

Geologists cannot see directly into the interior of the Earth. They have to rely on various techniques and methods to infer the appearance and physical characteristics of earth's interior. In this section, we will see how the Earth is structured, what the physical characteristics are, and just how this impacts us living on the Earth.

The Earth's interior is the basis for geology. If you recall from the Plate Tectonics section, earth exists as we see it today because of plate tectonics. We also learned how plate tectonics is important in the formation of rock, mountains, volcanoes and earthquakes. Studying the interior of the Earth helps learn about all of these and the processes that helped create the Earth and currently drive plate tectonics.

Please watch this short video and take a trip through the various layers of the Earth down to its core:

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Learning Outcomes

- Analyze and compare properties, material, and layers within the Earth's geosphere
- Use a current working model of the planet's interior to describe the Earth's interior and its magnetism

Ok, let's get started! [Or insert another appropriate transition statement here.]

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6.2: The Geosphere

ANALYZE AND COMPARE PROPERTIES, MATERIAL, AND LAYERS WITHIN THE EARTH'S GEOSPHERE

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Inside the Earth

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6.3: Inside the Earth

Before you can learn about plate tectonics, you need to know something about the layers that are found inside Earth. These layers are divided by composition into core, mantle, and crust or by mechanical properties into lithosphere and asthenosphere. Scientists use information from earthquakes and computer modeling to learn about Earth's interior.

EXPLORING EARTH'S INTERIOR

How do scientists know what is inside the Earth? We don't have direct evidence! Rocks yield some clues, but they only reveal information about the outer crust. In rare instances, a mineral, such as a diamond, comes to the surface from deeper down in the crust or the mantle. To learn about Earth's interior, scientists use energy to "see" the different layers of the Earth, just like doctors can use an MRI, CT scan, or x-ray to see inside our bodies.

SEISMIC WAVES

One ingenious way scientists learn about Earth's interior is by looking at how energy travels from the point of an earthquake. These are **seismic waves** (figure 1). Seismic waves travel outward in all directions from where the ground breaks at an earthquake. These waves are picked up by seismographs around the world. Two types of seismic waves are most useful for learning about Earth's interior.

- P-waves (primary waves) are fastest, traveling at about 6 to 7 kilometers (about 4 miles) per second, so they arrive first at the seismometer. P-waves move in a compression/expansion type motion, squeezing and unsqueezing earth materials as they travel. This produces a change in volume for the material. P-waves bend slightly when they travel from one layer into another. Seismic waves move faster through denser or more rigid material. As P-waves encounter the liquid outer core, which is less rigid than the mantle, they slow down. This makes the P-waves arrive later and further away than would be expected. The result is a P-wave shadow zone. No P-waves are picked up at seismographs 104° to 140° from the earthquakes focus.

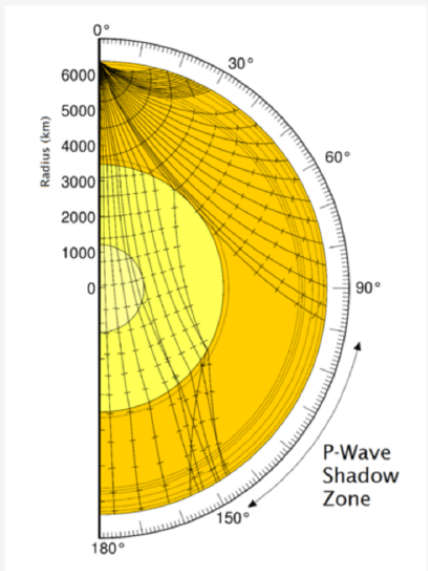


Figure 1. How P-waves travel through Earth's interior.

- S-waves (secondary waves) are about half as fast as P-waves, traveling at about 3.5 km (2 miles) per second, and arrive second at seismographs. S-waves move in an up and down motion perpendicular to the direction of wave travel. This produces a change in shape for the earth materials they move through. Only solids resist a change in shape, so S-waves are only able to propagate through solids. S-waves cannot travel through liquid.

By tracking seismic waves, scientists have learned what makes up the planet's interior (figure 2).

- P-waves slow down at the mantle core boundary, so we know the outer core is less rigid than the mantle.
- S-waves disappear at the mantle core boundary, so the outer core is liquid.

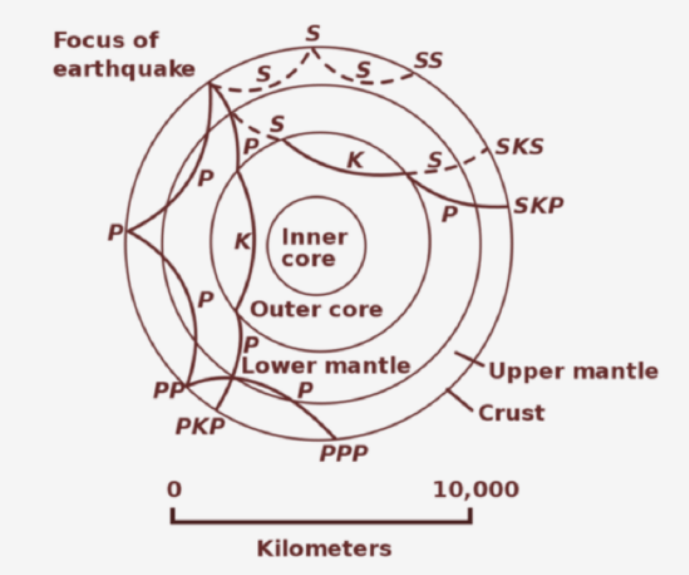


Figure 2. Letters describe the path of an individual P-wave or S-wave. Waves traveling through the core take on the letter K.

This animation shows a seismic wave shadow zone.

Other Clues About Earth's Interior

1. Earth's overall density is higher than the density of crustal rocks, so the core must be made of something dense, like metal.
2. Since Earth has a magnetic field, there must be metal within the planet. Iron and nickel are both magnetic.
3. Meteorites are the remains of the material that formed the early solar system and are thought to be similar to material in Earth's interior (figure 3).



Figure 3. This meteorite contains silica minerals and iron-nickel. The material is like the boundary between Earth's core and mantle.

THE EARTH'S LAYERS

The layers scientists recognize are pictured in figure 4.

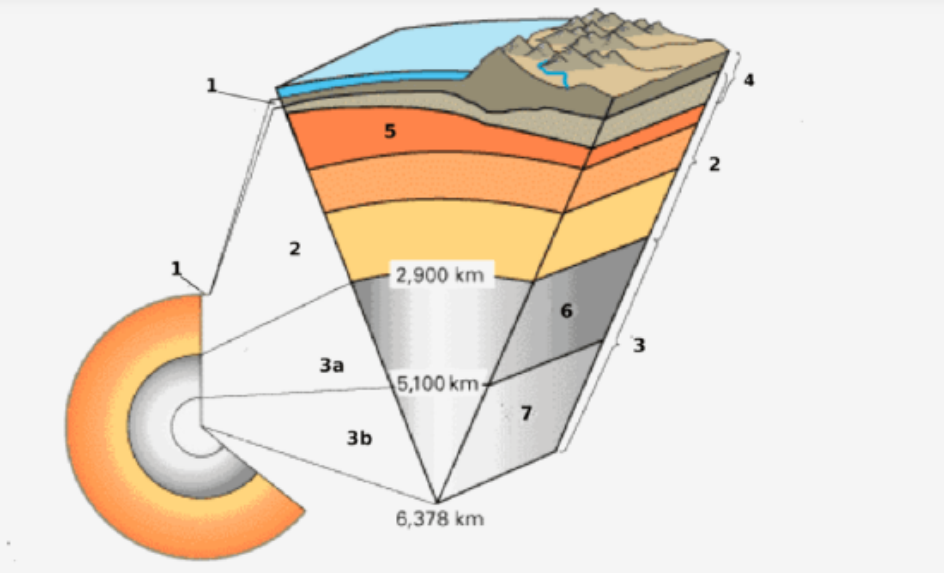


Figure 4. A cross section of Earth showing the following layers: (1) crust (2) mantle (3a) outer core (3b) inner core (4) lithosphere (5) asthenosphere (6) outer core (7) inner core.

Core, mantle, and crust are divisions based on composition:

1. The **crust** is less than 1% of Earth by mass. The **oceanic crust** is mafic, while**continental crust** is often more felsic rock.
2. The **mantle** is hot, ultramafic rock. It represents about 68% of Earth's mass.
3. The **core** is mostly iron metal. The core makes up about 31% of the Earth.

Lithosphere and asthenosphere are divisions based on mechanical properties:

1. The lithosphere is composed of both the crust and the portion of the upper mantle that behaves as a brittle, rigid solid.
2. The asthenosphere is partially molten upper mantle material that behaves plastically and can flow.

This animation shows the layers by composition and by mechanical properties.

Crust and Lithosphere

Earth's outer surface is its crust; a cold, thin, brittle outer shell made of rock. The crust is very thin, relative to the radius of the planet. There are two very different types of crust, each with its own distinctive physical and chemical properties, which are summarized in table 1.

Table 1.

Crust	Thickness	Density	Composition	Rock types
Oceanic	5-12 km (3-8 mi)	3.0 g/cm^3	Mafic	Basalt and gabbro
Continental	Avg. 35 km (22 mi)	2.7 g/cm^3	Felsic	All types

Oceanic crust is composed of mafic magma that erupts on the seafloor to create basalt lava flows or cools deeper down to create the intrusive igneous rock gabbro (figure 5).



Figure 5. Gabbro

Sediments, primarily muds and the shells of tiny sea creatures, coat the seafloor. Sediment is thickest near the shore where it comes off the continents in rivers and on wind currents.

Continental crust is made up of many different types of igneous, metamorphic, and sedimentary rocks. The average composition is granite, which is much less dense than the mafic rocks of the oceanic crust (figure 6). Because it is thick and has relatively low density, continental crust rises higher on the mantle than oceanic crust, which sinks into the mantle to form basins. When filled with water, these basins form the planet's oceans.



Figure 6. This granite from Missouri is more than 1 billion years old.

The **lithosphere** is the outermost mechanical layer, which behaves as a brittle, rigid solid. The lithosphere is about 100 kilometers thick. Look at figure 4. Can you find where the crust and the lithosphere are located? How are they different from each other?

The definition of the lithosphere is based on how earth materials behave, so it includes the crust and the uppermost mantle, which are both brittle. Since it is rigid and brittle, when stresses act on the lithosphere, it breaks. This is what we experience as an earthquake.

Mantle

The two most important things about the mantle are: (1) it is made of solid rock, and (2) it is hot. Scientists know that the mantle is made of rock based on evidence from seismic waves, heat flow, and meteorites.

The properties fit the ultramafic rock peridotite, which is made of the iron- and magnesium-rich silicate minerals (figure 7). Peridotite is rarely found at Earth's surface.



Figure 7. Peridotite is formed of crystals of olivine (green) and pyroxene (black).

Scientists know that the mantle is extremely hot because of the heat flowing outward from it and because of its physical properties.

Heat flows in two different ways within the Earth:

1. **Conduction:** Heat is transferred through rapid collisions of atoms, which can only happen if the material is solid. Heat flows from warmer to cooler places until all are the same temperature. The mantle is hot mostly because of heat conducted from the core.
2. **Convection:** If a material is able to move, even if it moves very slowly, convection currents can form.

Convection in the mantle is the same as convection in a pot of water on a stove. Convection currents within Earth's mantle form as material near the core heats up. As the core heats the bottom layer of mantle material, particles move more rapidly, decreasing its density and causing it to rise. The rising material begins the convection current. When the warm material reaches the surface, it spreads horizontally. The material cools because it is no longer near the core. It eventually becomes cool and dense enough to sink back down into the mantle. At the bottom of the mantle, the material travels horizontally and is heated by the core. It reaches the location where warm mantle material rises, and the mantle **convection cell** is complete (figure 8).

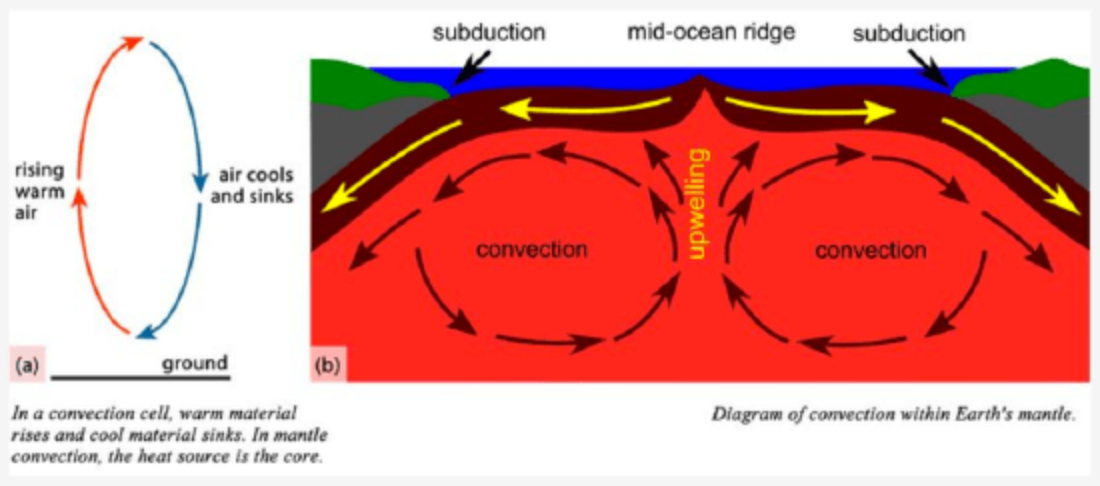


Figure 8. Convections

Core

At the planet's center lies a dense metallic core. Scientists know that the core is metal because:

1. The density of Earth's surface layers is much less than the overall density of the planet, as calculated from the planet's rotation. If the surface layers are less dense than average, then the interior must be denser than average. Calculations indicate that the core is about 85% iron metal with nickel metal making up much of the remaining 15%.
2. Metallic meteorites are thought to be representative of the core. The 85% iron/15% nickel calculation above is also seen in metallic meteorites (figure 9).



Figure 9. An iron meteorite is the closest thing to the Earth's core that we can hold in our hands.

If Earth's core were not metal, the planet would not have a magnetic field. Metals such as iron are magnetic, but rock, which makes up the mantle and crust, is not.

Scientists know that the outer core is liquid and the inner core is solid because:

1. S-waves stop at the inner core.
2. The strong magnetic field is caused by convection in the liquid outer core. Convection currents in the outer core are due to heat from the even hotter inner core.

The heat that keeps the outer core from solidifying is produced by the breakdown of radioactive elements in the inner core.

LESSON SUMMARY

- 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 causes mantle convection.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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6.4: Inside the Earth

USE A CURRENT WORKING MODEL OF THE PLANET'S INTERIOR TO DESCRIBE THE EARTH'S INTERIOR AND ITS MAGNETISM

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Beyond Simple Layers
- Reading: The Interior of the Earth

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6.5: Beyond Simple Layers

The following table summarizes the physical layers of the earth.

Lithosphere	Asthenosphere	Upper Mesosphere	Lower Mesosphere	Outer Core	Inner Core
physical behavior: rigid, brittle at shallow depths	*physical behavior:* ductile	*physical behavior:* rigid, not brittle, rapid increase in density with depth	*physical behavior:* denser and more rigid than upper mesosphere	*physical behavior:* liquid	*physical behavior:* rigid, not brittle
thickness: 5 to 200 km	*thickness:* 100 to 300 km	*thickness:* 300 to 400 km	*thickness:* 2,300 km	*thickness:* 2,300 km	*thickness:* 1,200 km

EARTH'S MAGNETIC FIELD ORIGINATES IN THE CORE

The liquid outer core is the source of the earth's magnetic field, as a result of its metallic nature, which means it contains electrons not attached to particular nuclei. Heat is transferred upward to the mantle from the inner core via convective cells, in which the liquid in the outer core flows in looping patterns. The combination of the loose electrons and looping convective flow with the rotation of the earth results in a geodynamo that produces a magnetic field. Because the magnetic field is generated by a dynamically convecting and rotating sphere of liquid, it is unstable. Every now and then, after several hundred thousand to several million years, the earth's magnetic field becomes unstable to the point that it temporarily shuts down. When it restarts, its north and south magnetic poles must inevitably be reversed, according to the physics of magnetic fields produced spontaneously from geodyamos. (For comparison, the magnetic field of the Sun, which is also produces by convecting electrical charges in a rotating sphere, becomes magnetically unstable and reverses its magnetic field on a more regular basis, every 11 years.)

Given that the inner core is a solid metallic sphere, made mostly of iron and nickel, surrounded entirely by liquid, it can be pictured as a giant ball bearing spinning in a pressurized fluid. Detailed studies of earthquake waves passing though the inner core have found evidence that it is spinning – rotating – just slightly faster than the rest of the earth.

BEYOND SIMPLE LAYERS

The interior of the earth is not simply layered. Some of the layers, particularly the crust and lithosphere, are highly variable in thickness. The boundaries between layers are rough and irregular. Some layers penetrate other layers at certain places. Variations in the thickness of the earth's layers, irregularities in layer boundaries, and interpenetrations of layers, reflect the dynamic nature of the earth.

For example, the lithosphere penetrates deep into the mesosphere at subduction zones. Although it is still a matter of research and debate, there is some evidence that subducted plates may penetrate all the way into the lower mesosphere. If so, plate tectonics is causing extensive mixing and exchange of matter in the earth, from the bottom of the mantle to the top of the crust.

As another example, hot spots may be places where gases and fluids rise from the core-mantle boundary, along with heat. Studies of helium isotopes in hot spot volcanic rocks find evidence that much of the helium comes from deep in the earth, probably from the lower mesosphere.

HOW DO WE KNOW?

We humans have no hands-on access to samples of the earth's interior from deeper than the upper mantle. The earth's core is so dense and so deep, it is completely inaccessible. Contrary to a popular misconception, lava does not come from the earth's core. Magma and lava come from only the lithosphere and asthenosphere, the upper 200 km of earth's 6,400 km thickness. Attempts have been made to drill through the crust to reach the mantle, without success. Given the lack of actual pieces of the earth from deeper than the asthenosphere, how do we know about the internal layers of the earth, what they are made of, and what their

properties and processes are?

Igneous Rocks and Fault Blocks

There are two sources of rock samples from the lower lithosphere and asthenosphere, igneous rocks and fault blocks. Some igneous rocks contain xenoliths, pieces of solid rock that were adjacent to the body of magma, became incorporated into the magma, and were carried upward in the magma. From xenoliths in plutonic and volcanic igneous rocks, many samples of the lower crust and upper mantle have been identified and studied.

Another source of pieces of the lower crust and upper mantle is fault zones and exposed orogenic zones (root zones of mountains that have been exposed after much uplift and erosion). Some slabs of thrust-faulted rock contain lithospheric mantle rock. In ophiolites, ultramafic rock from the mantle part of the lithosphere is a defining attribute. Most ophiolites and thrust-faulted slices of rock that contain pieces of the upper mantle are related to either subduction zones or transform plate boundaries.

Seismic Waves

P-waves and S-waves move through different parts of the earth's interior in different ways. Analogous to how you can see what is in the room around you by interpreting the light that your eyes receive, light that has interacted with the things in the room around you to give it its characteristics, seismologists can interpret recordings of seismic waves to "see" inside the earth. Such imaging of the earth's interior is based on how the different layers of the earth have affected the seismic waves in different ways.

Where seismic waves speed up or slow down, they refract, changing the direction in which they are traveling. Where seismic waves encounter an abrupt boundary between two very different layers, some of the seismic wave energy is reflected, bouncing back at the same angle it struck. The reflections and refractions of seismic waves allow the layers and boundaries within the earth to be located and studied.

Here are some examples of what we have been able to distinguish in the earth's interior from the study of seismic waves and how they travel through the layers of the earth:

1. The thickness of the crust. This is a measure of the thickness of the crust based on the abrupt increase in speed of seismic waves that occurs when they enter the mantle. The boundary between the crust and mantle, as inferred from the change in the speed of P- and S-waves, is called the Mohorovicic discontinuity, named after the Croatian seismologist who first discerned it; usually it is referred to simply as the Moho. It is mainly from seismic waves that we know how thin oceanic crust is and how thick continental crust is.
2. The thickness of the lithosphere. Where seismic waves pass down from the lithosphere into the asthenosphere, they slow down. This is because of the lower rigidity and compressibility of the rocks in the layer below the lithosphere. The zone below the lithosphere where seismic waves travel more slowly is called the low velocity zone. The low velocity zone is probably coincident with the asthenosphere.
3. The boundary between the upper and lower mesosphere (upper and lower mantle). This shows up as an increase in seismic wave speed at a depth of 660 km.
4. The boundary between the mantle and the core. This is marked by S-waves coming to an abrupt stop, presumably because the outer core is liquid, and a sudden large reduction in the speed of P-waves, as they enter the liquid core where there is no rigidity to contribute to P-wave speed.
5. The inner core. This was first recognized by refraction of P-waves passing through this part of the core, due to an abrupt increase in their speed, which was not shown by P-waves traveling through only the outer part of the core.
6. Seismic tomography: imaging slabs and masses at various orientations in the earth, not just in layers. By combining data from many seismometers, three-dimensional images of zones in the earth that have higher or lower seismic wave speeds can be constructed. Seismic tomography shows that in some places there are masses of what may be subducted plates that have penetrated below the asthenosphere into the mesosphere and, in some cases, penetrated into the lower mesosphere, the deepest part of the mantle. In other places, subducted plates appear to have piled up at the base of the upper mesosphere without penetrating into the lower mesosphere.

Gravity

Isaac Newton was the first to calculate the total mass of the earth. This gives us an important constraint on what the earth is made of, because, by dividing the mass of the earth by the volume of the earth, we know the average density of the earth. Whatever the earth is made of, it must add up to the correct amount of mass. Gravity measurements, and the earth's mass, tell us that the

interior of the earth must be denser than the crust, because the average density of earth is much higher than the density of the crust.

Because different parts of the crust, mantle, and core have different thicknesses and densities, the strength of gravity over particular points on earth varies slightly. These variations from the average strength of earth's gravity are called gravity anomalies. Mapping and analyzing gravity anomalies, in some cases by using satellites, and also be measuring the effect of gravity anomalies on the surface shape of the ocean, has given us much insight into subduction zones, mid-ocean spreading ridges, and mountain ranges, including constraints on the depths of their roots.

Moment of Inertia

The earth's gravity tells us how much total mass the earth has, but does not tell us how the mass is distributed within the earth. A property known as moment of inertia, which is the resistance (inertia) of an object to changes in its spin (rotation), is determined by exactly how matter is distributed in a spinning object, from its core to its surface. The earth's moment of inertia is measured by its effect on other objects with which it interacts gravitationally, including the Moon, and satellites. Knowing the earth's moment of inertia provides a way of checking and refining our understanding of the mass and density of each of the earth's internal layers.

Meteorites

Studies of meteorites, which are pieces of asteroids that have landed on earth, along with astronomical studies of what the Sun, the other planets, and orbiting asteroids are made of, give us a model for the general chemical composition of objects in the inner solar system, which are made mainly of elements that form rocks and metals, as opposed to the outer planets such as Jupiter, which are made mostly of light, gas-forming elements. The general compositional model of the rocky and metallic part of the solar system has much higher percentages of iron, nickel, and magnesium than is found in the earth's crust.

If the earth's mantle is made of ultramafic rock, as is found in actual samples of the upper mantle in xenoliths and ophiolites, that would account for part of the missing iron, nickel, and magnesium. But much more iron and nickel would still be missing. If the core is made mostly of iron, and abundant nickel as well, it would give the earth an overall composition similar to the composition of other objects in the inner solar system, and similar to the proportions of rock and metal-forming elements measured in the Sun.

A mantle with an ultramafic composition, and a core made mostly of iron plus nickel, would make earth's composition match the composition of the rest of the solar system, and give those layers the right densities to account for the earth's moment of inertia and total mass.

Experiments

Geology, like other sciences, is based on experiment along with observation and theory. earth scientists and physicists have developed experimental methods to study how materials behave at the pressures and temperatures of the earth's interior, including core temperatures and pressures. They can measure such properties as the density, the state of matter (liquid or solid), the rigidity, the compressibility, and the speed at which seismic waves pass through these materials at high pressures and temperatures. These studies allow further refinement of our knowledge of what the interior of the earth is made of and how it behaves. These experiments support the theory that the mantle is ultramafic and the core is mostly iron and nickel, because they show that materials with those compositions have the same density and seismic wave speeds as have been observed in the earth.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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6.6: The Interior of the Earth

INTRODUCTION

Three centuries ago, the English scientist Isaac Newton calculated, from his studies of planets and the force of gravity, that the average density of the Earth is twice that of surface rocks and therefore that the Earth's interior must be composed of much denser material. Our knowledge of what's inside the Earth has improved immensely since Newton's time, but his estimate of the density remains essentially unchanged. Our current information comes from studies of the paths and characteristics of earthquake waves travelling through the Earth, as well as from laboratory experiments on surface minerals and rocks at high pressure and temperature. Other important data on the Earth's interior come from geological observation of surface rocks and studies of the Earth's motions in the Solar System, its gravity and magnetic fields, and the flow of heat from inside the Earth.The planet Earth is made up of three main shells: the very thin, brittle crust, the mantle, and the core; the mantle and core are each divided into two parts. All parts are drawn to scale on the cover of this publication, and a table at the end lists the thicknesses of the parts. Although the core and mantle are about equal in thickness, the core actually forms only 15 percent of the Earth's volume, whereas the mantle occupies 84 percent. The crust makes up the remaining 1 percent. Our knowledge of the layering and chemical composition of the Earth is steadily being improved by earth scientists doing laboratory experiments on rocks at high pressure and analyzing earthquake records on computers.

THE CRUST

Because the crust is accessible to us, its geology has been extensively studied, and therefore much more information is known about its structure and composition than about the structure and composition of the mantle and core. Within the crust, intricate patterns are created when rocks are redistributed and deposited in layers through the geologic processes of eruption and intrusion of lava, erosion, and consolidation of rock particles, and solidification and recrystallization of porous rock.

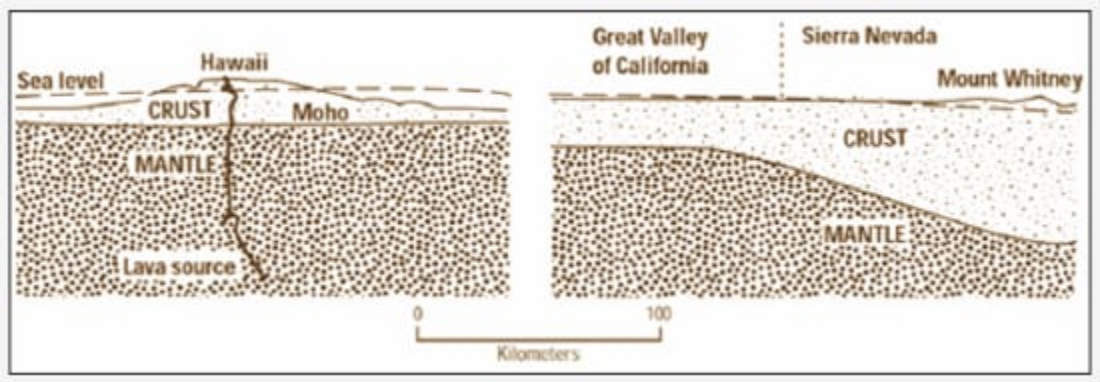


Figure 1. The oceanic crust at the island of Hawaii is about 5 kilometers thick. The thickness of the continental crust under eastern California ranges from 25 kilometers under the Great Valley to 60 kilometers under the Sierra Nevada.

By the large-scale process of plate tectonics, about twelve plates, which contain combinations of continents and ocean basins, have moved around on the Earth's surface through much of geologic time. The edges of the plates are marked by concentrations of earthquakes and volcanoes. Collisions of plates can produce mountains like the Himalayas, the tallest range in the world. The plates include the crust and part of the upper mantle, and they move over a hot, yielding upper mantle zone at very slow rates of a few centimeters per year, slower than the rate at which fingernails grow. The crust is much thinner under the oceans than under continents (see figure above).

The boundary between the crust and mantle is called the Mohorovicic discontinuity (or Moho); it is named in honor of the man who discovered it, the Croatian scientist Andrija Mohorovicic. No one has ever seen this boundary, but it can be detected by a sharp increase downward in the speed of earthquake waves there. The explanation for the increase at the Moho is presumed to be a change in rock types. Drill holes to penetrate the Moho have been proposed, and a Soviet hole on the Kola Peninsula has been drilled to a depth of 12 kilometers, but drilling expense increases enormously with depth, and Moho penetration is not likely very soon.

THE MANTLE

Our knowledge of the upper mantle, including the tectonic plates, is derived from analyses of earthquake waves (see figure for paths); heat flow, magnetic, and gravity studies; and laboratory experiments on rocks and minerals. Between 100 and 200 kilometers below the Earth's surface, the temperature of the rock is near the melting point; molten rock erupted by some volcanoes originates in this region of the mantle. This zone of extremely yielding rock has a slightly lower velocity of earthquake waves and is presumed to be the layer on which the tectonic plates ride. Below this low-velocity zone is a transition zone in the upper mantle; it contains two discontinuities caused by changes from less dense to more dense minerals. The chemical composition and crystal forms of these minerals have been identified by laboratory experiments at high pressure and temperature. The lower mantle, below the transition zone, is made up of relatively simple iron and magnesium silicate minerals, which change gradually with depth to very dense forms. Going from mantle to core, there is a marked decrease (about 30 percent) in earthquake wave velocity and a marked increase (about 30 percent) in density.

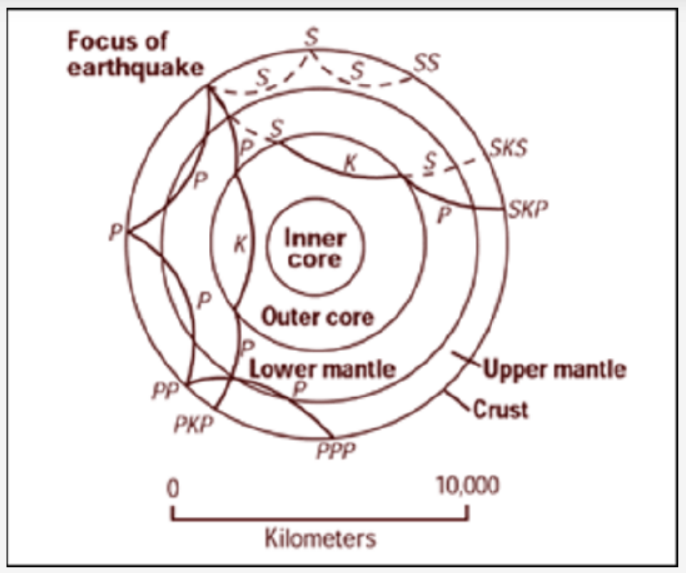


Figure 2. Cross section of the whole Earth, showing the complexity of paths of earthquake waves. The paths curve because the different rock types found at different depths change the speed at which the waves travel. Solid lines marked P are compressional waves; dashed lines marked S are shear waves. S waves do not travel through the core but may be converted to compressional waves (marked K) on entering the core (PKP, SKS). Waves may be reflected at the surface (PP, PPP, SS).

The core was the first internal structural element to be identified. It was discovered in 1906 by R.D. Oldham, from his study of earthquake records, and it helped to explain Newton's calculation of the Earth's density. The outer core is presumed to be liquid because it does not transmit shear (S) waves and because the velocity of compressional (P) waves that pass through it is sharply reduced. The inner core is considered to be solid because of the behavior of P and S waves passing through it.

Data from earthquake waves, rotations and inertia of the whole Earth, magnetic-field dynamo theory, and laboratory experiments on melting and alloying of iron all contribute to the identification of the composition of the inner and outer core. The core is presumed to be composed principally of iron, with about 10 percent alloy of oxygen or sulfur or nickel, or perhaps some combination of these three elements.

This table of depths, densities, and composition is derived mostly from information in a textbook by Don L. Anderson. Scientists are continuing to refine the chemical and mineral composition of the Earth's interior by laboratory experiments, by using pressures 2 million times the pressure of the atmosphere at the surface and temperatures as high as 20000C.

Table 1. Data on the Earth's Interior

	Thickness (km)	Density (g/cm)		Types of Rock Found
		Top	Bottom	
Crust	30	2.2	2.9	Silicic rocks. Andesite, basalt at base.
Upper mantle	720	3.4	4.4	Peridotite, eclogite, olivine, spinel, garnet, pyroxene. Perovskite, oxides

Table 1. Data on the Earth's Interior				
Lower mantle	2,171	4.4	5.6	Magnesium and silicon oxides.
Outer core	2,259	9.9	12.1	Iron + oxygen, sulfur, nickel alloy.
Inner Core	1,221	12.8	13.1	Iron + oxygen, sulfur, nickel alloy.
Total Thickness	**6,401**			

THE STRUCTURE OF THE MOON

The Moon, our fellow-traveler in space, has a diameter half that of the Earth's core, and it revolves around the Earth, as all the planets revolve around the Sun, under the force of gravity. Moonquakes of very low energy are caused by land tides produced by the pull of Earth's gravity, and, from analysis of moonquake data, scientists believe the Moon has two layers: a crust, from the surface to 65 kilometers depth, and an inner, more dense mantle from the crust to the center at 3,700 kilometers. The crust is presumed to be com- posed primarily of rocks containing feldspar, calcium aluminum silicate, and lesser pyroxene, iron and magnesium silicate; the crust also contains basalt in the mares, which contains less iron and more titanium than earth basalt. The mantle is thought to be made up of calcic peridotite, containing both pyroxene and feldspar.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
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6.7: Putting It Together

SUMMARY

You should now have a better understanding of just important the study of the Earth's interior is and the impact it has on various aspects of our lives. In particular, we have looked at these items:

1. The various layers of the Earth including where they are, what they are made of and how they behave physically
2. How geologists use indirect methods to study earth's interior
3. Earth's magnetic field including how it is generated and why it's important
4. The influence the interior has on plate tectonics

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7: CRUSTAL DEFORMATION

Understanding crustal deformation helps explain the forces necessary to bend and fold rocks like those shown above which help create mountains. This section will discuss the types of forces needed to accomplish such a powerful feat. Have you ever wondered how strong those forces would have to be? The answer to that is beyond our comprehension.

7.1: Why It Matters

7.2: Stress and Strain

7.3: Stress in Earth's Crust

7.4: Forces of Plate and Fault Motion

7.5: Stress and Strain

7.6: Common Folds and Faults

7.7: Geologic Structures

7.8: Putting It Together

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7.1: Why It Matters

CORRELATE STRUCTURAL GEOLOGY AS IT PERTAINS TO CRUSTAL DEFORMATION

Understanding crustal deformation helps explain the forces necessary to bend and fold rocks like those shown above which help create mountains. This section will discuss the types of forces needed to accomplish such a powerful feat. Have you ever wondered how strong those forces would have to be? The answer to that is beyond our comprehension.



Figure 1. Chevron folds with flat-lying axial planes, Millook Haven, North Cornwall, UK

Along with these forces, we will investigate various types of folds as well as different types of faults. If you recall from the plate tectonics sections, earthquakes occur along active fault lines. This section helps us better understand how faults work.

Learning Outcomes

- Compare and contrast stress versus strain in the Earth's crust
- Explain how forces of tension, compression, and shear relate to plate and fault motion
- Interpret and model common fold and fault types

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7.2: Stress and Strain

COMPARE AND CONTRAST STRESS VERSUS STRAIN IN THE EARTH'S CRUST

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Stress in Earth's Crust

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7.3: Stress in Earth's Crust

INTRODUCTION

Enormous slabs of lithosphere move unevenly over the planet's spherical surface, resulting in earthquakes. This chapter deals with two types of geological activity that occur because of plate tectonics: mountain building and earthquakes. First, we will consider what can happen to rocks when they are exposed 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. Four types of stresses act on materials.

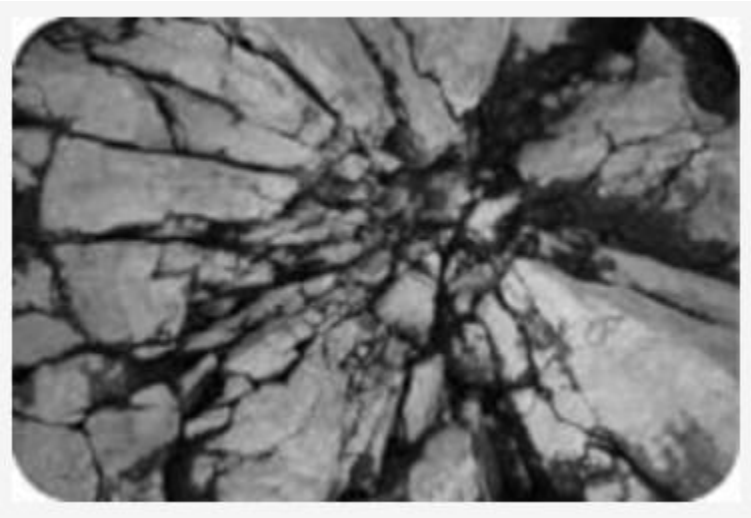


Figure 1. Stress caused these rocks to fracture.

- A deeply buried rock is pushed down by the weight of all the material above it. Since the rock cannot move, it cannot deform. This is called **confining stress.**
- **Compression** squeezes rocks together, causing rocks to fold or fracture (break) (figure 1). Compression is the most common stress at convergent plate boundaries.
- Rocks that are pulled apart are under **tension**. Rocks under tension lengthen or break apart. Tension is the major type of stress at divergent plate boundaries.
- When forces are parallel but moving in opposite directions, the stress is called **shear** (figure 2). Shear stress is the most common stress at transform plate boundaries.

When stress causes a material to change shape, it has undergone **strain** or**deformation.** Deformed rocks are common in geologically active areas.



Figure 2. Shearing in rocks. The white quartz vein has been elongated by shear.

A rock's response to stress depends on the rock type, the surrounding temperature, and pressure conditions the rock is under, the length of time the rock is under stress, and the type of stress.

Rocks have three possible responses to increasing stress (illustrated in figure 3):

- **elastic deformation**: the rock returns to its original shape when the stress is removed.
- **plastic deformation**: the rock does not return to its original shape when the stress is removed.
- **fracture**: the rock breaks.

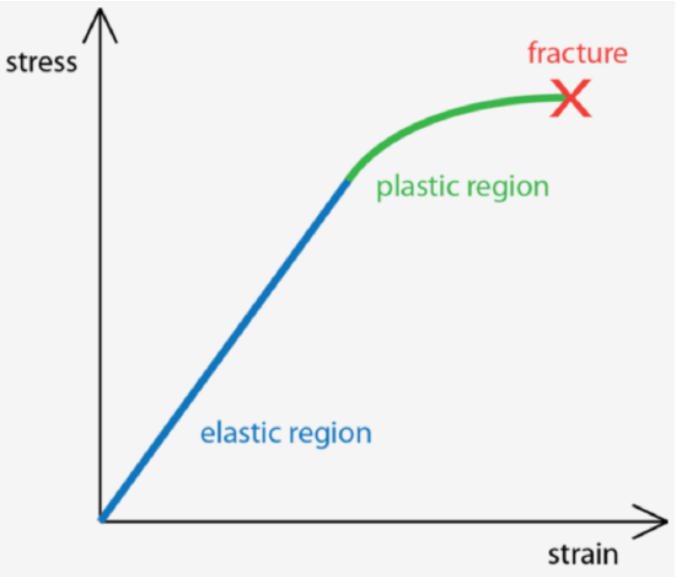


Figure 3. With increasing stress, the rock undergoes: (1) elastic deformation, (2) plastic deformation, and (3) fracture.

Under what conditions do you think a rock is more likely to fracture? Is it more likely to break deep within Earth's crust or at the surface? What if the stress applied is sharp rather than gradual?

- At the Earth's surface, rocks usually break quite quickly, but deeper in the crust, where temperatures and pressures are higher, rocks are more likely to deform plastically.
- Sudden stress, such as 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 important for deciphering the geologic history of a region because they follow certain rules.

1. Sedimentary rocks are formed with the oldest layers on the bottom and the youngest on top.
2. Sediments are deposited horizontally, so sedimentary rock layers are originally horizontal, as are some volcanic rocks, such as ash falls.
3. Sedimentary rock layers that are not horizontal are deformed.

You can trace the deformation a rock has experienced by seeing how it differs from its original horizontal, oldest-on-bottom position (figure 4a). This deformation produces geologic structures such as folds, joints, and faults that are caused by stresses (figure 4b). Using the rules listed above, try to figure out the geologic history of the geologic column below.

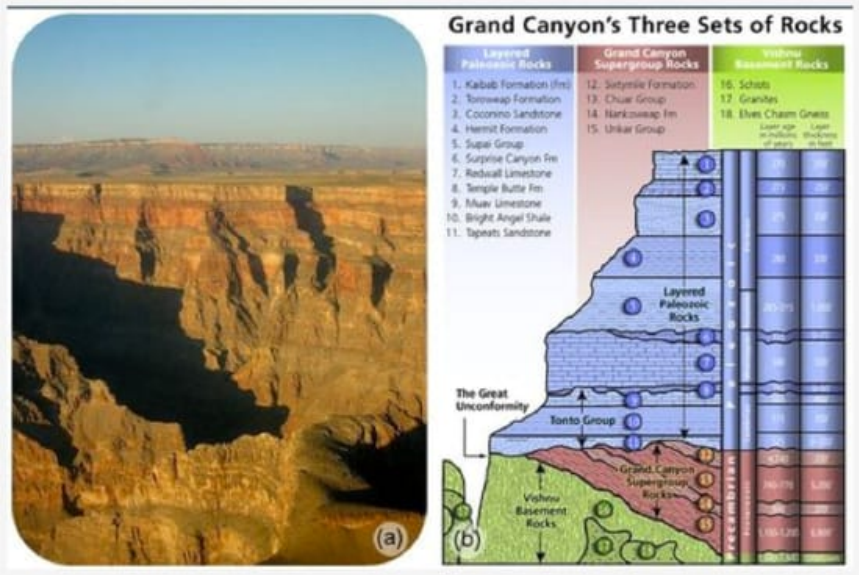


Figure 4. (a) In the Grand Canyon, the rock layers are exposed like a layer cake. Each layer is made of sediments that were deposited in a particular environment – perhaps a lake bed, shallow offshore region, or a sand dune. (b) In this geologic column of the Grand Canyon, the sedimentary rocks of the "Layered Paleozoic Rocks" column (layers 1 through 11) are still horizontal. Grand Canyon Supergroup rocks (layers 12 through 15) have been tilted. Vishnu Basement Rocks are not sedimentary (rocks 16 through 18). The oldest layers are on the bottom and youngest are on the top.

Folds

Rocks deforming plastically under compressive stresses crumple into **folds** (figure 5). They do not return to their original shape. If the rocks experience more stress, they may undergo more folding or even fracture.

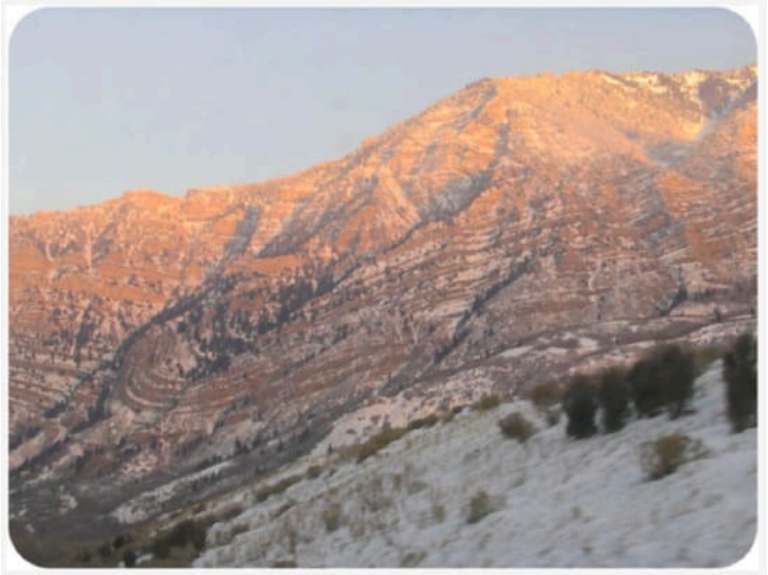


Figure 5. Snow accentuates the fold exposed in these rocks in Provo Canyon, Utah.

Three types of folds are seen.

- Mononcline: A **monocline** is a simple bend in the rock layers so that they are no longer horizontal (see figure 6 for an example).



Figure 6. At Colorado National Monument, the rocks in a monocline plunge toward the ground.

- Anticline: An **anticline** is a fold that arches upward. The rocks dip away from the center of the fold (figure 7). The oldest rocks are at the center of an anticline and the youngest are draped over them.

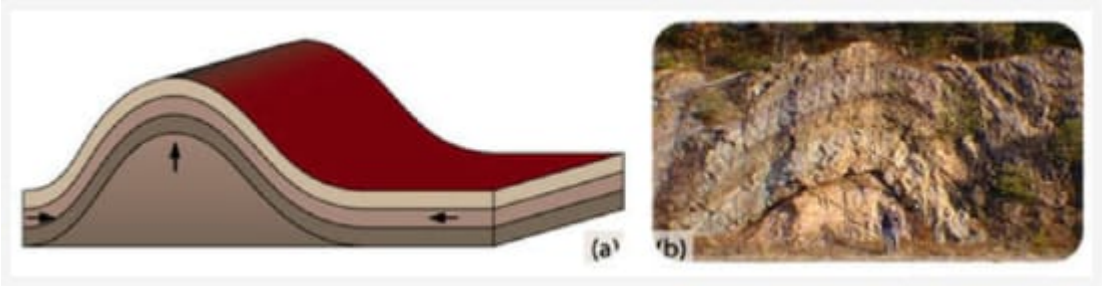
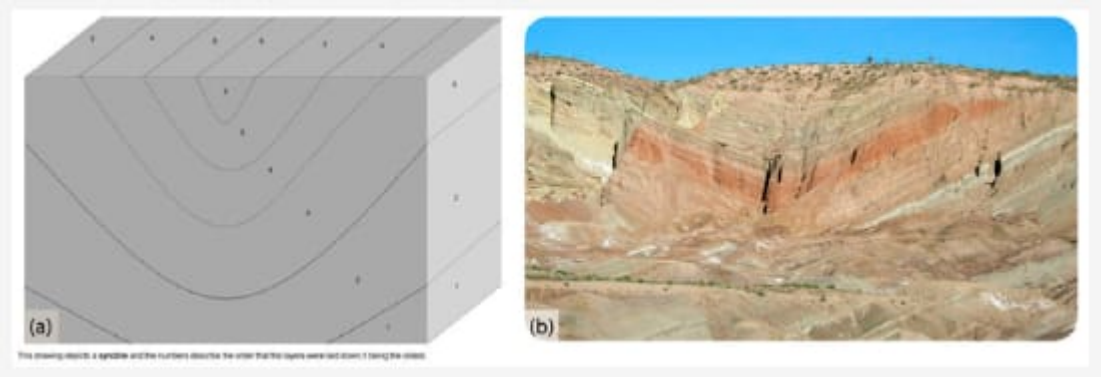


Figure 7. (a) Schematic of an anticline. (b) An anticline exposed in a road cut in New Jersey.

When rocks arch upward to form a circular structure, that structure is called a **dome.** If the top of the dome is sliced off, where are the oldest rocks located?

- Syncline: A **syncline** is a fold that bends downward. The youngest rocks are at the center and the oldest are at the outside (figure 8).



When rocks bend downward in a circular structure, that structure is called a **basin** (figure 9). If the rocks are exposed at the surface, where are the oldest rocks located?

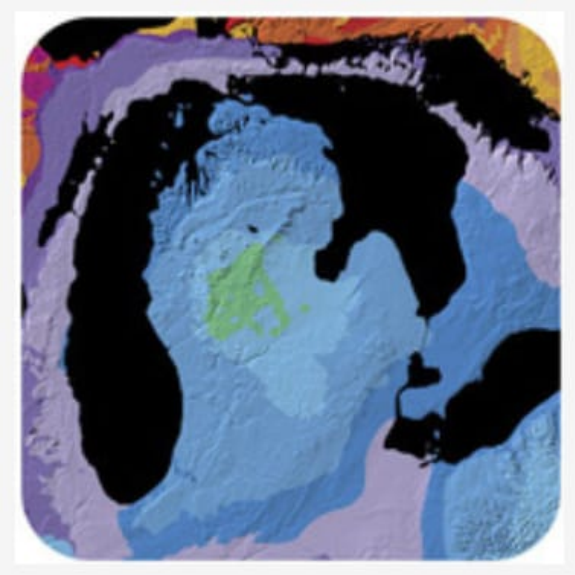


Figure 9. Basins can be enormous. This is a geologic map of the Michigan Basin, which is centered in the state of Michigan but extends into four other states and a Canadian province.

Faults

A rock under enough stress will fracture. If there is no movement on either side of a fracture, the fracture is called a **joint**, as shown in (figure 10).



Figure 10. Granite rocks in Joshua Tree National Park showing horizontal and vertical jointing. These joints formed when the confining stress was removed from the granite.

If the blocks of rock on one or both sides of a fracture move, the fracture is called a **fault** (figure 11). Sudden motions along faults cause rocks to break and move suddenly. The energy released is an earthquake.



Figure 11. Faults are easy to recognize as they cut across bedded rocks.

Slip is the distance rocks move along a fault. Slip can be up or down the fault plane. Slip is relative, because there is usually no way to know whether both sides moved or only one. 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** (figure 12). There are 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.

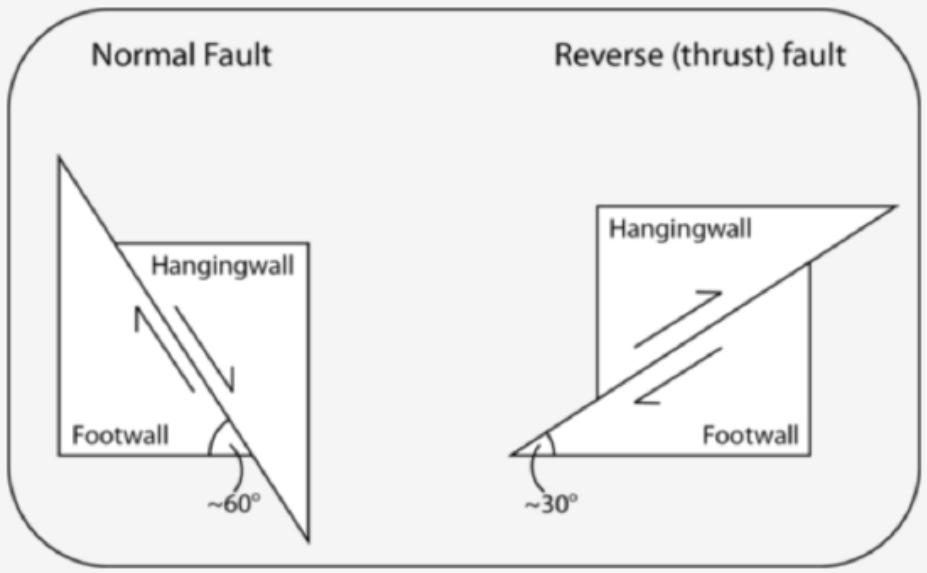


Figure 12. This diagram illustrates the two types of dip-slip faults: normal faults and reverse faults. Imagine miners extracting a resource along a fault. The hanging wall is where miners would have hung their lanterns. The footwall is where they would have walked.

Here is an animation of a normal fault.

A **thrust fault** is a type of reverse fault in which the fault plane angle is nearly horizontal. Rocks can slip many miles along thrust faults (**Figure** 13).



Figure 13. At Chief Mountain in Montana, the upper rocks at the Lewis Overthrust are more than 1 billion years older than the lower rocks. How could this happen?

Here is an animation of a thrust fault.

Normal faults can be huge. They are responsible for uplifting mountain ranges in regions experiencing tensional stress (figure 14).



Figure 14. The Teton Range in Wyoming rose up along a normal fault.

A **strike-slip fault** is a dip-slip fault in which the dip of the fault plane is vertical. Strike-slip faults result from shear stresses (figure 15).

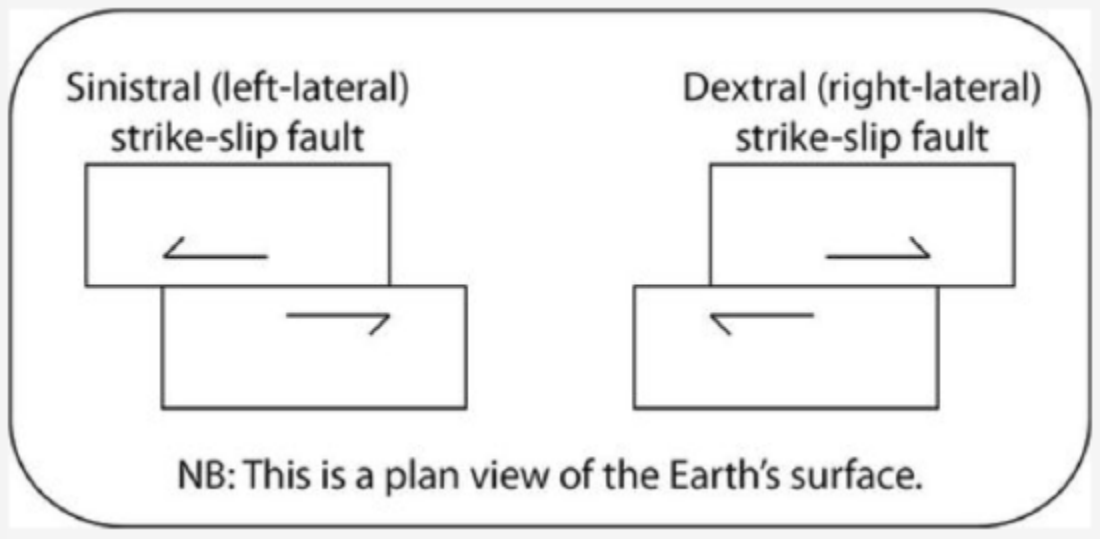


Figure 15. Imagine placing one foot on either side of a strike-slip fault. One block moves toward you. If that block moves toward your right foot, the fault is a right-lateral strike-slip fault; if that block moves toward your left foot, the fault is a left-lateral strike-slip fault.

California's San Andreas Fault is the world's most famous strike-slip fault. It is a right-lateral strike slip fault (figure 16).



Figure 16. The San Andreas is a massive transform fault.

Here is a strike-slip fault animation.

People sometimes say that California will fall into the ocean someday, which is not true. This animation shows movement on the San Andreas into the future.

STRESS AND MOUNTAIN BUILDING

Two converging continental plates smash upwards to create mountain ranges (figure 17). Stresses from this **uplift** cause folds, reverse faults, and thrust faults, which allow the crust to rise upwards.

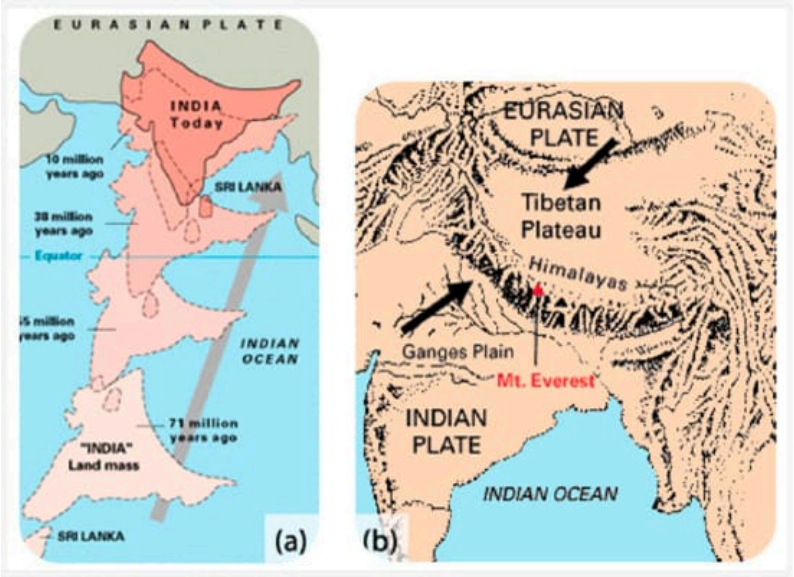


Figure 17. (a) The world's highest mountain range, the Himalayas, is growing from the collision between the Indian and the Eurasian plates. (b) The crumpling of the Indian and Eurasian plates of continental crust creates the Himalayas.

Subduction of oceanic lithosphere at convergent plate boundaries also builds mountain ranges (figure 18).



Figure 18. The Andes Mountains are a chain of continental arc volcanoes that build up as the Nazca Plate subducts beneath the South American Plate.

When tensional stresses pull crust apart, it breaks into blocks that slide up and drop down along normal faults. The result is alternating mountains and valleys, known as a basin-and-range (figure 19).

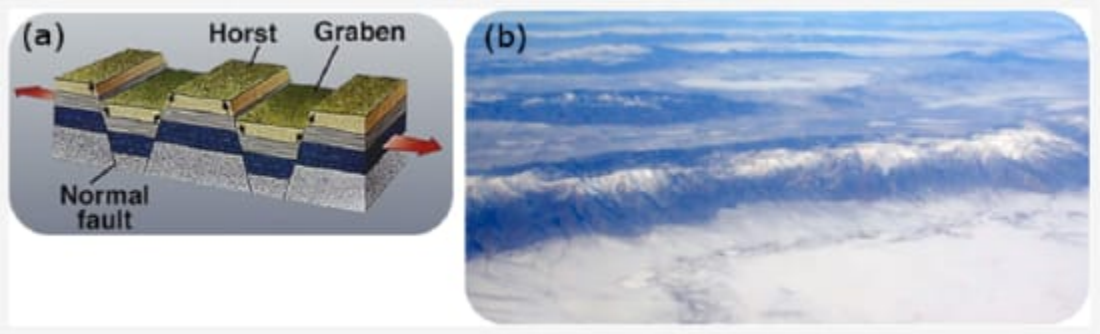


Figure 19. (a) In basin-and-range, some blocks are uplifted to form ranges, known as horsts, and some are down-dropped to form basins, known as grabens. (b) Mountains in Nevada are of classic basin-and-range form.

This is a very quick animation of movement of blocks in a basin-and-range setting.

LESSON SUMMARY

- Stress is the force applied to a rock and may cause deformation. The three main types of stress are typical of the three types of plate boundaries: compression 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 (the fault plane is inclined to the horizontal) and strike-slip (the fault plane is perpendicular to the horizontal).
- The world's largest mountains grow at convergent plate boundaries, primarily by thrust faulting and folding.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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7.4: Forces of Plate and Fault Motion

EXPLAIN HOW FORCES OF TENSION, COMPRESSION, AND SHEAR RELATE TO PLATE AND FAULT MOTION

[Insert brief introductory statement here.]

Open Educational Resources

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- Reading: Stress and Strain

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7.5: Stress and Strain

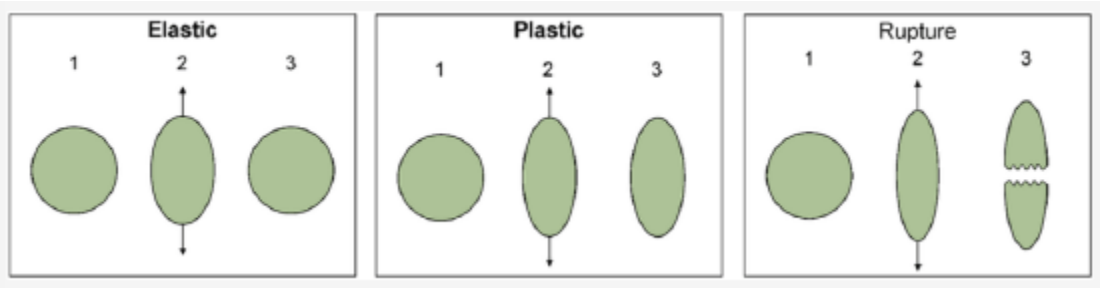
The earth's crust is constantly subjected to forces that push, pull, or twist it. These forces are called stress. In response to stress, the rocks of the earth undergo strain, also known as deformation. Strain is any change in volume or shape.There are four general types of stress. One type of stress is uniform, which means the force applies equally on all sides of a body of rock. The other three types of stress, tension, compression and shear, are non-uniform, or directed, stresses.All rocks in the earth experience a uniform stress at all times. This uniform stress is called lithostatic pressure and it comes from the weight of rock above a given point in the earth. Lithostatic pressure is also called hydrostatic pressure. (Included in lithostatic pressure are the weight of the atmosphere and, if beneath an ocean or lake, the weight of the column of water above that point in the earth. However, compared to the pressure caused by the weight of rocks above, the amount of pressure due to the weight of water and air above a rock is negligible, except at the earth's surface.) The only way for lithostatic pressure on a rock to change is for the rock's depth within the earth to change.Because lithostatic pressure is a uniform stress, a change in lithostatic pressure does not cause fracturing and slippage along faults. Nevertheless, it may be the cause of certain types of earthquakes. In subducting tectonic plates, the increased pressure of greater depth within the earth may cause the minerals in the plate to metamorphose spontaneously into a new set of denser minerals that are stable at the higher pressure. This is thought to be the likely cause of certain types of deep earthquakes in subduction zones, including the deepest earthquakes ever recorded.

Rocks are also subjected to the three types of directed (non-uniform) stress – tension, compression, and shear.

- **Tension** is a directed (non-uniform) stress that pulls rock apart in opposite directions. The tensional (also called extensional) forces pull away from each other.
- **Compression** is a directed (non-uniform) stress that pushes rocks together. The compressional forces push towards each other.
- **Shear** is a directed (non-uniform) stress that pushes one side of a body of rock in one direction, and the opposite side of the body of rock in the opposite direction. The shear forces are pushing in opposite ways.

In response to stress, rock may undergo three different types of strain – elastic strain, ductile strain, or fracture.

- **Elastic strain** is reversible. Rock that has undergone only elastic strain will go back to its original shape if the stress is released.
- **Ductile strain** is irreversible. A rock that has undergone ductile strain will remain deformed even if the stress stops. Another term for ductile strain is plastic deformation.
- **Fracture** is also called rupture. A rock that has ruptured has abruptly broken into distinct pieces. If the pieces are offset—shifted in opposite directions from each other—the fracture is a fault.



DUCTILE AND BRITTLE STRAIN

Earth's rocks are composed of a variety of minerals and exist in a variety of conditions. In different situations, rocks may act either as ductile materials that are able to undergo an extensive amount of ductile strain in response to stress, or as brittle materials, which will only undergo a little or no ductile strain before they fracture. The factors that determine whether a rock is ductile or brittle include:

- Composition—Some minerals, such as quartz, tend to be brittle and are thus more likely to break under stress. Other minerals, such as calcite, clay, and mica, tend to be ductile and can undergo much plastic deformation. In addition, the presence of water in rock tends to make it more ductile and less brittle.

- Temperature—Rocks become softer (more ductile) at higher temperature. Rocks at mantle and core temperatures are ductile and will not fracture under the stresses that occur deep within the earth. The crust, and to some extent the lithosphere, are cold enough to fracture if the stress is high enough.
- Lithostatic pressure—The deeper in the earth a rock is, the higher the lithostatic pressure it is subjected to. High lithostatic pressure reduces the possibility of fracture because the high pressure closes fractures before they can form or spread. The high lithostatic pressures of the earth's sub-lithospheric mantle and solid inner core, along with the high temperatures, are why there are no earthquakes deep in the earth.
- Strain rate—The faster a rock is being strained, the greater its chance of fracturing. Even brittle rocks and minerals, such as quartz, or a layer of cold basalt at the earth's surface, can undergo ductile deformation if the strain rate is slow enough.

Most earthquakes occur in the earth's crust. A smaller number of earthquakes occur in the uppermost mantle (to about 700 km deep) where subduction is taking place. Rocks in the deeper parts of the earth do not undergo fracturing and do not produce earthquakes because the temperatures and pressures there are high enough to make all strain ductile. No earthquakes originate from below the the earth's upper mantle.

STRESS AND FAULT TYPES

The following correlations can be made between types of stress in the earth, and the type of fault that is likely to result:

- Tension leads to normal faults.
- Compression leads to reverse or thrust faults.
- **Horizontal shear leads to strike-slip faults.**

Correlations between type of stress and type of fault can have exceptions. For example, zones of horizontal stress will likely have strike-slip faults as the predominant fault type. However there may be active normal and thrust faults in such zones as well, particularly where there are bends or gaps in the major strike-slip faults.

To give another example, in a region of compression stress in the crust, where sheets of rock are stacked on active thrust faults, strike-slip faults commonly connect some of the thrust faults together.

REFLECTION QUESTIONS

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- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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7.6: Common Folds and Faults

INTERPRET AND MODEL COMMON FOLD AND FAULT TYPES

[Insert brief introductory statement here.]

Open Educational Resources

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- Reading: Geologic Structures

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7.7: Geologic Structures

INTRODUCTION

Geologic structures such as faults and folds are the architecture of the earth's crust. Geologic structures influence the shape of the landscape, determine the degree of landslide hazard, bring old rocks to the surface, bury young rocks, trap petroleum and natural gas, shift during earthquakes, and channel fluids that create economic deposits of metals such as gold and silver.

Folds, faults, and other geologic structures accommodate large forces such as the stress of tectonic plates jostling against each other, and smaller forces such as the stress of gravity pulling on a steep mountainside. An understanding of the structures that shape the earth's crust can help you see when and where the crust was subjected to pushing or pulling, terrane accretion or crustal rifting.

PHYSICAL BEHAVIOR OF ROCKS: STRESS AND GEOLOGIC STRUCTURES

Before exploring geologic structures, we need to look at how rocks respond to the forces that create the structures. Stress refers to the physical forces that cause rocks to deform. There are three basic types of stress that deform rocks:

- compression (pushing together)
- tension (pulling apart)
- shear (twisting or rotating)

In response to stress, rocks will undergo some form of bending or breaking, or both. The bending or breaking of rock is called deformation or strain.

If rocks tend to break, they are said to be brittle. If a rock breaks, it is said to undergo brittle behavior. If rocks tend to bend without breaking, they are said to be ductile. If a rock bends but is able to return to its original position when the stress is released, it is said to undergo elastic behavior. If a rock bends and stays bent after stress is released, it is said to undergo plastic behavior.

A combination of elastic and brittle behavior causes earthquakes. Rocks get bent in an elastic fashion until they reach their limit, then they break in brittle fashion. The rocks on either side of a break act like rubber bands and snap back into their original shape. The snap is an earthquake. The break along which the rocks slide back to their original shape is a fault.

Earthquakes and faults occur in the shallow crust, where rocks are relatively cold and therefore brittle. In the deep crust and in the earth's mantle, rocks are very hot and subject to high pressure caused by the weight of the overlying rock. The heat and pressure cause deep crustal and mantle rocks to be ductile. In fact, rocks deep in the continental crust and upper mantle can be so hot and soft that they behave almost like a slow-moving liquid, even though they are actually solid. They "flow," or bend in a plastic manner, at a geological pace.

Now let us look at the specific types of geologic structures, the breaks and bends that deform rock in response to stress.

FOLDS

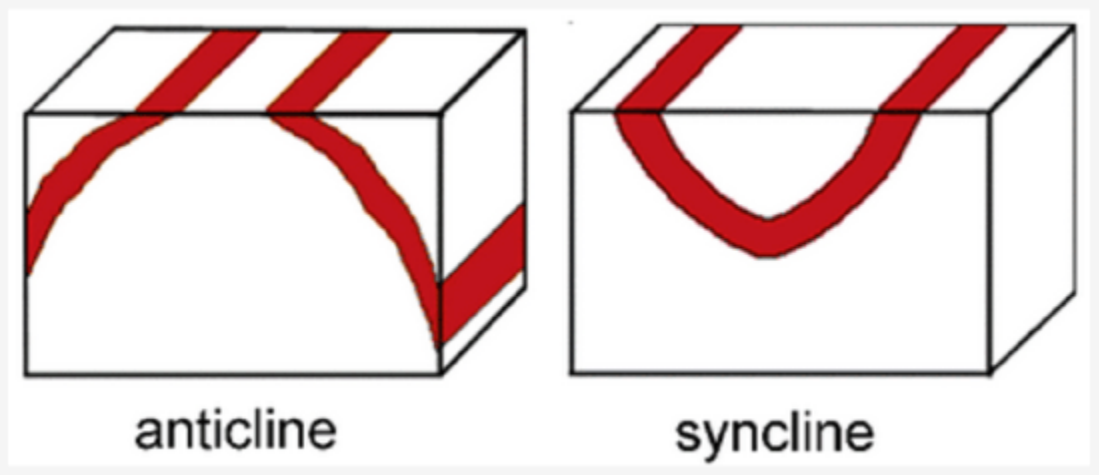
Ductile rocks behave plastically and become folded in response to stress. Even in the shallow crust where rocks are cool and relatively brittle, folding can occur if the stress is slow and steady and gives the rock enough time to gradually bend. If the stress is applied too quickly, rocks in the shallow crust will behave as brittle solids and break. Deeper in the crust, where the rocks are more ductile, folding happens more readily, even when the stress and strain occurs rapidly.

Anticlines and Synclines

The most basic types of folds are anticlines and synclines. Imagine a rug, the sides of which have been pushed toward each other forming ridges and valleys – the ridges are "up" folds and the valleys are "down" folds. In terms of geologic structures, the up

folds are called anticlines and the down folds are called synclines.

In block diagrams like those shown below, the top of the block is the horizontal surface of the earth, the map view. The other two visible sides of the box are cross-sections, vertical slices through the crust. The colored layers represent stratified geologic formations that were originally horizontal, such as sedimentary beds or lava flows. Use the block diagrams to visualize the three-dimensional shapes of the geologic structures. Keep in mind that erosion has stripped away the upper parts of these structures so that map view reveals the interior of these structures.



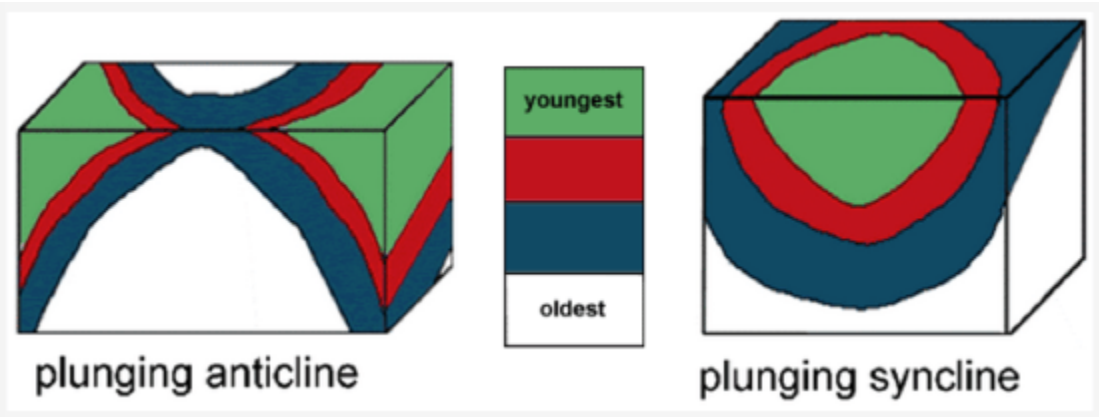
In map view, an anticline appears as parallel beds of the same rock type that dip away from the center of the fold. In an anticline, the oldest beds, the ones that were originally underneath the other beds, are at the center, along the axis of the fold. The axis is an imaginary line that marks the center of the fold on the map.

In map view, a syncline appears as a set of parallel beds that dip toward the center. In a syncline the youngest beds, the ones that were originally on top of the rest of the beds, are at the center, along the axis of the fold.

Anticlines and synclines form in sections of the crust that are undergoing compression, places where the crust is being pushed together.

Plunging Anticlines and Synclines

A plunging anticline or a plunging syncline is one that has its axis tilted from the horizontal so that the fold is plunging into the earth along its length. Plunge direction is the direction in which the axis of the fold tilts down into the earth.



In map view, a plunging anticline makes a U-shaped or V-shaped pattern that points, or closes, in the direction of plunge. A cross-section at a right angle to the axis of a plunging anticline looks the same as an anticline.

In map view, a plunging syncline makes a U-shaped or V-shaped pattern that opens in the direction of plunge.

Basins and Domes

A basin is a bowl-like depression in the strata (layers of rock). A basin is similar to a syncline, but instead of an axis it has a single point at the center. The strata all dip toward the center point and the youngest rock is at the center. In map view, the strata form concentric circles – a bull's eye pattern – around the center point.

A dome is an bulge in strata. A dome is similar to an anticline, but instead of an axis it has a single point at the center. The strata all dip away from the center point and the oldest rock is at the center. In map view, the strata form concentric circles – a bull's eye pattern – around the center point.

FAULTS

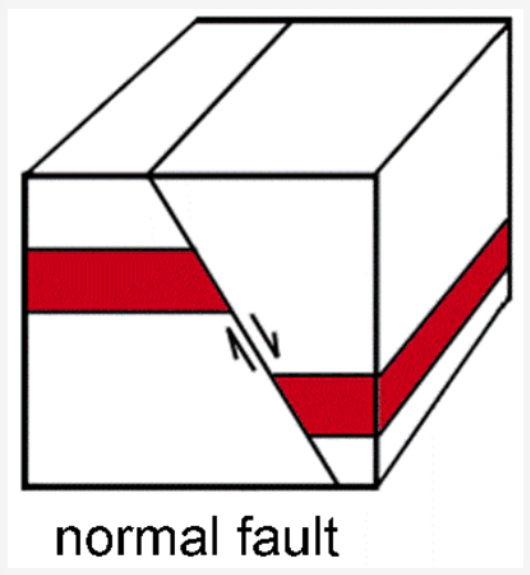
A fault is a planar surface within the earth, along which rocks have broken and slid. Faults are caused by elastic strain that culminates in brittle failure. The rocks on either side of a fault have shifted in opposite directions, called the offset directions. If a fault is not vertical, there are rocks above the fault and rocks beneath the fault.

The rocks above a fault are called the hanging wall.

The rocks beneath a fault are called the footwall.

Normal and Detachment Faults

In a normal fault, the hanging wall has moved down relative to the footwall.

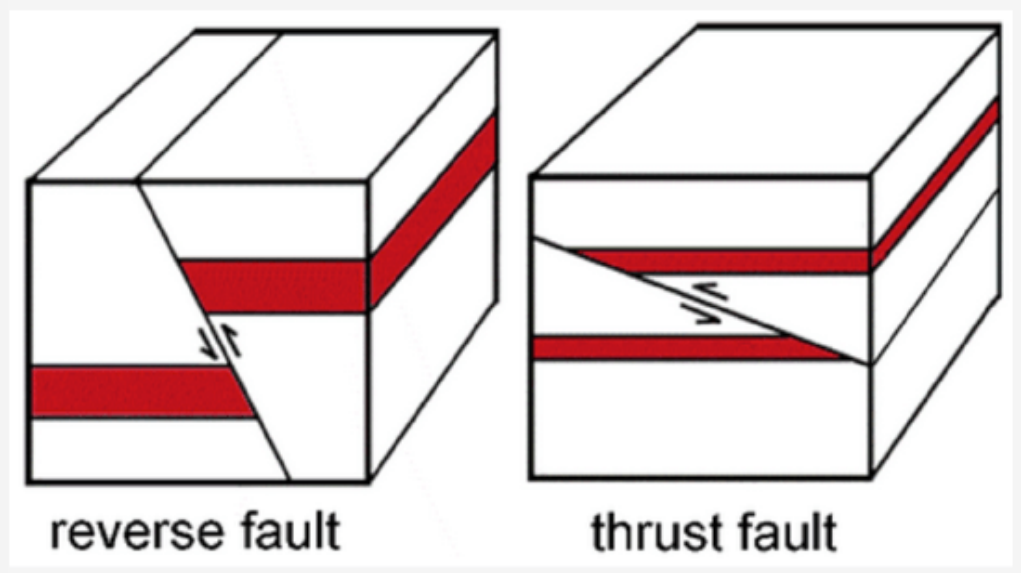


A detachment fault is a particular kind of normal fault that generally dips at a low angle. It separates rocks that were deep in the crust and ductile (granite and gneiss) from rocks of the upper crust (sedimentary or volcanic) that were brittle. Detachment faults occur along the boundaries of metamorphic core complexes (see below).

Normal and detachment faults form in sections of the crust that are undergoing tension, places where the crust is being stretched apart. A divergent plate boundary is a zone of large normal faults. Normal faults also occur in other zones of crustal tension, such as in the Basin and Range landscape region of the western United States.

Reverse and Thrust Faults

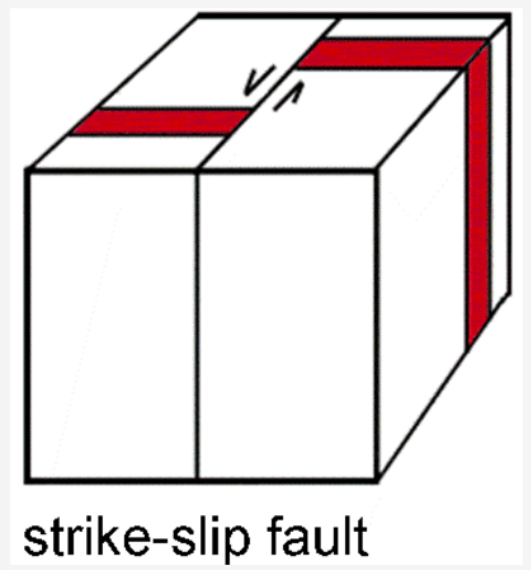
In a reverse or thrust fault, the hanging wall has moved up relative to the footwall. The difference between a reverse fault and a thrust fault is that a reverse fault has a steeper dip, more than 30°.



Reverse and thrust faults form in sections of the crust that are undergoing compression. A convergent plate boundary is a zone of major reverse and thrust faults. In fact, subduction zones are sometimes referred to as mega-thrust faults. Reverse and thrust faults also occur in other settings where the crust is being compressed, such as the Transverse Mountain Ranges, just north of Los Angeles.

Strike-Slip Faults

Strike-slip faults are steep or vertical faults along which the rocks on either side have moved horizontally in opposite directions. A transform plate boundary is a zone of large strike-slip faults. The San Andreas fault is an example of a major strike-slip fault at a transform boundary. Strike-slip faults also occur in other settings.



REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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7.8: Putting It Together

SUMMARY

In this section, you learned the following:

1. The magnitude of forces needed to fold and deform the Earth's crust
2. The difference between stress and strain and what they can produce
3. The different types of forces acting on the Earth: tension, compression, and shearing
4. The different types of folds and forces associated with them
5. The different types of faults and forces associated with them
6. What the outcomes are of crustal deformation

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8: EARTHQUAKES

- Topic hierarchy

8.1: Why It Matters
8.2: P, S, and Surface Waves
8.3: Seismic Waves
8.4: Causes and Hazards
8.5: The Nature of Earthquakes
8.6: Earthquakes
8.7: Magnitude and Intensity
8.8: Earthquake Intensity
8.9: Magnitude vs. Intensity
8.10: Predicting Seismic Activity
8.11: Earthquake Prediction
8.12: Seismicity and Earthquake Prediction
8.13: Deciphering Geologic Materials
8.14: Earth's Interior
8.15: Putting It Together

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8.1: Why It Matters

INTERPRET TYPES, CAUSES, EFFECTS, AND SCIENTIFIC MEASUREMENTS OF EARTHQUAKES AND SEISMIC WAVES

Introduction

Have you ever wondered why California or Japan has so many earthquakes? Have you ever been in an earthquake and felt the solid ground shake beneath your feet?

Imagine you are going about your normal routine for the day and it is time for you to wrap up your day to head home. As you start gathering your things to take home and work your way out to your car, the following happens:

YouTube Video

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This earthquake measured a 9.0 on the Richter scale and was the most powerful earthquake to hit Japan and the fourth most powerful recorded by humans. Aftershocks numbered over 1,000, with some over a 6.0 on the Richter scale. Almost 16,000 people died, over 6,000 were injured, and 2,500 were missing. The earthquake also damaged a nuclear facility causing major radioactive leaks. The World Bank estimated the economic cost of damage at $235 billion!

Once the shaking subsided, the following happened:

YouTube Video

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Learning Outcomes

- Compare and contrast properties and mechanics of P, S, and Surface waves
- Investigate the causes, common locations and hazards of earthquakes
- Define and compare magnitude versus intensity
- Recognize our limited ability to predict seismic activity
- Explain how seismic waves are used to decipher geologic materials in the crust and in the Earth's deeper interior

Ok, let's get started!

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8.2: P, S, and Surface Waves

COMPARE AND CONTRAST PROPERTIES AND MECHANICS OF P, S, AND SURFACE WAVES

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Seismic Waves

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8.3: Seismic Waves

The point on a fault within earth's crust where the fracturing begins and most slippage occurs is called the focus of the earthquake. Another name for it is the hypocenter. The point on the earth's surface directly above the focus is the epicenter. The epicenter is not where the earthquake originated. Earthquakes originate within the earth. The epicenter is the point on the surface of the earth directly above where the earthquake originated.

When an earthquake occurs, some of the energy it releases is turned into heat within the earth. Some of the energy is expended in breaking and permanently deforming the rocks and minerals along the fault. The rest of the energy, which is most of the energy, is radiated from the focus of the earthquake in the form of seismic waves.

Seismic waves fall into two general categories: body waves, which travel through the interior of the earth, and surface waves, which travel only at the earth's surface.

BODY WAVES

There are two types of body waves: P-waves and S-waves. The P in P-waves stands for primary, because these are the fastest seismic waves and are the first to be detected once an earthquake has occurred. P-waves travel through the earth's interior many times faster than the speed of a jet airplane, taking only a few minutes to travel across the earth.

P-waves are predominantly compressional waves. As a P-wave passes, material compresses in the same direction the wave is moving, and then extends back to its original thickness once the wave has passed. The speed at which P-waves travel through material is determined by:

- rigidity—how strongly the material resists being bent sideways and is able to straighten itself out once the shearing force has passed – the more rigid the material, the faster the P-waves
- compressibility—how much the material can be compressed into a smaller volume and then recover its previous volume once the compressing force has passed; the more compressible the material, the faster the P-waves
- density—how much mass the material contains in a unit of volume; the greater the density of the material, the slower the P-waves

The animations below show P-waves propogating across a plane (left) and from a point source (right). They are from Wikipedia.org/wiki/P-wave uploaded November, 2006 by Christophe Dang Ngoc Chan.

P-waves travel through liquids and gases as well as through solids. Although liquids and gases have zero rigidity, they have compressibility, which enables them to transmit P-waves. Sound waves are P-waves moving through the air.

Because the earth's mantle becomes more rigid and compressible as the depth below the asthenosphere increases, P-waves travel faster as they go deeper in the mantle. The density of the mantle also increases with depth below the asthenosphere. The higher density reduces the speed of seismic waves. However, the effects of increased rigidity and compressibility in the deep mantle are much greater than the effect of the increased density.

P-waves travel through materials with rigidity and/or compressiblity, and density	
greater rigidity	faster P-waves
greater compressibility	faster P-waves
greater density	slower P-waves

The S in S-waves stands for secondary, because they are the second-fastest seismic waves and the second type to be detected once an earthquake has occurred. Although S-waves are slower than P-waves, they still travel fast, over half the speed of P-waves, moving at thousands of kilometers per hour through the earth's crust and mantle.

S-waves are shear waves (though that is not what the S stands for). They move by material flexing or deforming sideways (shearing) from the direction of wave travel, and then returning to the original shape once the wave passes. The speed at which S-waves travel through material is determined only by:

- rigidity — how strongly the material resists being bent sideways and is able to straighten itself out once the shearing force has passed – the more rigid the material, the faster the S-waves
- density — how much mass the material contains in a unit of volume – the greater the density of the material, the slower the S-waves

The animations below show S-waves propogating across a plane (left) and from a point source (right). They are from Wikipedia.org/wiki/S-wave uploaded November, 2006 by Christophe Dang Ngoc Chan.

S-waves can travel only through solids, because only solids have rigidity. S-waves cannot travel through liquids or gases.

Because the earth's mantle becomes more rigid as its depth below the asthenosphere increases, S-waves travel faster as they go deeper in the mantle. The density of the mantle also increases at greater depth, which has the effect of reducing the speed of seismic waves, but the increase in rigidity is much greater than the increase in density, so S-waves speed up as they get deeper in the mantle, in spite of the increased density.

S-waves travel through materials with rigidity and density	
greater rigidity	faster S-waves
greater density	slower S-waves

SURFACE WAVES

There are two types of surface waves, Rayleigh waves and Love waves. Rayleigh waves are named after Lord Rayleigh (John Strutt), an English aristocrat who, in his work as a scientist and mathematician, developed a detailed mathematical accounting of the type of surface wave named after him. Rayleigh waves are set off by the combined effect of P- and S-waves on the earth's surface. Rayleigh waves are sometimes called rolling waves. In Rayleigh waves the surface of the earth rises up and sinks down in crests and troughs, similar to waves on the surface of water. People who are outdoors during a major earthquake commonly see Rayleigh waves moving across the surface of the earth, and can feel the ground rising and falling as the waves pass beneath them.

Love waves, sometimes called L-waves, are named after Augustus Love, an English mathematician and physicist who first modeled them mathematically. Love waves involve the surface shearing sideways and then returning to its original form as each wave passes.

All surface waves travel slower than body waves and Rayleigh waves are slower than Love waves.

REFLECTION QUESTIONS

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- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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8.4: Causes and Hazards

INVESTIGATE THE CAUSES, COMMON LOCATIONS AND HAZARDS OF EARTHQUAKES

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: The Nature of Earthquakes
- Reading: Earthquakes

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8.5: The Nature of Earthquakes

INTRODUCTION

An **earthquake** is sudden ground movement caused by the sudden release of energy stored in rocks. Earthquakes happen when so much stress builds up in the rocks that the rocks rupture. The 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

The description of how earthquakes occur is called **elastic rebound theory** (figure 1).

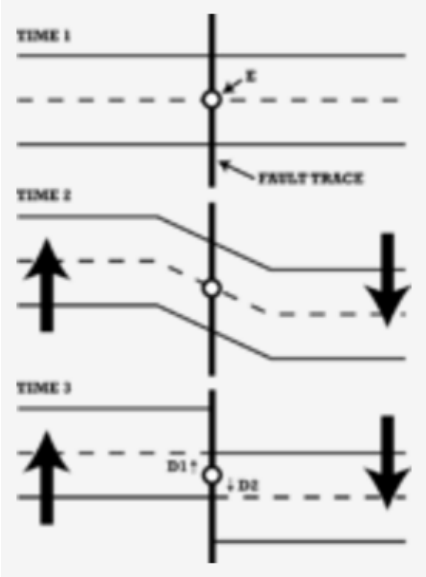


Figure 1. Elastic rebound theory. Stresses build on both sides of a fault, causing the rocks to deform plastically (Time 2). When the stresses become too great, the rocks break and end up in a different location (Time 3). This releases the built up energy and creates an earthquake.

Elastic rebound theory in an animation.

In an earthquake, the initial point where the rocks rupture in the crust is called the **focus**. The epicenter is the point on the land surface that is directly above the focus. In about 75% of earthquakes, the focus is 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 where people live. However, it is the epicenter of an earthquake that is reported by scientists and the media (figure 2).

This animation shows the relationship between focus and epicenter of an earthquake.

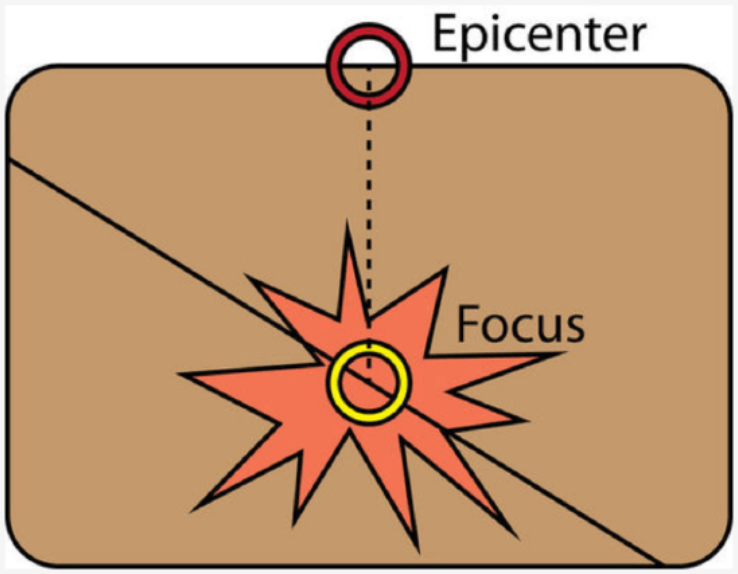


Figure 2. In the vertical cross section of crust, there are two features labeled – the focus and the epicenter, which is directly above the focus.

EARTHQUAKE ZONES

Nearly 95% of all earthquakes take place along one of the three types of plate boundaries, but earthquakes do occur along all three types of plate boundaries.

- About 80% of all earthquakes strike around the Pacific Ocean basin because it is lined with convergent and transform boundaries (figure 3).
- About 15% take place in the Mediterranean-Asiatic Belt, where convergence is causing the Indian Plate to run into the Eurasian Plate.
- The remaining 5% are scattered around other plate boundaries or are intraplate earthquakes.

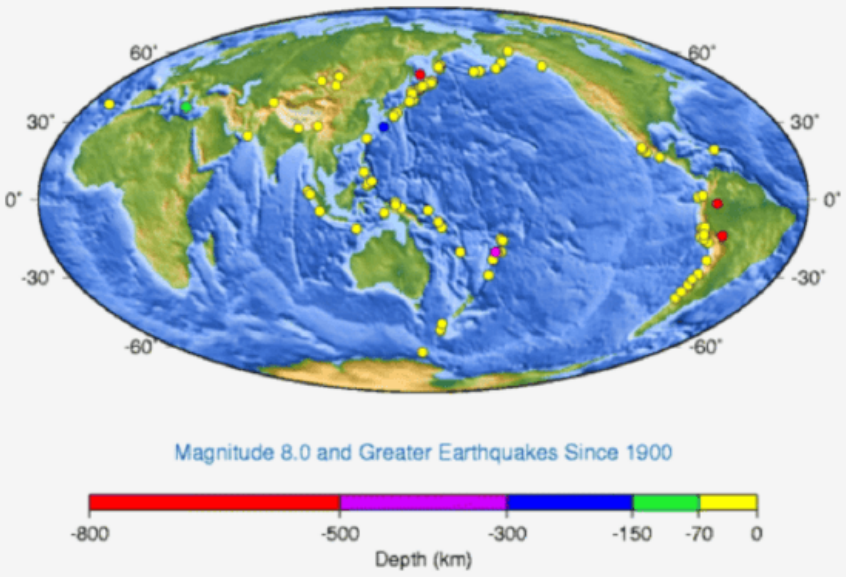


Figure 3. Earthquake epicenters for magnitude 8.0 and greater events since 1900. The earthquake depth shows that most large quakes are shallow focus, but some subducted plates cause deep focus quakes.

Transform Plate Boundaries

Deadly earthquakes occur at transform plate boundaries. Transform faults have shallow focus earthquakes. Why do you think this

is so? The faults along the San Andreas Fault zone produce around 10,000 earthquakes a year. Most are tiny, but occasionally one is massive. In the San Francisco Bay Area, the Hayward Fault was the site of a magnitude 7.0 earthquake in 1868. The 1906 quake on the San Andreas Fault had a magnitude estimated at about 7.9 (figure 4).



Figure 4. (a) The San Andreas Fault zone in the San Francisco Bay Area. (b) The 1906 San Francisco earthquake is still the most costly natural disaster in California history. About 3,000 people died and 28,000 buildings were lost, mostly in the fire.

Recent California earthquakes:

- 1989: Loma Prieta earthquake near Santa Cruz, California. Magnitude 7.1 quake, 63 deaths, 3,756 injuries, 12,000+ people homeless, property damage about $6 billion.
- 1994: Northridge earthquake on a blind thrust fault near Los Angeles. Magnitude 6.7, 72 deaths, 12,000 injuries, damage estimated at $12.5 billion.

Although California is prone to many natural hazards, including volcanic eruptions at Mt. Shasta or Mt. Lassen, and landslides on coastal cliffs, the natural hazard the state is linked with is earthquakes. In this video, the boundaries between three different tectonic plates and the earthquakes that result from their interactions are explored:

YouTube Video

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New Zealand also has strike-slip earthquakes, about 20,000 a year! Only a small percentage of those are large enough to be felt. A 6.3 quake in Christchurch in February 2011 killed about 180 people.

Convergent Plate Boundaries

Earthquakes at convergent plate boundaries mark the motions of subducting lithosphere as it plunges through the mantle (Figure 5). Eventually the plate heats up enough deform plastically and earthquakes stop.

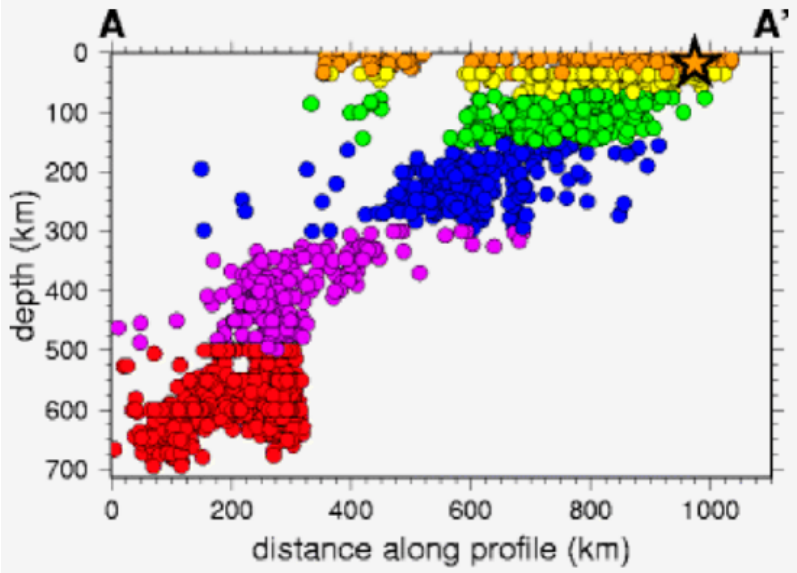


Figure 5. This cross section of earthquake epicenters with depth outlines the subducting plate with shallow, intermediate, and deep earthquakes.

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 earthquakes annually.

In March 2011 an enormous 9.0 earthquake struck off of Sendai in northeastern Japan. This quake, called the 2011 Tōhoku earthquake, was the most powerful ever to strike Japan and one of the top five known in the world. Damage from the earthquake was nearly overshadowed by the tsunami it generated, which wiped out coastal cities and towns (figure 6). Two months after the earthquake, about 25,000 people were dead or missing, and 125,000 buildings had been damaged or destroyed. Aftershocks, some as large as major earthquakes, have continued to rock the region.



Figure 6. Destruction in Ofunato, Japan, from the 2011 Tōhoku Earthquake.

A map of aftershocks is seen here.

Here is an interactive feature article about the earthquake.

The Pacific Northwest of the United States is at risk from a potentially massive earthquake that could strike any time. Subduction of the Juan de Fuca plate beneath North America produces active volcanoes, but large earthquakes only hit every 300 to 600 years. The last was in 1700, with an estimated magnitude of around 9.

Here is an image of earthquakes beneath the Pacific Northwest and the depth to the epicenter.

Elastic rebound at a subduction zone generates an earthquake in this animation.

Massive earthquakes are the hallmark of the thrust faulting and folding when two continental plates converge (figure 7). The 2001 Gujarat earthquake in India was responsible for about 20,000 deaths, and many more people became injured or homeless.



Figure 7. Damage from the 2005 Kashmir earthquake

In Understanding Earthquakes: From Research to Resilience, scientists try to understand the mechanisms that cause earthquakes and tsunamis and the ways that society can deal with them:

YouTube Video

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Divergent Plate Boundaries

Earthquakes at mid-ocean ridges are small and shallow because the plates are young, thin, and hot. On land where continents split apart, earthquakes are larger and stronger.

Intraplate Earthquakes

Intraplate earthquakes are the result of stresses caused by plate motions acting in solid slabs of lithosphere. In 1812, a magnitude 7.5 earthquake struck near New Madrid, Missouri. The earthquake was strongly felt over approximately 50,000 square miles and altered the course of the Mississippi River. Because very few people lived there at the time, only 20 people died. Many more people live there today (figure 8). A similar earthquake today would undoubtedly kill many people and cause a great deal of property damage.

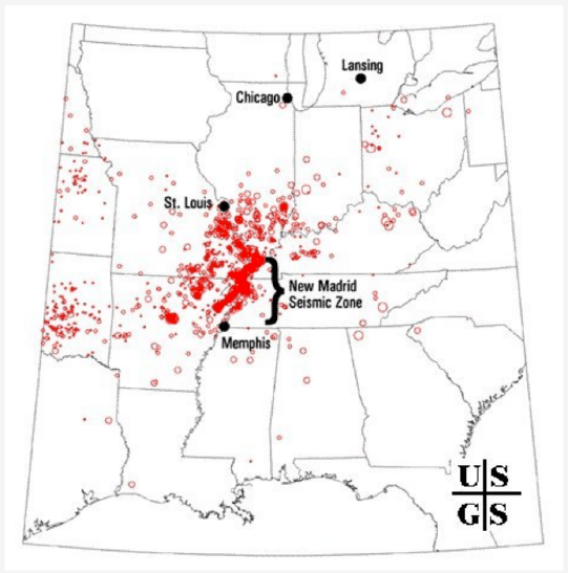


Figure 8. The New Madrid Seismic Zone is within the North American plate. Around 4,000 earthquakes have occurred in the region since 1974.

REFLECTION QUESTIONS

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- How can the content in this section help you demonstrate mastery of a specific skill?
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8.6: Earthquakes

SEISMOLOGY

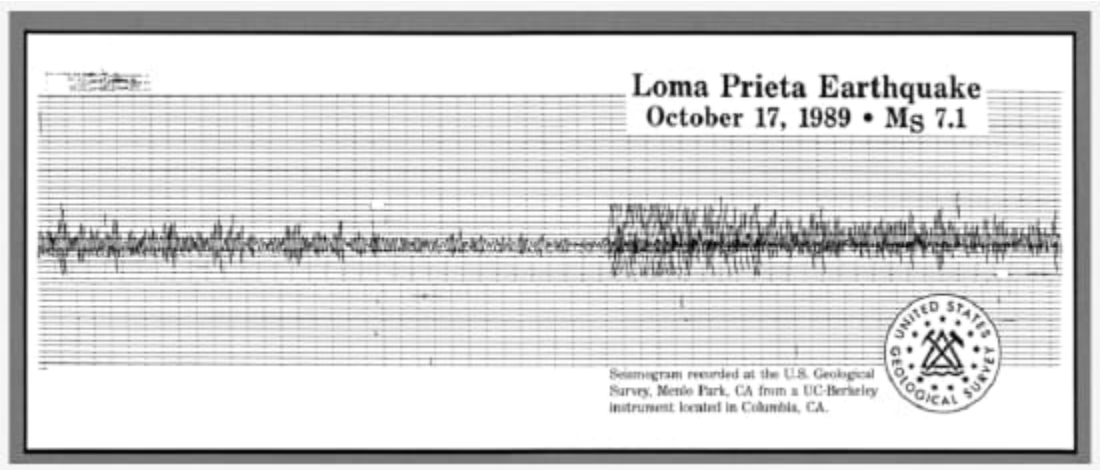
Seismology is the study of seismic waves. Seismology is also the study of earthquakes, mainly through the waves they produce. By measuring and analyzing seismic waves, seismologists can derive such information as:

- The epicenter of an earthquake
- The depth of an earthquake focus
- The magnitude (power) of an earthquake
- The type of fault movement that produced an earthquake
- Whether an earthquake beneath the ocean is likely to have generated a tsunami (a set of giant ocean waves)

In addition to information about earthquakes and faults, seismology gives us knowledge of the layers of the earth. Much of what we know about the crust, lithosphere, asthenosphere, mantle, and core comes from seismology. See the Earth's interior Basics page.

Seismology also gives us information about underground nuclear testing that takes place anywhere on earth, allows possible oil reservoirs to be located within the earth's crust, and helps us predict when a volcano is about to erupt.

Seismographs and seismometers are the instruments used to measure seismic waves. The traditional analog seismograph utilizes a pen (stylus) embedded in a heavy weight, which is suspended on springs. When the earth moves during an earthquake, a piece of paper rolling beneath the stylus moves with the earth, but the stylus, with its weight suspended on springs, remains stationary, drawing lines on the sheet of paper that show the seismic motions of the earth. The USGS photo below shows a seismogram from a seismograph located in Columbia, California that recorded the 1989 Loma Prieta Earthquake.



With modern technology, seismographs with pens and rolling sheets of paper are being replaced by seismometers with electronic sensors and computer screens. Seismographs and seismometers both produce a seismogram, which is a graphic record of the seismic waves, viewed either on paper or on a computer monitor.

Locating Earthquakes Epicenters

Because P-waves travel faster than S-waves, the farther away you are from an earthquake, the greater the time lag between when the first P-wave arrives from the earthquake and when the first S-wave arrives. This difference in arrival time can be used to determine the distance to the earthquake. If three seismograph stations, at three different locations, each determine their distance to the earthquake, the location of the earthquake epicenter can be determined by triangulation. From each seismograph station location on a map, a circle is drawn with a radius equal to the distance to the earthquake from the seismograph station. The earthquake epicenter must be somewhere on that circle. Where all three circles intersect at a single point, that point is the

earthquake epicenter.

In today's world, many seismograph stations share data via the Internet. Once an earthquake occurs, data from several seismograph stations, usually more than three, is combined and calculated by computer to determine a statistically best fit epicenter location.

Determining Earthquake Depth

The depth of the earthquake focus is also calculated using combined seismograph data from several stations, but it is a more difficult calculation. As a result, the calculated depth of an earthquake is somewhat less precise than the determination of the epicenter location. For example, an epicenter may be located to within 1 km, but the depth to the focus may be plus or minus several kilometers.

Most earthquakes occur in the crust or upper lithosphere, less than 70 km (50 miles) deep in the earth. Earthquakes that are less than 70 km deep are called shallow earthquakes. Earthquakes that occur between 70 and 300 km deep are intermediate-depth earthquakes. Earthquakes 300-700 km deep are called deep earthquakes. None deeper have been detected.

Most intermediate-depth earthquakes, and all deep earthquakes, occur in subduction zones. In these zones, subducting oceanic lithosphere remains cold and brittle, prone to undergoing fracture and producing earthquakes, even as it sinks down into mantle depths.

In theory, once a subducting plate is several hundred km deep, its temperature should have increased enough by conduction of heat from surrounding mantle, and the lithostatic pressure become high enough, to prevent any brittle behavior. Earthquakes at that depth, therefore, should not occur by fracture and slippage along faults the way most earthquakes do in the shallow crust and upper lithospheric mantle. The deepest earthquakes, down to 700 km, are probably due instead to olivine, the most abundant mineral in the subducting plate, contracting into a new crystal lattice with a denser structure. This contraction occurs in response to the increased lithostatic pressure encountered by the subducting slab as it sinks deep into the mantle.

Calculating Earthquake Magnitude

The magnitude of an earthquake is a number that allows earthquakes to be compared with each other in terms of their relative power. For several decades, earthquake magnitudes were calculated based on a method first developed by Charles Richter, a seismologist based in California. Richter used seismograms of earthquakes that occurred in the San Andreas fault zone to calibrate his magnitude scale.

Two measurements are factored together to determine the Richter magnitude of an earthquake: the amplitude of the largest waves recorded on a seismogram of the earthquake, and the distance to the epicenter of the earthquake. The maximum amplitude seismic wave – the height of the tallest one – is measured in mm on a seismogram. The distance to the epicenter must also be taken into account because the greater the distance from the earthquake, the smaller the waves get. The effect of distance is factored out of the calculation. There is no upper limit defined for the Richter scale, but after a century of seismograph measurements, it appears that rocks in the earth release their stress before building up enough energy to reach magnitude 10.

The Richter scale was found to not transfer very well from the San Andreas fault zone, a transform plate boundary, to the much more powerful earthquakes that occur at convergent plate boundaries, particularly subduction zone earthquakes. Therefore, the Richter scale has been replaced by the moment magnitude scale, symbolized as $\mathbf{M_w}$.

The moment magnitude scale is broadly similar to the Richter scale, but it takes more factors into account, including the total area of the fault that moves during the earthquake, and how much it moves. This produces a magnitude number that is a better indicator of the total amount of energy released by the earthquake. Because the moment magnitude scale has replaced the Richter scale, we will assume from here on that we are referring to moment magnitude, not Richter magnitude, when we speak of earthquake magnitude.

The magnitude scale portrays energy logarithmically to approximately base 32. For example, a magnitude 6.0 earthquake releases about 32 times as much energy as a magnitude 5.0 earthquake. A magnitude 7.0 releases about 32 x 32 = 1024 times as much energy as a magnitude 5.0 earthquake. A magnitude 9.0 earthquake, which rarely occurs, releases over a million times as much energy as a magnitude 5.0 earthquake.

Ranking Earthquake Intensity

Earthquake intensity is very different from earthquake magnitude. Earthquake intensity is a ranking based on the observed effects of an earthquake in each particular place. Therefore, each earthquake produces a range of intensity values, ranging from highest in the epicenter area to zero at a distance from the epicenter. The most commonly used earthquake intensity scale is the Modified Mercalli earthquake intensity scale. Refer to the Modified Mercalli Intensity Scale page on the US Geological Survey Earthquake Hazards Program website for an abbreviated version.

The table below shows approximately how many earthquakes occur each year in each magnitude range and what the intensity might be at the epicenter for each magnitude range.

Magnitude	Average number per year	Modified Mercalli Intensity	Description
0 – 1.9	>1 million	—	micro – not felt
2.0 – 2.9	>1 million	I	minor – rarely felt
3.0 – 3.9	about 100,000	II – III	minor – noticed by a few people
4.0 – 4.9	about 10,000	IV – V	light – felt by many people, minor damage possible
5.0 – 5.9	about 1,000	VI – VII	moderate – felt by most people, possible broken plaster and chimneys
6.0 – 6.9	about 130	VII – IX	strong – damage variable depending on building construction and substrate
7.0 – 7.9	about 15	IX – X	major – extensive damage, some buildings destroyed
8.0 – 8.9	about 1	X – XII	great – extensive damage over broad areas, many buildings destroyed
9.0 and above	< 1	XI – XII	great – extensive damage over broad areas, most buildings destroyed

EARTHQUAKES AND PLATE BOUNDARIES

Most, but not all, earthquakes occur at or near plate boundaries. A great deal of stress is concentrated and a great deal of strain, much of it in the form of rupture of the earth, takes place at locations where two plates diverge, transform, or converge relative to each other.

Tension is the dominant stress at divergent plate boundaries. Normal faults and rift valleys as the predominant earthquake-related structures at divergent plate boundaries. Earthquakes at divergent plate boundaries are usually relatively shallow, and, though they can be damaging, the most powerful earthquakes at divergent plate boundaries are not nearly as powerful as the most powerful earthquakes at convergent plate boundaries.

Transform plate boundaries are zones dominated by horizontal shear, with strike-slip faults the most characteristic fault type. Most transform plate boundaries cut through relatively thin oceanic crust, part of the structure of the ocean floor, and produce relatively shallow earthquakes that are only rarely of major magnitude. However, where transform plate boundaries and their strike-slip faults cut through the thicker crust of islands or the even thicker crust of continents, more stress may need to build up before the thicker masses of rock will rupture, and so the magnitudes of earthquakes can be higher than in transform plate boundary zones confined to thin oceanic crust. This is evident in such places as the San Andreas fault zone of California, where a transform fault cuts through continental crust and earthquakes there sometimes exceed 7.0 in magnitude.

Convergent plate boundaries are dominated by compression. The major faults found in convergent plate boundaries are usually reverse or thrust faults, including a master thrust fault at the boundary between the two plates and typically several more major thrust faults running roughly parallel to the plate boundary. The most powerful earthquakes that have been measured are subduction earthquakes, up to greater than 9.0 in magnitude. All subduction zones in the world are at risk of subduction earthquakes with magnitudes up to or even greater than 9.0 in extreme cases, and are likely to produce tsunamis. This includes

the Cascadia subduction zone of northern California and coastal Oregon and Washington, the Aleutian subduction zone of southern Alaska, the Kamchatka subduction zone of Pacific Russia, the Acapulco subduction zone of southern Pacific Mexico, the Central American subduction zone, the Andean subduction zone, the West Indian or Caribbean subduction zone, and subduction zones of Indonesia, Japan, the Phillipines, and several more subduction zones in the western and southwestern Pacific Ocean.

INTRAPLATE EARTHQUAKES

Some earthquakes take place far away from plate boundaries. Earthquakes can occur wherever there is sufficient stress in the earth's crust to drive rocks to rupture.

For example, Hawaii is thousands of km (thousands of miles) from any plate boundary, but the volcanoes that compose the islands have built up so rapidly that they are still undergoing gravitational stabilization. Sectors of the Hawaiian islands occasionally slump along normal faults, producing intraplate earthquakes. Most of the earthquakes occur on the big island of Hawaii, which is composed of the youngest, most recently built volcanoes. The geologic record shows that parts of the older islands have undergone major collapses in the last few million years, with sections of the islands sliding out to the seafloor in landslides floored on shallow normal faults.

Another example is the Basin and Range region of the western United States, including Nevada and eastern Utah, where the crust is subjected to tension. Earthquakes occur there on normal faults, far inland from the plate boundaries on the West Coast. The tension in the crust of the Basin and Range province may be partly due to a mid-ocean ridge system that subducted beneath California and is now located beneath the Basin and Range, causing tension in the lithosphere.

The region around Yellowstone National Park also undergoes occasional major earthquakes on normal faults. Earthquakes in that area may be due to the Yellowstone hot spot causing differential thermal expansion of the lithosphere in a broad zone round the hot spot center.

Several East Coast cities, including Boston, New York, and Charleston in South Carolina, have experienced damaging earthquakes in the last two centuries. The faults beneath these cities may date back to the rifting of Pangea and the opening up of the Atlantic Ocean beginning around 200 million years ago.

In the area of the town of New Madrid, along the Mississippi River in southeastern Missouri and western Tennessee, great earthquakes occurred in 1811-1812. Minor to moderate earthquakes continue to occur there, keeping active the possibility of damaging earthquakes occurring there again in the future. The fault system beneath that area may date from times of continental collision and continental rifting in the distant geologic past, and recent stress in the crust around New Madrid may be from the massive build-up of sediment in the Mississippi River delta region, which spreads out to the south of that area.

EARTHQUAKES AND VOLCANOES

The connections between earthquakes and volcanoes are not always obvious. However, when magma is moving up beneath a volcano, and when a volcano is erupting, it produces earthquakes. Volcanic earthquakes are distinct from the more common type of earthquakes that occur by elastic rebound along faults.

Seismologists can use the patterns and signals of earthquakes coming from beneath volcanoes to predict that the volcano is about to erupt, and can use seismic waves to see that a volcano is undergoing an eruption even if the volcano is at a remote location, hidden in darkness, or hidden in storm clouds.

Volcanic vents, and volcanoes in general, are commonly located along faults, or at the intersection of several faults. Major faults that already exist in the crust may be natural paths to channel rising magma. However, on major volcanic edifices, shallower faults are a product of the development of the volcano. There are feedback effects between the upward pressure of magma buoyancy in the crust, the growth of faults in volcanic zones, and the venting of volcanoes, which is not yet completely understood.

As was noted at the beginning of this section, not quite all earthquakes are due to the slippage of solid blocks of rock along faults. When a volcano undergoes a powerful pyroclastic eruption – in other words, when a volcano explodes – it causes the earth to shake. Earthquakes caused by an explosive volcanic eruptions produce a different seismic signal than earthquakes caused by slippage along faults.

Another example of earthquakes that are caused at least in part by magma movement, rather than by slippage of entirely solid

rock along faults, is earthquakes set off by the movement of magma upward beneath a volcano, or up to higher levels in the crust whether or not there is a volcano on top. Such upward movement of magma within the crust is sometimes called magma injection. Seismologists are still researching the interactions between movement of magma in the crust, and related slippage along faults that may be caused by the pressure and movement of the magma.

EARTHQUAKE HAZARDS

Earthquakes can be hazardous to humans and property in a variety of ways. Earthquake hazards arise from a combination of factors such as the size of the earthquake, distance to the epicenter, the underlying material and geologic structures, and building construction.

Ground Shaking

Ground shaking is caused by seismic waves During a significant earthquake, a particular location, and any building at that location, will be shaken by body waves (P- and S-) and surface waves (Rayleigh and Love. Each type of wave will have a different frequency (different number of waves passing by each second), and can shear or move a building in a different way, sometimes simultaneously. Adjacent neighborhoods or towns may experience very different intensities from the same earthquake, based on how far they are from the epicenter and what sort of rocks or sediments are in the ground beneath each area. Places underlain by thick deposits of unconsolidated sediments will experience a higher amplitude of shaking, at the same distance from the same earthquake, than places underlain by solid bedrock all the way to the surface. If unconsolidated sediments are fine-grained and wet, they may undergo liquefaction, increasing the damage to buildings and infrastructure and therefore increasing the intensity of the earthquake there. If unconsolidated sediments are overlain by a layer of artificial fill, the area is likely to experience more intense shaking and undergo more ground settling, and liquefaction if wet, than places that have not had a layer of artificial fill added.

Mexico City, one of the most populated cities in the world, is in a basin in the mountains of Mexico. Much of the city is built on artificial fill on top of fine-grained sediments from an extensive lake and wetlands that were drained and filled in as the city grew. As a result of how seismic waves are amplified in soft sediments, the shaking of the ground in Mexico City during an earthquake is greater than it is in areas outside the basin, which have bedrock close to the surface. During the 1985 earthquake, which originated offshore of Acapulco on the Pacific coast, 300 km (200 miles) away, many buildings in Mexico City collapsed and more than 20,000 people died.

The Marina District in northern San Francisco is built on artificial fill on wet bayshore sediments. Rubble and debris from buildings that collapsed or burned in that district as a result of the 1906 earthquake was used as artificial fill beneath structures built during the reconstruction of that area. In 1989, the Loma Prieta earthquake caused collapse of several buildings in the Marina District, and several people died there. Another example of a structure on wet ground covered by artificial fill that collapsed during the Loma Prieta earthquake is the Cypress viaduct in Oakland, CA. The USGS photo below shows the failed support columns.

Permanent Ground Displacement

During large earthquakes, the ground may permanently shift to a new position up, down, or sideways (up to 10 or more m, 30 or 40 ft, in extreme cases). This change in the location of the ground, which also tilts the ground, may cause disruption of roads and utilities and, in coastal cities, submergence or emergence of harbor facilities. Even ground shifts of less than a meter (a foot or two) can cause serious disruption to infrastructure.

Earth Rupture

During most earthquakes, some rupturing of the earth's surface takes place along the fault trace. This produces a fault scarp, which may have up to several m (up to 10 ft or more) of vertical displacement. This can disrupt roads and utilities, and any buildings on a fault that ruptures may undergo extensive damage.

Rupture of the earth during an earthquake may also occur on secondary faults. Earthquake-induced rupture of the earth's surface may also take place in weak zones of surface sediment that fracture and spread. If enough spreading of a ruptured surface layer takes place, it can be classified as a landslide. The NOAA photo below shows substantial damage in the Turnagain-By-The-Sea subdivision caused by the 1964 Great Alaskan Earthquake.

Landslides and Avalanches

On steep slopes and in mountainous areas, large earthquakes can set off many landslides, rockfalls, or avalanches. These can damage buildings, towns, or roads in the path of the landslides.

Liquefaction

If fine- or medium-grained, unconsolidated sediments are saturated with groundwater, the shaking that occurs during an earthquake may cause the sediment grains to lose contact with each other and become suspended in the water, temporarily turning what was solid ground into liquid ground. Building and other structures may sink, tilt, or slide a short distant in liquefied ground, causing serious damage.

Fires

Fires are a secondary rather than a primary effect of earthquakes. Broken electrical wires and natural gas pipes commonly set off fires during earthquakes. To compound the problem, the water supply may also be disrupted by earthquake damage, making it impossible to put the fire out with water from fire hydrants. The fire that broke out as a result of the great San Francisco earthquake of 1906 burned much of the city to the ground, causing more extensive damage to buildings than the shaking of the ground did during the earthquake.

Tsunamis

A tsunami is a set of waves in the ocean (or a large lake) with an extremely long wavelength, typically over 100 km long. Tsunamis move at many 100s of km per hour in deep water. Tsunamis can be set off by violent volcanic eruptions originating just below sea level, by giant landslides that either occur underwater or tumble into the sea from coastal mountains, by large meteorite impacts, and, most commonly, by earthquakes that greatly shake the ocean floor, which commonly happens at subduction zones.

The amplitude, or crest height, of an individual tsunami wave may be only about 1 m (roughly 3 feet high) in the open ocean. It is common for a tsunami to pass ships at sea without being noticed. However, as the wave approaches shore where the bottom grows shallower, the crest builds up to a height of up to several tens of meters (over 30 feet in some cases). The wave crest may wash ashore for several minutes before subsiding. Even a tsunami wave of no higher than 3 m (10 feet) coming ashore can cause extensive damage in harbors and to shores, as the long-wavelength wave keeps pouring in for several minutes.

Tsunamis consist of more than one wave, so a second wave crest may climb ashore several minutes later. Some tsunamis lead with the wave trough, so the first thing noticed as that type of tsunami approaches a shore is a dramatic drawback, or retreat, of the sea, like the tide suddenly going out. Such a drawback will inevitably be followed by a rising tsunami wave crest.

The tsunamis from the Sumatra earthquake of 2004 killed over 100,000 people in coastal areas of the Indian Ocean, some on shores several thousand km (several thousand miles) away from the epicenter of the earthquake. The great southeast Alaska earthquake of 1964 generated a tsunami that killed 16 people on the coast of Oregon and northern California, over 1,000 km (600 miles) away. Tsunamis have been known to cross the entire Pacific Ocean and cause fatalities a third of the way around the world. Hawaii, in the middle of the Pacific Ocean, has been damaged by tsunamis, originating from subduction earthquakes on the Pacific Rim, several times in the last few centuries. Japan, with its complex set of subduction zones and its eastern shoreline open to the Pacific Ocean, has experienced over 100 tsunamis in its recorded history, most recently as a result of a great subduction earthquake off the northern island in 2011 which resulted in several coastal towns being destroyed and thousands of people dying. The last great tsunami generated by the Cascadia subduction zone along the coast of the Pacific Northwest flooded coastal areas of Washington, Oregon northern California, and Vancouver Island in Canada. It occurred in 1701, long before the region was as populated as it is now. Subduction continues in the Cascadia subduction zone and more tsunamis can be expected to be generated by earthquakes there in the future.

Mitigating Earthquake Damage

Much can be done to reduce the risk of fatalities during earthquakes, and to reduce the damage to buildings and infrastructure; in other words, to mitigate the effects of earthquakes.

In many cases, it is collapsed buildings that cause the most harm during an earthquake. Buildings should be constructed in ways

that make them unlikely to collapse during an earthquake. The strategies that engineers have developed include having sufficient flexibility in the structure to absorb shaking during an earthquake. Bricks, mortar, and concrete are rigid and brittle. However, bricks and mortar, and concrete, can be reinforced with steel to make them better able to survive an earthquake. Wood and steel are more flexible than bricks, mortar, and concrete, and lend themselves to the type of building that, properly designed and built according to code, is likely to survive an earthquake without collapsing.

The way a building is attached to its foundation, and how the foundation is anchored in the earth, are important considerations in earthquake design. Many houses built in the the early and mid-1900s in California were not attached to their foundations, based on the assumption that the weight of a house would keep it on its foundation. It turned out to be a bad assumption. Earthquakes caused houses to slide off their foundations. Many home-owners in the state have taken steps to make sure that their houses are now attached to their foundations; if a home-owner buys earthquake insurance, it is usually required by the insurance company that they do so. A large building or skyscraper built in an earthquake-prone area will normally have a great deal of flexibility built into it, including some sort of elastic strain absorption mechanism focused on points where the building attaches to its foundation.

Infrastructure—roads, bridges, utilities—can be built with margins of safety for the event of an earthquake. This includes gas pipelines designed to slide back and forth on their supports and having built-in shutoff valves that may be activated by automatic sensors, electric lines and grids with similar flexibility and shut-off capabilities, and roads, overpasses, and bridges built to withstand shaking during an earthquake.

Development and enforcement of building codes aimed at reducing risk from earthquakes often requires resources that are not available in impoverished regions. This leads to a higher likelihood that buildings will collapse from the same size earthquake in some areas of the world than in other areas.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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8.7: Magnitude and Intensity

DEFINE AND COMPARE MAGNITUDE VERSUS INTENSITY

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Earthquake Intensity
- Reading: Magnitude vs. Intensity

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8.8: Earthquake Intensity

MEASURING EARTHQUAKES

People have always tried to quantify the size of and damage done by earthquakes. Since early in the 20th century, there have been three methods. What are the strengths and weaknesses of each?

- Mercalli Intensity Scale. Earthquakes are described in terms of what nearby residents felt and the damage that was done to nearby structures.
- Richter magnitude scale. Developed in 1935 by Charles Richter, this scale uses a seismometer to measure the magnitude of the largest jolt of energy released by an earthquake.
- Moment magnitude scale. Measures the total energy released by an earthquake. Moment magnitude is calculated from the area of the fault that is ruptured and the distance the ground moved along the fault.

The Richter scale and the moment magnitude scale are logarithmic.

- The amplitude of the largest wave increases ten times from one integer to the next.
- An increase in one integer means that thirty times more energy was released.
- These two scales often give very similar measurements.

How does the amplitude of the largest seismic wave of a magnitude 5 earthquake compare with the largest wave of a magnitude 4 earthquake? How does it compare with a magnitude 3 quake? 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.

How does an increase in two integers on the moment magnitude scale compare in terms of the amount of energy released? Two integers equals a 900-fold increase in released energy.

Which scale do you think is best? With the Richter scale, a single sharp jolt measures higher than a very long intense earthquake that releases more energy. The moment magnitude scale more accurately reflects the energy released and the damage caused. Most seismologists now use the moment magnitude scale.

The way scientists measure earthquake intensity and the two most common scales, Richter and moment magnitude, are described along with a discussion of the 1906 San Francisco earthquake in *Measuring Earthquakes* video:

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

ANNUAL EARTHQUAKES

In a single year, on average, more than 900,000 earthquakes are recorded and 150,000 of them are strong enough to be felt. Each year about 18 earthquakes are major with a Richter magnitude of 7.0 to 7.9, and on average one earthquake has a magnitude of 8 to 8.9.

Magnitude 9 earthquakes are rare. The United States Geological Survey lists five since 1900 (see figure 1 and table 1). All but the Great Indian Ocean Earthquake of 2004 occurred somewhere around the Pacific Ocean basin.



Figure 1. The 1964 Good Friday Earthquake centered in Prince William Sound, Alaska released the second most amount of energy of any earthquake in recorded history.

Table 1. Earthquakes of magnitude 9 or greater

Location	Year	Magnitude
Valdivia, Chile	1960	9.5
Prince William Sound, Alaska	1964	9.2
Great Indian Ocean Earthquake	2004	9.1
Kamchatka, Alaska	1952	9.0
Tōhoku, Japan	2011	9.0

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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8.9: Magnitude vs. Intensity

Magnitude and Intensity measure different characteristics of earthquakes. Magnitude measures the energy released at the source of the earthquake. Magnitude is determined from measurements on seismographs. Intensity measures the strength of shaking produced by the earthquake at a certain location. Intensity is determined from effects on people, human structures, and the natural environment.

MAGNITUDE / INTENSITY COMPARISON

The following table gives intensities that are typically observed at locations near the epicenter of earthquakes of different magnitudes.

Magnitude	**Typical Maximum Modified Mercalli Intensity**
1.0 – 3.0	I
3.0 – 3.9	**II – III**
4.0 – 4.9	**IV – V**
5.0 – 5.9	**VI – VII**
6.0 – 6.9	**VII – IX**
7.0 and higher	**VIII** or higher

ABBREVIATED MODIFIED MERCALLI INTENSITY SCALE

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 quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. 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 motor 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 few instances of 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 badly 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. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.

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 (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.

XII. Damage total. Lines of sight and level are distorted. Objects thrown into the air.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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8.10: Predicting Seismic Activity

RECOGNIZE OUR LIMITED ABILITY TO PREDICT SEISMIC ACTIVITY

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Earthquake Prediction
- Reading: Seismicity and Earthquake Prediction

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8.11: Earthquake Prediction

EARTHQUAKE PREDICTION

Scientists are a long way from being able to predict earthquakes. A good prediction must be accurate as to where an earthquake will occur, when it will occur, and at what magnitude it will be so that people can evacuate. An unnecessary evacuation is expensive and causes people not to believe authorities the next time an evacuation is ordered.

Where an earthquake will occur is the easiest feature to predict. Scientists know that earthquakes take place at plate boundaries and tend to happen where they've occurred before (figure 1). Earthquake-prone communities should always be prepared for an earthquake. These communities can implement building codes to make structures earthquake safe.

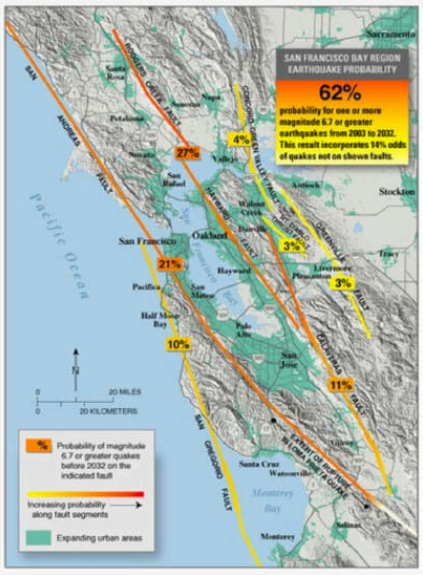


Figure 1. The probabilities of earthquakes striking along various faults in the San Francisco area between 2003 (when the work was done) and 2032.

When an earthquake will occur is much more difficult to predict. Since stress on a fault builds up at the same rate over time, earthquakes should occur at regular intervals (figure 2). But so far scientists cannot predict when quakes will occur even to within a few years.

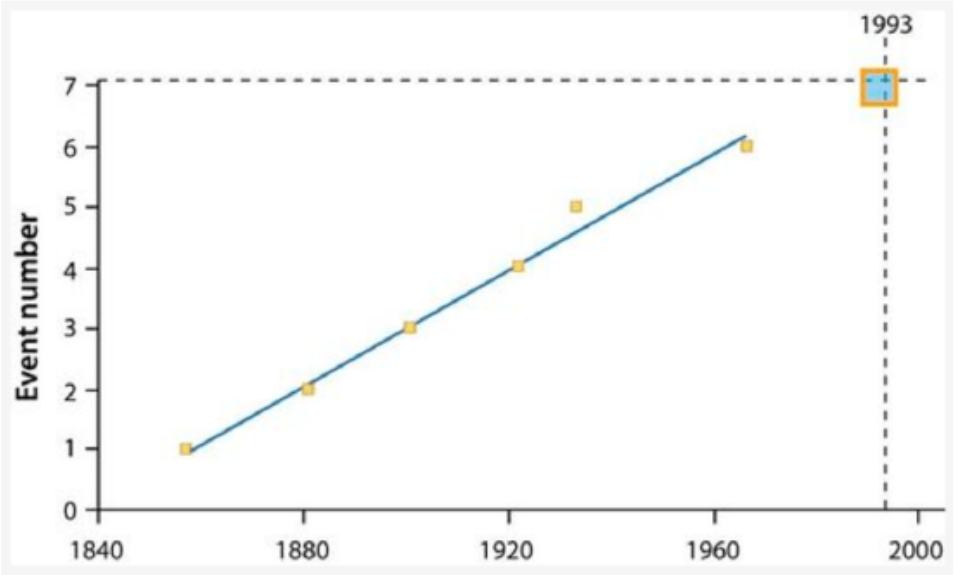


Figure 2. Around Parkfield, California, an earthquake of magnitude 6.0 or higher occurs about every 22 years. So seismologists predicted that one would strike in 1993, but that quake came in 2004 – 11 years late.

Signs sometimes come before a large earthquake. Small quakes, called foreshocks, sometimes occur a few seconds to a few weeks before a major quake. However, many earthquakes do not have foreshocks and small earthquakes are not necessarily followed by a large earthquake. Often, the rocks around a fault will dilate as microfractures form. Ground tilting, caused by the buildup of stress in the rocks, may precede a large earthquake, but not always. Water levels in wells fluctuate as water moves into or out of fractures before an earthquake. This is also an uncertain predictor of large earthquakes. The relative arrival times of P-waves and S-waves also decreases just before an earthquake occurs.

Folklore tells of animals behaving erratically just before an earthquake. Mostly these anecdotes are told after the earthquake. If indeed animals sense danger from earthquakes or tsunami, scientists do not know what it is they could be sensing, but they would like to find out.

The geology of California underlies the state's wealth of natural resources as well as its natural hazards. This video explores the enormous diversity of California's geology:

YouTube Video

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8.12: Seismicity and Earthquake Prediction

Seismicity is the study of how often earthquakes occur in a particular area, which types of earthquakes occur there, and why.

In the United States, the areas that most frequently experience earthquakes are the coast of California, Oregon, and Washington, the southern coast and Aleutian Islands of Alaska, Hawaii, and the mountain west from the Rocky Mountains to the Pacific coast. The central and eastern United States rarely experience significant earthquakes.

Earthquake epicenters compiled on a map show that, on a global basis, most earthquakes occur around the rim of the Pacific Ocean, in the mountains of southern Asia from China to the Middle East, and in the Mediterranean Sea area. Earthquake epicenters also trace the mid-ocean ridges across the floors of the oceans.

Because nearly all earthquakes occur on faults, determining seismic risks on a finer scale largely consists of identifying, mapping, and studying active faults in each state or region. However, many active faults are hidden, either because any scarps they formed at the surface have been eroded or covered by sediments, soil, and vegetation, or because they are blind faults. A hidden fault is often not identified and located until one or more significant earthquakes has occurred on it and the seismic waves have been studied to determine its location and type of fault motion.

Information used to determine the seismicity of an area includes:

- frequency of earthquakes in the past, as deduced from:
  - historic records
  - geologic studies that examine evidence of the prehistoric earthquake record
- location of known active faults
- seismologic data collected on recent earthquakes that have occurred in the area
- tectonic setting of the area in terms of proximity to plate boundaries, and information about the plate boundary if one is nearby
- stress and strain being experienced by the crust in that area based on measurements from GPS equipment and from stress and strain measurements conducted in boreholes
- underground geologic layers and structures in that area based on cross-sections from geologic mapping, data from drilling, and remote imaging of deeper layers of the crust and mantle

Based on this information, the seismic risk of a particular area can be quantified statistically. For example, the odds of a major earthquake happening in the next century, or in the next 10 years, can be estimated for a specific seismic zone.

However, no scientific method has yet been developed that can predict precisely when the next earthquake in a specific region will happen, where it will happen, or what its magnitude will be. Scientists have looked into using such possible pre-earthquake indicators as ground tilting, changes in well water levels, changes in radon gas in groundwater near fault zones, changes in electrical conductivity in the earth around faults, changes or patterns in seismic activity that can be measured by seismometers even though it is not felt by humans, and strange animal behavior which, according to numerous, largely unconfirmed anecdotes, takes place before an earthquake. But, so far, none of these types of data have been found to lead to reliable earthquake predictions.

People have also looked into correlations between earthquakes and phases of the Moon, earthquakes and the time of day (such as dawn when the Sun is first shining on the ground), and so on. No connections have been found between earthquakes and these other types of phenomena.

As the study of seismicity stands now, we can identify which areas on earth will undergo major earthquakes in the coming decades and centuries, we can delineate which areas on earth are at risk for the most powerful types of earthquakes, and map the coastal areas that are most at risk of being inundated by a tsunami, but we cannot pinpoint in advance the date or location of the next major earthquake.

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8.13: Deciphering Geologic Materials

EXPLAIN HOW SEISMIC WAVES ARE USED TO DECIPHER GEOLOGIC MATERIALS IN THE CRUST AND IN THE EARTH'S DEEPER INTERIOR

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Earth's Interior

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8.14: Earth's Interior

INTRODUCTION

If we could journey to the center of the earth we would have to travel about 6,400 km (4,000 miles). Along the way to earth's core we would pass layers of rock that can be classified in two different ways, either by their chemistry or their physical behavior.

According to the chemical composition of the rocks, earth's interior can be differentiated into three layers—crust, mantle, and core.

When considering the rocks of earth's interior in terms of their physical behavior, six layers can be differentiated from the surface to the core. The characteristics that distinguish these six different layers are based on the relative strength of a given layer in response to stress and whether it is solid or liquid.

TOUR THROUGH THE LAYERS OF EARTH

The chemical compositions and physical behaviors of the rocks of earth's interior converge in many ways but it is worthwhile to become familiar with the each of the different set of layers individually before exploring how they overlap.

The chemical composition and physical behavior of rock inside the earth relate to each other because the chemical composition of a rock is one of the factors that determines its physical behavior. However, the physical behavior of rock also depends on the pressure and temperature it is subjected to at its depth within the earth. As depth inside the earth increases, the pressure and temperature increase. Some layers in the earth are harder or softer than adjacent layers, even though they have the same composition, because they are at different pressures and temperatures.

Surface to Core, Chemically

Crust

The tour starts at the surface with earth's crust. Generally speaking, the crust is predominately silicon oxide and aluminum oxide. Continental crust is thicker and less dense than oceanic crust. Earth's crust varies in thickness from less than 5 km (under mid-ocean spreading ridges) to more than 70 km (beneath the highest mountain range).

Mantle

The next layer down chemically is the mantle. The mantle has an ultramafic composition – it contains more iron, magnesium, less aluminum and somewhat less silicon than the crust. The mantle is roughly 2,900 km thick. In terms of volume, the mantle is the largest of earth's three chemical layers.

Core

The final stop on the chemical tour is the core, which is mostly iron and nickel. The core is about 3,500 km thick.

The following table summarizes the chemical layers of the earth.

Chemical Layers of Earth		
Crust	**Mantle**	**Core**
composition: high Si, Al, & O	*composition:* moderate Si, high Mg & Fe	*composition:* Fe & Ni
thickness: 5 to 70 km	*thickness:* 2,900 km	*thickness:* 3,500 km

Surface to Core, Physically

Lithosphere

Starting at the surface, the first layer is the lithosphere. We humans, and the other creatures that live on earth, occupy the surface of the lithosphere. The lithosphere is entirely solid except where there are zones of magma beneath volcanoes or in places undergoing magma intrusion. The volume of molten rock in the lithosphere is a tiny fraction, less than 0.1%, of the volume of the entire lithosphere.

The lithosphere itself has two parts. The top part is the crust. The bottom part is the lithospheric mantle. The two components of the lithosphere, in combination, form a relatively strong, rigid layer of rock that covers the earth. Earth's tectonic plates, all of which are in motion relative to each other, make up the lithosphere.

Asthenosphere

Beneath the lithosphere is a relatively weak and ductile layer of the mantle called the asthenosphere. Although the asthenosphere is solid, not liquid, it flows at geological rates, up to several cm (several inches) per year. In other words, the asthenosphere behaves much more plastically than the rigid lithosphere above it does.

The chemical composition of the asthenosphere is about the same as the chemical composition of the overlying lithospheric mantle. Why, then, is the asthenosphere soft and the lithosphere rigid? It is because at the depth of the asthenosphere, temperatures are very close to the melting point of the rock, weakening the rock. In fact, it is thought likely, from indirect evidence, that there is a small percentage of molten rock in the tiny spaces between the minerals of the asthenosphere, which contributes to the soft nature of the rock. However, the solid minerals of the asthenosphere are extensively in contact with each other, forming a material that is solid overall despite the possible presence of a small amount of partial melt.

The asthenosphere is the primary source of most magma. Because the asthenosphere is close to its melting point and may contain everywhere a small proportion of partly molten rock, it does not take much to cause magma to form and separate from the asthenosphere. As explained in the igneous rocks Basics page, melting of the asthenosphere can be caused by addition of fluid, particularly water, or by a decrease in pressure. In subduction zones, slabs of sinking lithosphere release water into the asthenosphere, causing the asthenosphere to melt and produce magma which rises into and through the crust, producing the volcanic arc that is found at every subduction zone. At divergent plate boundaries, the asthenosphere flows upward, or upwells, which reduces the lithostatic pressure enough to cause the rock of the asthenosphere to melt. That is why divergent plate boundaries are volcanic zones. The solidified lavas and intrusions at divergent plate boundaries produce new lithosphere, which fills in and replaces the plate material that spreads away on either side.

Upper Mesosphere

Beneath the asthenosphere is the rest of the mantle, the mesosphere. The mesosphere makes up most of the volume of the mantle. The mesosphere is entirely solid. The temperature and pressure of the rock in the mesosphere keep it from breaking; therefore, no earthquakes originate from the mesosphere.

The upper mesosphere is a transition zone in which the rock rapidly becomes denser with depth in response to the increasing lithostatic pressure.

Lower Mesosphere

The lower mesosphere starts at a depth of 660 km from earth's surface. At that depth there is an abrupt increase in density. This increase is caused by changes in the crystal structures of the most abundant minerals in the rock. These minerals change from less dense crystal structures above the boundary to more dense crystal structures below the boundary. The lower mesosphere undergoes little density change from its top boundary at 660 km to its base at 2900 km where it meets the outer core.

Outer Core

The bottom of the mesosphere is the boundary with the earth's core. The core is about twice as dense as the crust, and about 1.5

times as dense as the mantle. The outer core is liquid, as was discovered when it was first observed that S-waves will not pass through it.

Inner Core

The inner core is solid. The inner and outer cores are made of the same iron-rich, metallic composition. The temperature of the inner core is not very much greater than the temperature of the outer core. However, lithostatic pressure keeps increasing with depth and the inner core has the great weight of the rest of the earth pressing in on it. The pressure on the inner core is high enough to keep it in the solid state.

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8.15: Putting It Together

SUMMARY

Just to review, in the section we took an up close look at earthquakes. We made note of the following:

1. What seismic waves are and how they are generated
2. The different types of seismic waves and their characteristics
3. How seismic waves are used to give us a peak at the Earth's interior
4. What causes earthquakes and where they occur
5. The different ways earthquakes are measured
6. How different material responds to an earthquake
7. The inability of scientists to predict earthquakes with any accuracy

SYNTHESIS

I'm sure at least some of the reasons to study earthquakes go without saying. Geologists study earthquakes so they can better understand the cause of earthquakes which can in turn help with future predictions. Right now, there is very little ability to predict an earthquake. Geologists are interested in how the ground and different materials move during the earthquake. All of this information helps scientists and engineers understand what is required to build structures to withstand earthquakes. The hazards associated with earthquakes are some of the most dangerous and deadly as you saw in the videos at the beginning of the section.

So, why do California and Japan have so many earthquakes? California is located on the San Andreas Fault (one of many), which is a part of a transform plate boundary that is constantly moving. In the case of Japan, if you look back at the plate tectonics map, you will see Japan sits on top of *three* different tectonic plates that all moving in different ways. We now know that this movement is the main cause of earthquakes. As we continue to learn more about earthquakes, perhaps the next 9.0 earthquake will not do so much damage or claim so many lives.

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9: VOLCANIC ACTIVITY

Volcanoes are one of the most dynamic, powerful and destructive forces on the Earth. While they are majestic in appearance, they are often sleeping giants just waiting to wake up and make us take notice. Some of you may have seen volcanic eruptions in person or on TV. Volcanoes are the geologists' window into the Earth's interior. If you recall from the previous section, plate tectonics directly influences the location and types of volcanoes we find across the globe. Now we understand why the west coast of America as a chain of volcanoes in the Cascade Mountains and why Japan has so many active volcanoes.



- Topic hierarchy

9.1: Why It Matters

9.2: Products of Volcanic Activity

9.3: Volcanic Eruptions

9.4: Volcano Types

9.5: Types of Volcanoes

9.6: Basics-Volcanoes

9.7: Volcanic Hazards

9.8: Volcanoes

9.9: Types of Volcano Hazards

9.10: Putting It Together

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9.1: Why It Matters

EXPLAIN THE ORIGIN OF IGNEOUS PRODUCTS AND LANDFORMS AND THE CAUSES AND HAZARDS ASSOCIATED WITH VOLCANIC ACTIVITY

Volcanoes are one of the most dynamic, powerful and destructive forces on the Earth. While they are majestic in appearance, they are often sleeping giants just waiting to wake up and make us take notice. Some of you may have seen volcanic eruptions in person or on TV. Volcanoes are the geologists' window into the Earth's interior. If you recall from the previous section, plate tectonics directly influences the location and types of volcanoes we find across the globe. Now we understand why the west coast of America as a chain of volcanoes in the Cascade Mountains and why Japan has so many active volcanoes.

Occupation Focus: Volcanologists

Volcanologists have one of the most exciting yet dangerous jobs of all scientists. Please watch this video on the eruption of Mt. St. Helens in 1980 to learn more about volcanic eruptions, how scientists study the volcanoes and why volcanologists are important to society.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

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This video shows the most destructive eruption ever that happen to also be the loudest sound ever recorded on earth. This eruption actually blew the volcanoes out of existence, until recently as a new active volcano is currently forming in its place.

Learning Outcomes

- Classify and identify volcanic rocks, pyroclastic rocks, pyroclastic deposits, and types of lava
- Describe and compare different volcano types and the processes that form them
- Describe major volcanic hazards and their potential effects

Ok, let's get started!

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9.2: Products of Volcanic Activity

CLASSIFY AND IDENTIFY VOLCANIC ROCKS, PYROCLASTIC ROCKS, PYROCLASTIC DEPOSITS, AND TYPES OF LAVA

[Insert brief introductory statement here.]

Open Educational Resources

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- Reading: Volcanic Eruptions

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9.3: Volcanic Eruptions

INTRODUCTION

In 1980, Mount St. Helens blew up in the costliest and deadliest volcanic eruption in United States history. The eruption killed 57 people, destroyed 250 homes and swept away 47 bridges (figure 1).



Figure 1. Mount St. Helens on May 18, 1980.

Mt. St. Helens still has minor earthquakes and eruptions. The volcano now has a horseshoe-shaped crater with a lava dome inside. The dome is formed of viscous lava that oozes into place.

MAGMA COMPOSITION

Volcanoes do not always erupt in the same way. Each volcanic **eruption** is unique, differing in size, style, and composition of erupted material. One key to what makes the eruption unique is the chemical composition of the magma that feeds a volcano, which determines (1) the eruption style, (2) the type of volcanic cone that forms, and (3) the composition of rocks that are found at the volcano.

Remember from the Rocks chapter that different minerals within a rock melt at different temperatures. The amount of partial melting and the composition of the original rock determine the composition of the magma. Magma collects in **magma chambers** in the crust at 160 kilometers (100 miles) beneath the surface.

The words that describe composition of igneous rocks also describe magma composition.

- Mafic magmas are low in silica and contain more dark, magnesium and iron rich mafic minerals, such as olivine and pyroxene.
- Felsic magmas are higher in silica and contain lighter colored minerals such as quartz and orthoclase feldspar. The higher the amount of silica in the magma, the higher is its **viscosity.** Viscosity is a liquid's resistance to flow (figure 2).



Figure 2. Honey flows slowly. It is more viscous than water.

Viscosity determines what the magma will do. Mafic magma is not viscous and will flow easily to the surface. Felsic magma is viscous and does not flow easily. Most felsic magma will stay deeper in the crust and will cool to form igneous intrusive rocks such as granite and granodiorite. If felsic magma rises into a magma chamber, it may be too viscous to move and so it gets stuck. Dissolved gases become trapped by thick magma. The magma churns in the chamber and the pressure builds.

ERUPTIONS

The type of magma in the chamber determines the type of volcanic eruption. Although the two major kinds of eruptions—explosive and effusive—are described in this section, there is an entire continuum of eruption types. Which magma composition do you think leads to each type?

Explosive Eruptions

A large **explosive eruption** creates even more devastation than the force of the atom bomb dropped on Nagasaki at the end of World War II in which more than 40,000 people died. A large explosive volcanic eruption is 10,000 times as powerful. Felsic magmas erupt explosively. Hot, gas-rich magma churns within the chamber. The pressure becomes so great that the magma eventually breaks the seal and explodes, just like when a cork is released from a bottle of champagne. Magma, rock, and ash burst upward in an enormous explosion. The erupted material is called **tephra** (figure 3).



Figure 3. Ash and gases create a mushroom cloud above Mt. Redoubt in Alaska, 1989. The cloud reached 45,000 feet and caught a Boeing 747 in its plume.

Scorching hot tephra, ash, and gas may speed down the volcano's slopes at 700 km/h (450 mph) as a **pyroclastic flow.** Pyroclastic flows knock down everything in their path. The temperature inside a pyroclastic flow may be as high as 1,000°C (1,800°F) (figure 4).

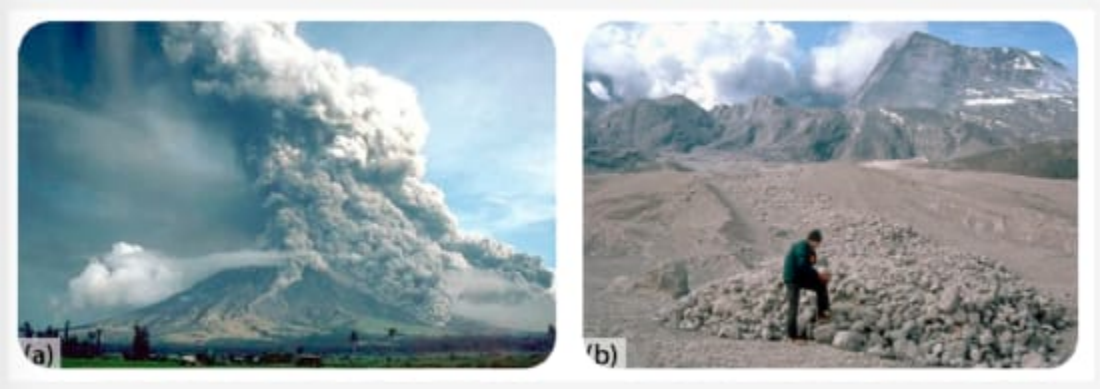


Figure 4. (a) An explosive eruption from the Mayon Volcano in the Philippines in 1984. Ash flies upward into the sky and pyroclastic flows pour down the mountainside. (b) The end of a pyroclastic flow at Mount St. Helens.

Watch this video of a pyroclastic flow at Montserrat volcano.

Prior to the Mount St. Helens eruption in 1980, the Lassen Peak eruption on May 22, 1915, was the most recent Cascades eruption. A column of ash and gas shot 30,000 feet into the air. This triggered a high-speed pyroclastic flow, which melted snow and created a volcanic mudflow known as a **lahar**. Lassen Peak currently has geothermal activity and could erupt explosively again. Mt. Shasta, the other active volcano in California, erupts every 600 to 800 years. An eruption would most likely create a large pyroclastic flow, and probably a lahar. Of course, Mt. Shasta could explode and collapse like Mt. Mazama in Oregon (figure 5).

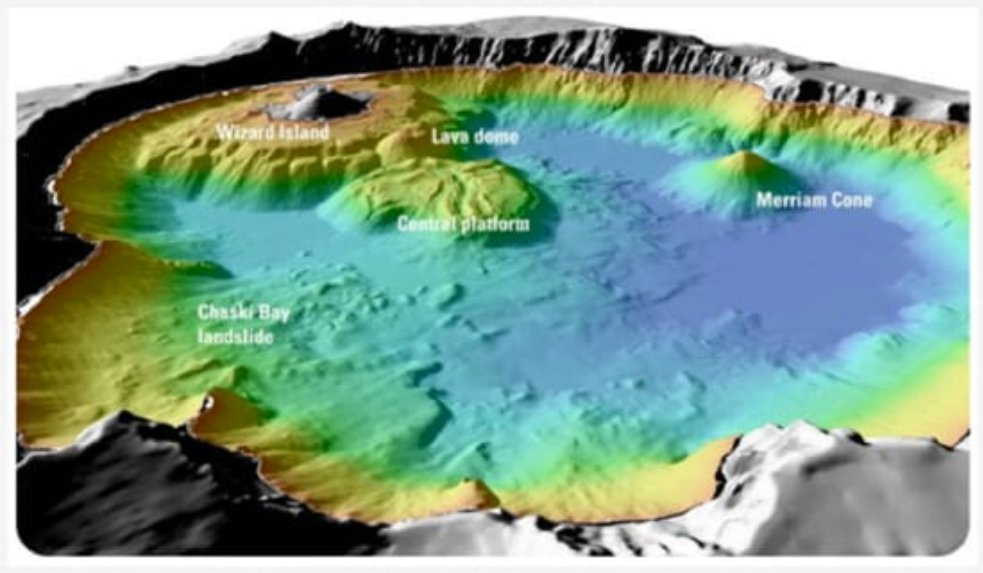


Figure 5. Crater Lake fills the caldera of the collapsed Mt. Mazama, which erupted with 42 times more power than Mount St. Helens in 1980. The bathymetry of the lake shows volcanic features such as cinder cones.

Volcanic gases can form poisonous and invisible clouds in the atmosphere. These gases may contribute to environmental problems such as acid rain and ozone destruction. Particles of dust and ash may stay in the atmosphere for years, disrupting weather patterns and blocking sunlight (figure 6).

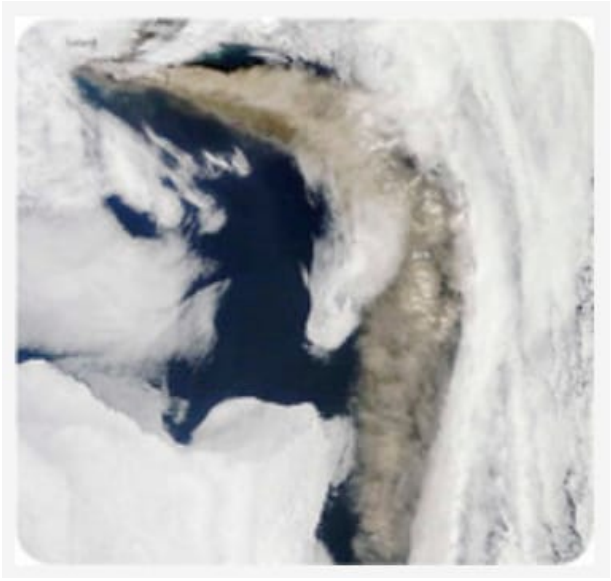


Figure 6. The ash plume from Eyjafjallajökull volcano in Iceland disrupted air travel across Europe for six days in April 2010.

Effusive Eruptions

Mafic magma creates gentler **effusive eruptions**. Although the pressure builds enough for the magma to erupt, it does not erupt with the same explosive force as felsic magma. People can usually be evacuated before an effusive eruption, so they are much less deadly. Magma pushes toward the surface through fissures. Eventually, the magma reaches the surface and erupts through a vent (figure 7).

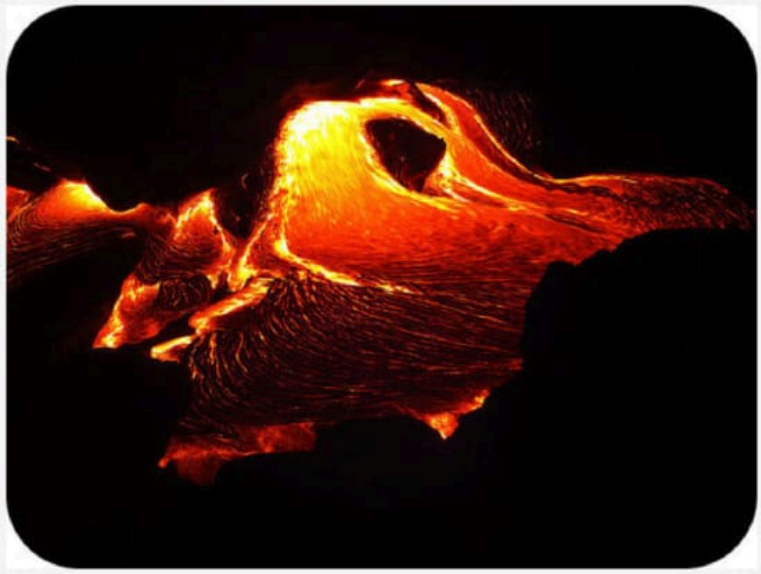


Figure 7. In effusive eruptions, lava flows readily, producing rivers of molten rock.

- The Kilauea volcanic eruption in 2008 is seen in this short video. http://www.youtube.com/watch?v=BtH79yxBIJI
- Watch this movie with thermal camera of a lava stream within the vent of a Hawaiian volcano.

Low-viscosity lava flows down mountainsides. Differences in composition and where the lavas erupt result in three types of lava flow coming from effusive eruptions (figure 8).

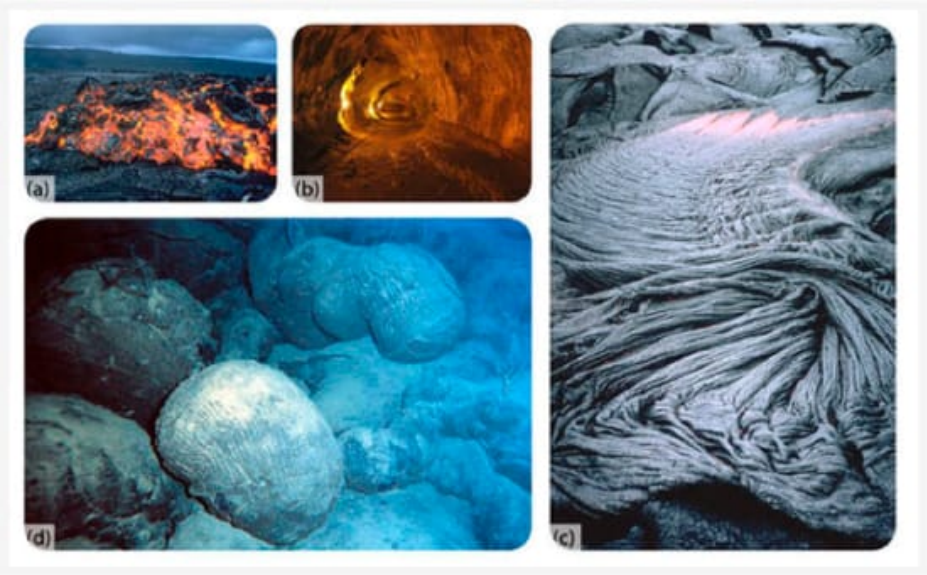


Figure 8. (a) A'a lava forms a thick and brittle crust that is torn into rough and jagged pieces. A'a lava can spread over large areas as the lava continues to flow underneath the crust's surface. (b) Pāhoehoe lava forms lava tubes where fluid lava flows through the outer cooled rock crust, as can be seen at the Thurston Lava Tube in Hawai'i Volcanoes National Park. (c) Pāhoehoe lava is less viscous than a'a lava so its surface looks is smooth and ropy. (d) Mafic lava that erupts underwater creates pillow lava. The lava cools very quickly to roughly spherical rocks. Pillow lava is common at mid-ocean ridges.

- Watch this videos of an undersea eruption. In this video you can hear the underwater eruption as well.

Although effusive eruptions rarely kill anyone, they can be destructive. Even when people know that a lava flow is approaching, there is not much anyone can do to stop it from destroying a building or road (figure 9).



Figure 9. A road is overrun by an eruption at Kilauea volcano in Hawaii.

PREDICTING VOLCANIC ERUPTIONS

Volcanologists attempt to forecast volcanic eruptions, but this has proven to be nearly as difficult as predicting an earthquake. Many pieces of evidence can mean that a volcano is about to erupt, but the time and magnitude of the eruption are difficult to pin down. This evidence includes the history of previous volcanic activity, earthquakes, slope deformation, and gas emissions.

History of Volcanic Activity

A volcano's history—how long since its last eruption and the time span between its previous eruptions—is a good first step to predicting eruptions. Which of these categories does the volcano fit into?

- Active: currently erupting or showing signs of erupting soon.
- Dormant: no current activity, but has erupted recently (figure 10).
- **Extinct:** no activity for some time; will probably not erupt again.



Figure 10. Mount Vesuvius destroyed Pompeii in 79 AD. Fortunately this volcano is dormant because the region is now much more heavily populated.

Active and dormant volcanoes are heavily monitored, especially in populated areas.

Earthquakes

Moving magma shakes the ground, so the number and size of earthquakes increases before an eruption. A volcano that is about to erupt may produce a sequence of earthquakes. Scientists use seismographs that record the length and strength of each earthquake to try to determine if an eruption is imminent.

Slope Deformation

Magma and gas can push the volcano's slope upward. Most ground deformation is subtle and can only be detected by tiltmeters, which are instruments that measure the angle of the slope of a volcano. But ground swelling may sometimes create huge changes in the shape of a volcano. Mount St. Helens grew a bulge on its north side before its 1980 eruption. Ground swelling may also increase rock falls and landslides.

Gas Emissions

Gases may be able to escape a volcano before magma reaches the surface. Scientists measure gas emissions in vents on or around the volcano. Gases, such as sulfur dioxide (SO_2), carbon dioxide (CO_2), hydrochloric acid (HCl), and even water vapor can be measured at the site (figure 11) or, in some cases, from a distance using satellites. The amounts of gases and their ratios are calculated to help predict eruptions.



Figure 11. Scientists monitoring gas emissions at Mount St. Helens.

Remote Monitoring

Some gases can be monitored using satellite technology (figure 12). Satellites also monitor temperature readings and deformation. As technology improves, scientists are better able to detect changes in a volcano accurately and safely.

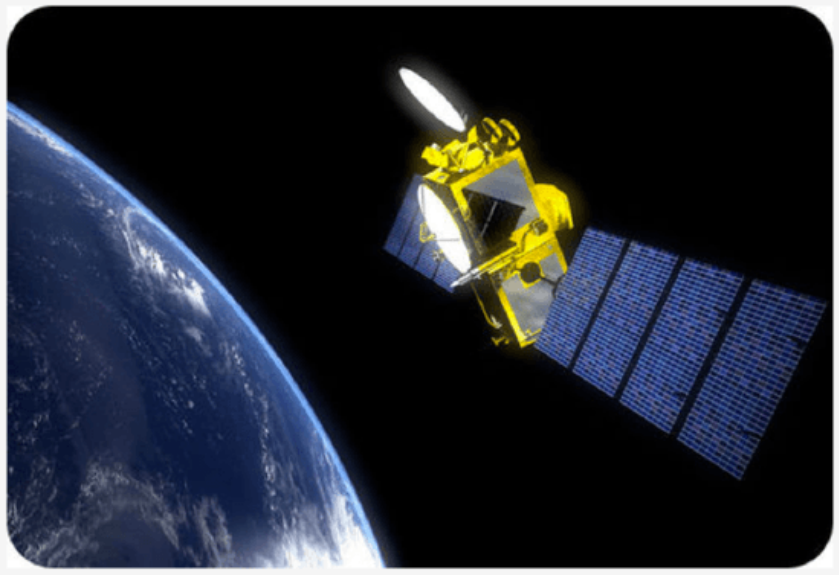


Figure 12. A satellite above Earth.

Since volcanologists are usually uncertain about an eruption, officials may not know whether to require an evacuation. If people are evacuated and the eruption doesn't happen, the people will be displeased and less likely to evacuate the next time there is a threat of an eruption. The costs of disrupting business are great. However, scientists continue to work to improve the accuracy of their predictions.

LESSON SUMMARY

- The style of a volcanic eruption depends on magma viscosity.
- Felsic magmas produce explosive eruptions. Mafic magmas produce effusive eruptions.
- Explosive eruptions happen along the edges of continents and produce tremendous amounts of material ejected into the air.
- Non-explosive eruptions produce lavas, such as a'a, pahoehoe, and pillow lavas.
- Volcanoes are classified as active, dormant, or extinct.
- Signs that a volcano may soon erupt include earthquakes, surface bulging, and gases emitted, as well as other changes that can be monitored by scientists.

Visit this USGS photo glossary to broaden your knowledge.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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9.4: Volcano Types

DESCRIBE AND COMPARE DIFFERENT VOLCANO TYPES AND THE PROCESSES THAT FORM THEM

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Types of Volcanoes
- Reading: Basics—Volcanoes

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9.5: Types of Volcanoes

INTRODUCTION

A volcano is a vent through which molten rock and gas escape from a magma chamber. Volcanoes differ in many features such as height, shape, and slope steepness. Some volcanoes are tall cones and others are just cracks in the ground (figure 1). As you might expect, the shape of a volcano is related to the composition of its magma.



Figure 1. Mount St. Helens was a beautiful, classic, cone-shaped volcano. The volcano's 1980 eruption blew more than 400 meters (1,300 feet) off the top of the mountain.

COMPOSITE VOLCANOES

Composite volcanoes are made of felsic to intermediate rock. The viscosity of the lava means that eruptions at these volcanoes are often explosive (figure 2).



Figure 2. Mt. Fuji, the highest mountain in Japan, is a dormant composite volcano.

The viscous lava cannot travel far down the sides of the volcano before it solidifies, which creates the steep slopes of a composite volcano. Viscosity also causes some eruptions to explode as ash and small rocks. The volcano is constructed layer by layer, as ash and lava solidify, one upon the other (figure 3). The result is the classic cone shape of composite volcanoes.

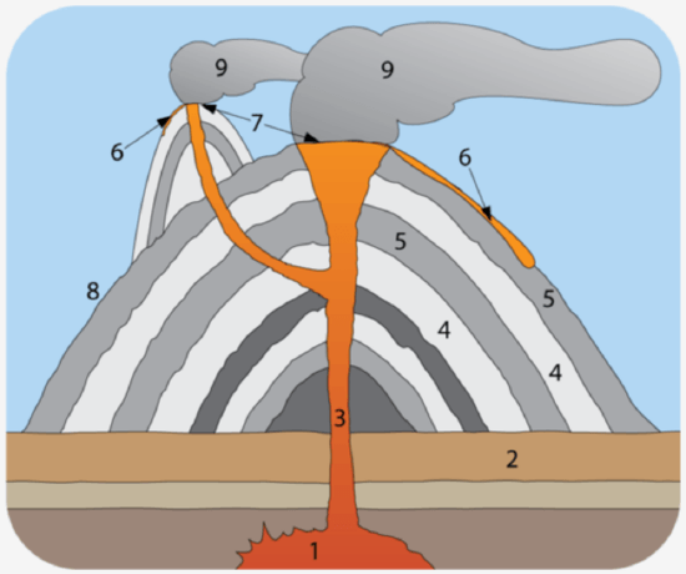


Figure 3. A cross section of a composite volcano reveals alternating layers of rock and ash: (1) magma chamber, (2) bedrock, (3) pipe, (4) ash layers, (5) lava layers, (6) lava flow, (7) vent, (8) lava, (9) ash cloud. Frequently there is a large crater at the top from the last eruption.

SHIELD VOLCANOES

Shield volcanoes get their name from their shape. Although shield volcanoes are not steep, they may be very large. Shield volcanoes are common at spreading centers or intraplate hot spots (figure 4).

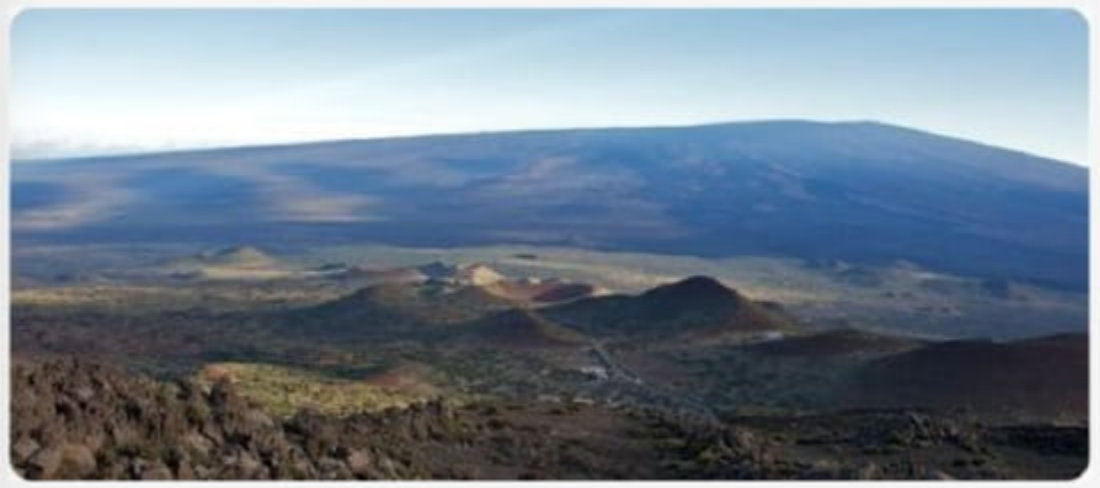


Figure 4. Mauna Loa Volcano in Hawaii (in the background) is the largest shield volcano on Earth with a diameter of more than 112 kilometers (70 miles). The volcano forms a significant part of the island of Hawaii.

The lava that creates shield volcanoes is fluid and flows easily. The spreading lava creates the shield shape. Shield volcanoes are built by many layers over time and the layers are usually of very similar composition. The low viscosity also means that shield eruptions are non-explosive.

This *Volcanoes 101* video from National Geographic discusses where volcanoes are found and what their properties come from:

YouTube Video

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CINDER CONES

Cinder cones are the most common type of volcano. A cinder cone has a cone shape, but is much smaller than a composite volcano. Cinder cones rarely reach 300 meters in height but they have steep sides. Cinder cones grow rapidly, usually from a single eruption cycle (figure 5). Cinder cones are composed of small fragments of rock, such as pumice, piled on top of one another. The rock shoots up in the air and doesn't fall far from the vent. The exact composition of a cinder cone depends on the composition of the lava ejected from the volcano. Cinder cones usually have a crater at the summit.



Figure 5. In 1943, a Mexican farmer first witnessed a cinder cone erupting in his field. In a year, Paricutín was 336 meters high. By 1952, it reached 424 meters and then stopped erupting.

Cinder cones are often found near larger volcanoes (figure 6).

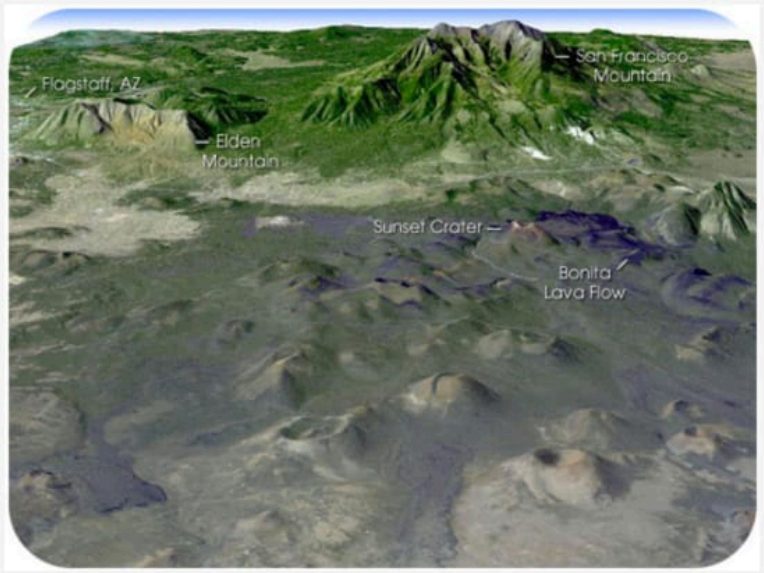


Figure 6. This Landsat image shows the topography of San Francisco Mountain, an extinct volcano, with many cinder cones near it in northern Arizona. Sunset crater is a cinder cone that erupted about 1,000 years ago.

SUPERVOLCANOES

Supervolcano eruptions are extremely rare in Earth history. It's a good thing because they are unimaginably large. A supervolcano must erupt more than 1,000 cubic km (240 cubic miles) of material, compared with 1.2 km^3 for Mount St. Helens or 25 km^3 for Mount Pinatubo, a large eruption in the Philippines in 1991. Not surprisingly, supervolcanoes are the most dangerous type of volcano.



Figure 7. The caldera at Santorini in Greece is so large that it can only be seen by satellite.

Supervolcanoes are a fairly new idea in volcanology. The exact cause of supervolcano eruptions is still debated. However, scientists think that a very large magma chamber erupts entirely in one catastrophic explosion. This creates a huge hole or **caldera** into which the surface collapses (figure 7).

The largest supervolcano in North America is beneath Yellowstone National Park in Wyoming. Yellowstone sits above a hotspot that has erupted catastrophically three times: 2.1 million, 1.3 million, and 640,000 years ago. Yellowstone has produced many smaller (but still enormous) eruptions more recently (figure 8). Fortunately, current activity at Yellowstone is limited to the region's famous geysers.

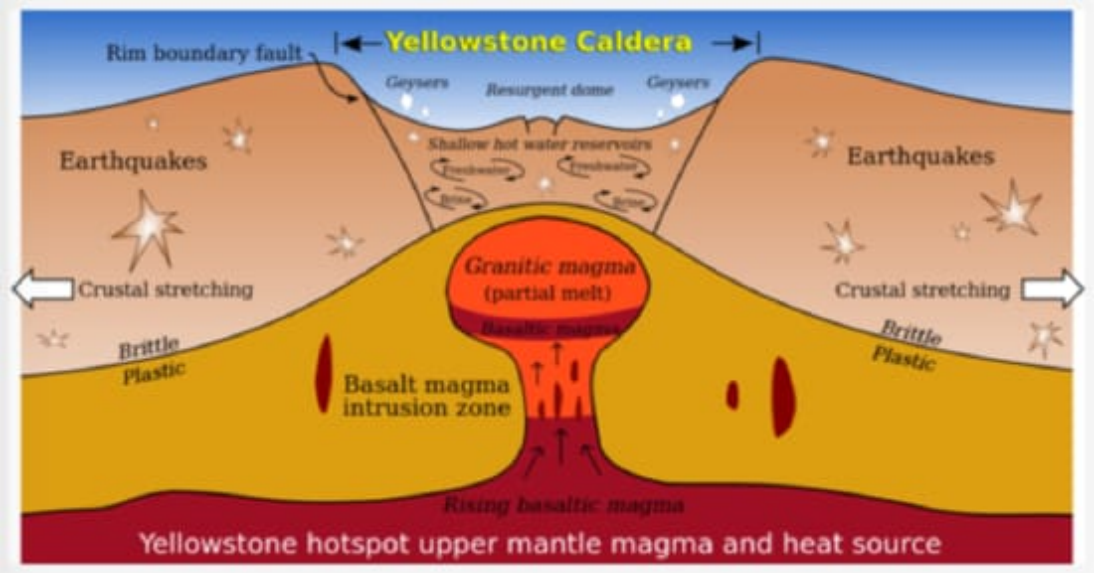


Figure 8. The Yellowstone hotspot has produced enormous felsic eruptions. The Yellowstone caldera collapsed in the most recent super eruption.

Long Valley Caldera, south of Mono Lake in California, is the second largest supervolcano in North America (figure 9). Long Valley had an extremely hot and explosive rhyolite about 700,000 years ago. An earthquake swarm in 1980 alerted geologists to the possibility of a future eruption, but the quakes have since calmed down.



Figure 9. The hot water that gives Hot Creek, California, its name is heated by hot rock below Long Valley Caldera.

- This site provides and interactive image of the geological features of Long Valley Caldera.

A supervolcano could change life on Earth as we know it. Ash could block sunlight so much that photosynthesis would be reduced and global temperatures would plummet. Volcanic eruptions could have contributed to some of the mass extinctions in our planet's history. No one knows when the next super eruption will be.

Interesting volcano videos are seen on National Geographic Videos, Environment Video, Natural Disasters, Earthquakes. One interesting one is "Mammoth Mountain," which explores Hot Creek and the volcanic area it is a part of in California.

LESSON SUMMARY

- Composite, shield, cinder cones, and supervolcanoes are the main types of volcanoes.
- Composite volcanoes are tall, steep cones that produce explosive eruptions.
- Shield volcanoes form very large, gently sloped mounds from effusive eruptions.
- Cinder cones are the smallest volcanoes and result from accumulation of many small fragments of ejected material.
- An explosive eruption may create a caldera, a large hole into which the mountain collapses.
- Supervolcano eruptions are devastating but extremely rare in Earth history.

REFLECTION QUESTIONS

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9.6: Basics-Volcanoes

INTRODUCTION

The Pacific Northwest is volcanically active. Nearly every type of volcano exists or has existed in the Pacific Northwest, and every type of volcanic eruption has occurred. The Cascade volcanic arc has been catastrophically active during recent human memory. In the last 10,000 years volcanic eruptions have also occurred in such places as eastern Idaho and central Oregon. In some landscape regions of the Northwest, the entire upper crust is almost entirely volcanic rock.

To understand volcanoes, you have to start with magma, the molten rock that comes up from the interior of the earth to form volcanoes. The composition, gas content, and crystal content of the magma determines the type of eruption that occurs, the kind of volcanic rock that forms, and the type of volcano that forms.

SHIELD VOLCANOES

Lava flow after lava flow of low-viscosity, mafic lava builds up a basaltic shield volcano. Shield volcanoes are the largest type of volcano on earth, as exemplified by Mauna Loa on the Island of Hawaii. Shield volcanoes in the Pacific Northwest include: Medicine Lake Volcano in northern California; Newberry Volcano (Paulina Peak) in Oregon; and Simco Volcano in south Central Washington, on the Yakima Indian Reservation near the town of Goldendale.

COMPOSITE CONES

Eruptions of intermediate lava as andesite flows, explosive eruptions of tephra, and intrusion within earlier flows to form dikes and sills, add up to form composite cones. Composite cones are the characteristic volcanoes of volcanic arcs along subduction zones. Composite cones of the Cascadia volcanic arc in the Pacific Northwest include Lassen Peak and Mt. Shasta in northern California, Mt. McGloughlin, Mt. Mazama (Crater Lake), Mt. Thielsen, the Three Sisters, Mt. Bachelor, Mt. Washington, Mt. Jefferson and Mt. Hood in Oregon, and Mt. Adams, Mt. St. Helens, Mt. Rainier, Glacier Peak, and Mt. Baker in Washington. Most of these volcanoes are over 10,000 feet above sea level in elevation. Along with abundant andesite and tephra, composite cones may also erupt lesser amounts of basalt, dacite and rhyolite. That is why they are called composite cones–they are a composite of many types of volcanic rock.

CINDER CONES

Fountain eruptions of volcanic ash, lapilli, blocks, and bombs, usually of mafic composition, pile up in a cone-shaped form to become a cinder cone. Cinder cones are usually less than 1,000 feet tall. Many composite cones and shield volcanoes have cinder cones on their flanks or close by. Cinder cones are small bumps compared to the much larger shield volcanoes or composite cones.

LAVA DOMES

Lava domes are steep-sided domes formed by the pile-up of viscous, felsic magma. It is not uncommon for a composite cone to erupt explosively, forming a crater, and then to erupt high-viscosity lava into the crater, forming a lava dome. The lava that forms the dome may be from the same magma that erupted explosively but, after venting most of its gas in the explosive eruption, it has lost its explosiveness and erupts as flows.

SPATTER CONES

Spatter cones are small volcanic landforms that from when lava spatters up in a small fountain and piles up in blobs of semi-molten material that accumulate into a solid, roughly cone-shaped form a few feet or a few tens of feet tall. A lava flow coming down the flank of a shield volcano or composite cone may spawn a subsidiary spatter cone by bursting out of a solidified crust.

FLOOD BASALTS

Flood basalts usually originate from fissure eruptions, cracks in the surface of the earth that rapidly disgorge huge volumes of lava. Flood basalts are high-volume, widespread flows of mafic magma that solidify into basalt flows that in some cases cover thousands of square miles. The Columbia River Basalts comprise one of the world's great flood basalt provinces. Some of the Columbia River basalt flows originated near the border of Idaho, covered much of eastern Washington and north central Oregon, and flowed down through the Columbia River gorge beyond the Cascade Range to cover parts of the Portland area and reach the Pacific Ocean, all in gigantic individual flows.

ASH FLOW TUFFS

Ash flow tuffs are large-volume tuffs that originate from huge, explosive eruptions of felsic magma. They are sometimes referred to as ignimbrites. Besides volcanic ash, ash flow tuffs may contain pieces of pumice, pieces of broken rock that were caught up in the eruption, and crystals that had already solidified in the magma before it erupted. All of these materials become welded together in the solidified ash flow tuff. Some ash flow tuffs cover hundreds or, in rare cases, thousands of square miles. The yellow rock that gives Yellowstone National Park its name is an ash flow tuff. The explosive eruptions that form ash flow tuffs usually create a caldera, as the volcano collapses on itself after venting tephra across the landscape.

PILLOW BASALTS

Pillow basalts form when mafic lava erupts underwater. The lava freezes on the outside against the cold water, but keeps flowing on the inside, bulging out into pillow-like shapes which break off from the main flow. These pillows can accumulate into a large volume of pillow basalts. Pillow basalts serve as an indicator that lava was erupted into a body of water. Much of the world's oceanic crust consists of basalt, most of which erupted onto the seafloor to form pillow basalts. Pillow basalt can also form when mafic lava erupts on land and flows into a lake or into the ocean. In some places, there are layers of pillow basalt in the Columbia River Basalts, showing that the basalt flowed into lakes, forming pillows as it entered the water.

TEPHRA

Tephra is also known as pyroclastic material—volcanic material that erupted explosively and flew through the air for some distance before landing on the ground. Tephra results from pyroclastic eruptions, which means explosive volcanic eruptions that hurl material into the air. There are several types of pyroclastic material, or tephra:

Volcanic Blocks

Blocks are large (>5 cm) pieces of tephra that were solid during the eruption. They tend to have blocky or jagged shapes.

Volcanic Bombs

Volcanic bombs are large (>5 cm) pieces of tephra that landed while still molten or semi-molten. They tend to have shapes that were streamlined while passing through the air, or else have a sort of splattered shape from hitting the ground while soft.

Lapilli

Lapilli are pieces of tephra between 0.5 and 5 cm across.

Volcanic Ash

Volcanic ash is fine-grained (<0.5 cm) tephra. It mainly consists of fine pieces of volcanic glass, which form by solidification and splintering of small pieces of the magma during the eruption. It may also contain pieces of crystals, from minerals that had already solidified in the magma before it erupted.

REFLECTION QUESTIONS

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9.7: Volcanic Hazards

DESCRIBE MAJOR VOLCANIC HAZARDS AND THEIR POTENTIAL EFFECTS

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Volcanoes
- Reading: Types of Volcano Hazards

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9.8: Volcanoes

WHERE VOLCANOES ARE LOCATED

Volcanoes are a vibrant manifestation of plate tectonics processes. Volcanoes are common along convergent and divergent plate boundaries. Volcanoes are also found within lithospheric plates away from plate boundaries. Wherever mantle is able to melt, volcanoes may be the result.

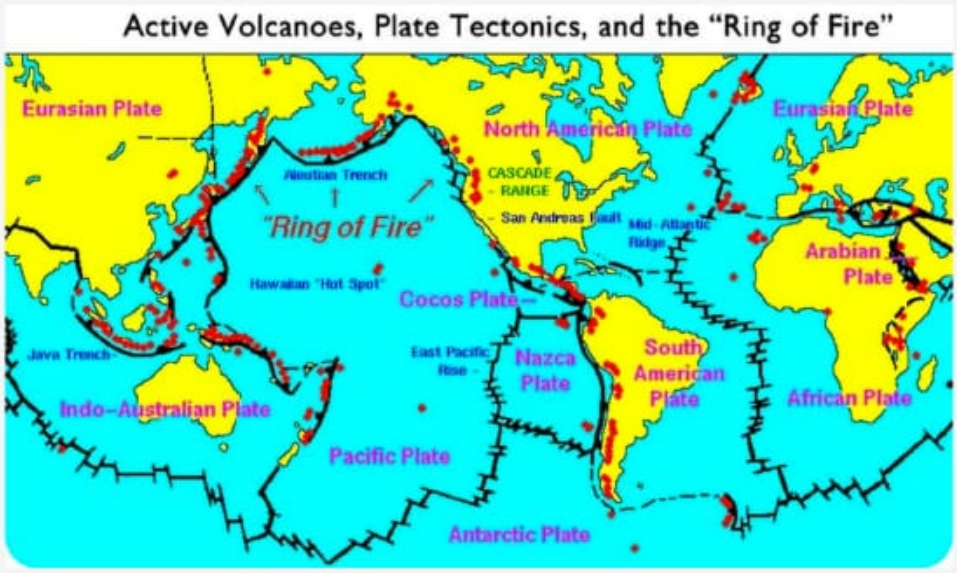


Figure 1. World map of active volcanoes.

See if you can give a geological explanation for the locations of all the volcanoes in figure 1. What is the Pacific Ring of Fire? Why are the Hawaiian volcanoes located away from any plate boundaries? What is the cause of the volcanoes along the mid-Atlantic ridge?

Volcanoes erupt because mantle rock melts. This is the first stage in creating a volcano. Remember from the chapter "Rocks" that mantle may melt if temperature rises, pressure lowers, or water is added. Be sure to think about how melting occurs in each of the following volcanic settings.

Convergent Plate Boundaries

Why does melting occur at convergent plate boundaries? The subducting plate heats up as it sinks into the mantle. Also, water is mixed in with the sediments lying on top of the subducting plate. This water lowers the melting point of the mantle material, which increases melting. Volcanoes at convergent plate boundaries are found all along the Pacific Ocean basin, primarily at the edges of the Pacific, Cocos, and Nazca plates. Trenches mark subduction zones, although only the Aleutian Trench and the Java Trench appear on the map in figure 1.

Remember your plate tectonics knowledge. Large earthquakes are extremely common along convergent plate boundaries. Since the Pacific Ocean is rimmed by convergent and transform boundaries, about 80% of all earthquakes strike around the Pacific Ocean basin (the ring of fire). Why are 75% of the world's volcanoes found around the Pacific basin? Of course, these volcanoes are caused by the abundance of convergent plate boundaries around the Pacific.

The Pacific Ring of Fire is where the majority of the volcanic activity on the Earth occurs. A description of the Pacific Ring of Fire along western North America is a description of the plate boundaries.

- Subduction at the Middle American Trench creates volcanoes in Central America.
- The San Andreas Fault is a transform boundary.

- Subduction of the Juan de Fuca plate beneath the North American plate creates the Cascade volcanoes.
- Subduction of the Pacific plate beneath the North American plate in the north creates the Aleutian Islands volcanoes.

The Cascades are shown on this interactive map with photos and descriptions of each of the volcanoes.

This incredible explosive eruption of Mount Vesuvius in Italy in A.D. 79 is an example of a composite volcano that forms as the result of a convergent plate boundary:

YouTube Video

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Divergent Plate Boundaries

Why does melting occur at divergent plate boundaries? Hot mantle rock rises where the plates are moving apart. This releases pressure on the mantle, which lowers its melting temperature. Lava erupts through long cracks in the ground, or **fissures.**



Figure 2. A volcanic eruption at Surtsey, a small island near Iceland.

Volcanoes erupt at mid-ocean ridges, such as the Mid-Atlantic ridge, where seafloor spreading creates new seafloor in the rift valleys. Where a hotspot is located along the ridge, such as at Iceland, volcanoes grow high enough to create islands (figure 2).

Eruptions are found at divergent plate boundaries as continents break apart. The volcanoes in figure 3 are in the East African Rift between the African and Arabian plates.

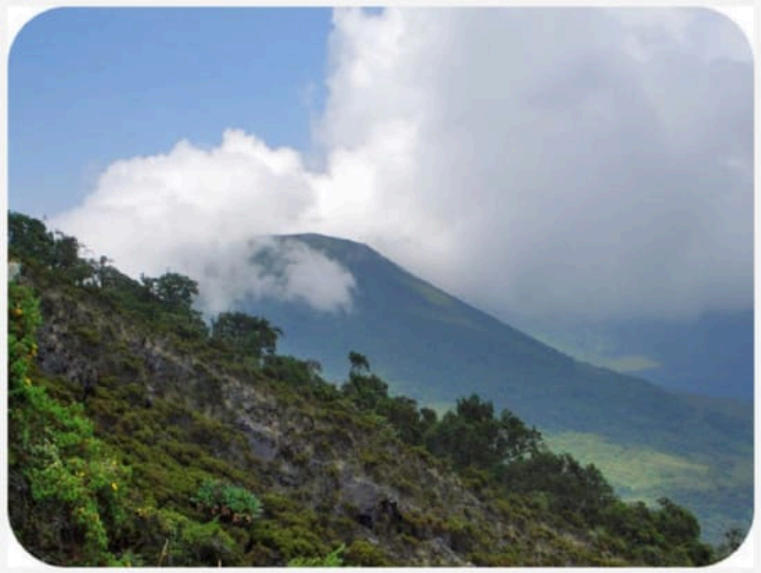


Figure 3. Mount Gahinga, a mountain in Uganda, located in the East African Rift valley.

Volcanic Hotspots

Although most volcanoes are found at convergent or divergent plate boundaries, intraplate volcanoes are found in the middle of a tectonic plate. Why is there melting at these locations? The Hawaiian Islands are the exposed peaks of a great chain of volcanoes that lie on the Pacific plate. These islands are in the middle of the Pacific plate. The youngest island sits directly above a column of hot rock called a mantle plume. As the plume rises through the mantle, pressure is released and mantle melts to create a hotspot (figure 4).

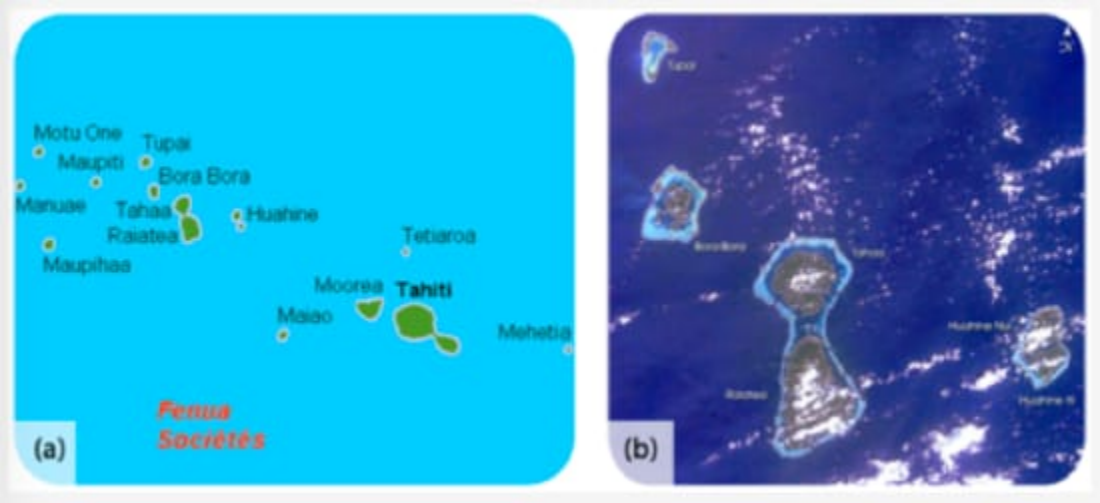


Figure 4. (a) The Society Islands formed above a hotspot that is now beneath Mehetia and two submarine volcanoes. (b) The satellite image shows how the islands become smaller and coral reefs became more developed as the volcanoes move off the hotspot and grow older.

Earth is home to about 50 known hot spots. Most of these are in the oceans because they are better able to penetrate oceanic lithosphere to create volcanoes. The hotspots that are known beneath continents are extremely large, such as Yellowstone (figure 5).

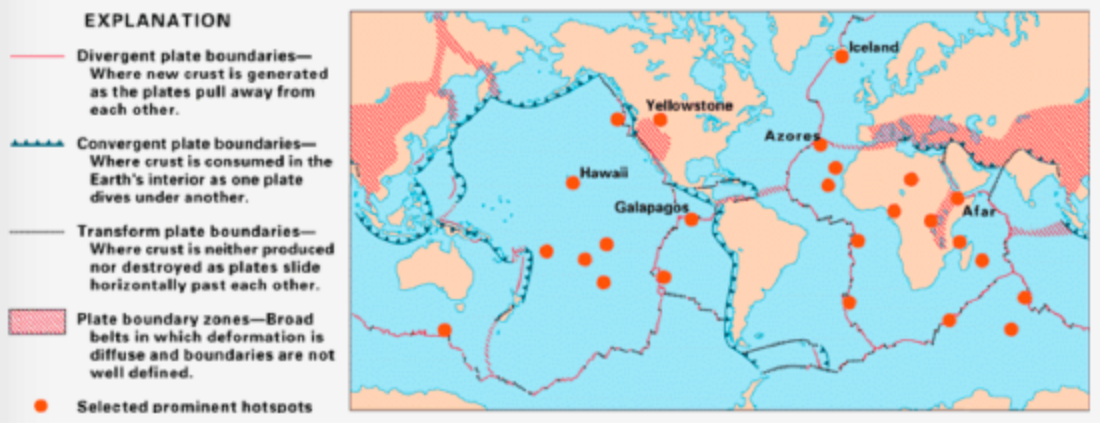


Figure 5. Prominent hotspots of the world.

A hot spot beneath Hawaii, the origin of the voluminous lava produced by the shield volcano Kilauea can be viewed here:

YouTube Video

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How would you be able to tell hotspot volcanoes from island arc volcanoes? At island arcs, the volcanoes are all about the same age. By contrast, at hotspots the volcanoes are youngest at one end of the chain and oldest at the other.

VOLCANIC LANDFORMS AND GEOTHERMAL ACTIVITY

Volcanoes are associated with many types of landforms. The landforms vary with the composition of the magma that created them. Hot springs and geysers are also examples of surface features related to volcanic activity.

Landforms From Lava

Volcanoes and Vents

The most obvious landforms created by lava are volcanoes, most commonly as cinder cones, composite volcanoes, and shield volcanoes. Eruptions also take place through fissures (**Figure** 6). The eruptions that created the entire ocean floor are essentially fissure eruptions.



Figure 6. A fissure eruption on Mauna Loa in Hawaii travels toward Mauna Kea on the Big Island.

Lava Domes

When lava is viscous, it is flows slowly. If there is not enough magma or enough pressure to create an explosive eruption, the magma may form a **lava dome.** Because it is so thick, the lava does not flow far from the vent (figure 7).



Figure 7. Lava domes are large, round landforms created by thick lava that does not travel far from the vent.

Lava flows often make mounds right in the middle of craters at the top of volcanoes, as seen in figure 8.



Figure 8. Lava domes may form in the crater of composite volcanoes as at Mount St. Helens

Lava Plateaus

A **lava plateau** forms when large amounts of fluid lava flows over an extensive area (figure 9). When the lava solidifies, it creates a large, flat surface of igneous rock.



Figure 9. Layer upon layer of basalt have created the Columbia Plateau, which covers more than 161,000 square kilometers (63,000 square miles) in Washington, Oregon, and Idaho.

Land

Lava creates new land as it solidifies on the coast or emerges from beneath the water (figure 10).



Figure 10. Lava hitting seawater creates new land.

Over time the eruptions can create whole islands. The Hawaiian Islands are formed from shield volcano eruptions that have grown over the last 5 million years (figure 11).



Figure 11. A compilation of satellite images of the Big Island of Hawaii with its five volcanoes.

Landforms From Magma

Magma intrusions can create landforms. Shiprock in New Mexico is the neck of an old volcano that has eroded away (figure 12).



Figure 12. The aptly named Shiprock in New Mexico.

Hot Springs and Geysers

Water sometimes comes into contact with hot rock. The water may emerge at the surface as either a hot spring or a geyser.

Hot Springs

Water heated below ground that rises through a crack to the surface creates a **hot spring** (figure 13). The water in hot springs may reach temperatures in the hundreds of degrees Celsius beneath the surface, although most hot springs are much cooler.



Figure 13. Even some animals enjoy relaxing in nature's hot tubs.

Geysers

Geysers are also created by water that is heated beneath the Earth's surface, but geysers do not bubble to the surface — they erupt. When water is both superheated by magma and flows through a narrow passageway underground, the environment is ideal for a geyser. The passageway traps the heated water underground, so that heat and pressure can build. Eventually, the pressure grows so great that the superheated water bursts out onto the surface to create a geyser (figure 14).



Figure 14. Castle Geyser is one of the many geysers at Yellowstone National Park. Castle erupts regularly, but not as frequently or predictably as Old Faithful.

Conditions are right for the formation of geysers in only a few places on Earth. Of the roughly 1,000 geysers worldwide and about half are found in the United States.

LESSON SUMMARY

- Most volcanoes are found along convergent or divergent plate boundaries.
- The Pacific Ring of Fire is the most geologically active region in the world.
- Volcanoes such as those that form the islands of Hawaii form over hotspots, which are melting zones above mantle plumes.
- Viscous lava can produce lava domes along a fissure or within a volcano.
- Lava plateaus form from large lava flows that spread out over large areas.
- Many islands are built by or are volcanoes.
- Igneous intrusions associated with volcanoes may create volcanic landforms.
- When magma heats groundwater, it can reach the surface as hot springs or geysers.

REFLECTION QUESTIONS

- What skill does this content help you develop?
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9.9: Types of Volcano Hazards

Volcanic eruptions are one of Earth's most dramatic and violent agents of change. Not only can powerful explosive eruptions drastically alter land and water for tens of kilometers around a volcano, but tiny liquid droplets of sulfuric acid erupted into the stratosphere can change our planet's climate temporarily. Eruptions often force people living near volcanoes to abandon their land and homes, sometimes forever. Those living farther away are likely to avoid complete destruction, but their cities and towns, crops, industrial plants, transportation systems, and electrical grids can still be damaged by tephra, ash, lahars, and flooding.

Fortunately, volcanoes exhibit precursory unrest that if detected and analyzed in time allows eruptions to be anticipated and communities at risk to be forewarned with reliable information in sufficient time to implement response plans and mitigation measures.

VOLCANIC GASES AND THEIR EFFECTS

Magma contains dissolved gases that are released into the atmosphere during eruptions. Gases are also released from magma that either remains below ground (for example, as an intrusion) or is rising toward the surface. In such cases, gases may escape continuously into the atmosphere from the soil, volcanic vents, fumaroles, and hydrothermal systems.

At high pressures deep beneath the earth's surface, volcanic gases are dissolved in molten rock. But as magma rises toward the surface where the pressure is lower, gases held in the melt begin to form tiny bubbles. The increasing volume taken up by gas bubbles makes the magma less dense than the surrounding rock, which may allow the magma to continue its upward journey. Closer to the surface, the bubbles increase in number and size so that the gas volume may exceed the melt volume in the magma, creating a magma foam. The rapidly expanding gas bubbles of the foam can lead to explosive eruptions in which the melt is fragmented into pieces of volcanic rock, known as tephra. If the molten rock is not fragmented by explosive activity, a lava flow will be generated.

Together with the tephra and entrained air, volcanic gases can rise tens of kilometers into Earth's atmosphere during large explosive eruptions. Once airborne, the prevailing winds may blow the eruption cloud hundreds to thousands of kilometers from a volcano. The gases spread from an erupting vent primarily as acid aerosols (tiny acid droplets), compounds attached to tephra particles, and microscopic salt particles.

Volcanic gases undergo a tremendous increase in volume when magma rises to the Earth's surface and erupts. For example, consider what happens if one cubic meter of 900°C rhyolite magma containing five percent by weight of dissolved water were suddenly brought from depth to the surface. The one cubic meter of magma now would occupy a volume of 670 m^3 as a mixture of water vapor and magma at atmospheric pressure (Sparks et. al., 1997)! The one meter cube at depth would increase to 8.75 m on each side at the surface. Such enormous expansion of volcanic gases, primarily water, is the main driving force of explosive eruptions.

The most abundant gas typically released into the atmosphere from volcanic systems is water vapor (H_2O), followed by carbon dioxide (CO_2) and sulfur dioxide (SO_2). Volcanoes also release smaller amounts of others gases, including hydrogen sulfide (H_2S), hydrogen (H_2), carbon monoxide (CO), hydrogen chloride (HCL), hydrogen fluoride (HF), and helium (He).

Examples of volcanic gas compositions, in volume percent concentrations (from Symonds et. al., 1994)

Volcano Tectonic Style Temperature	Kilauea Summit Hot Spot 1170°C	**Erta` Ale** Divergent Plate 1130°C	**Momotombo** Convergent Plate 820°C
H_2O	37.1	77.2	97.1
CO_2	48.9	11.3	1.44
SO_2	11.8	8.34	0.50
H_2	0.49	1.39	0.70

Examples of volcanic gas compositions, in volume percent concentrations (from Symonds et. al., 1994)			
CO	1.51	0.44	0.01
H_2S	0.04	0.68	0.23
HCl	0.08	0.42	2.89
HF	—	—	0.26

The volcanic gases that pose the greatest potential hazard to people, animals, agriculture, and property are sulfur dioxide, carbon dioxide, and hydrogen fluoride. Locally, sulfur dioxide gas can lead to acid rain and air pollution downwind from a volcano. Globally, large explosive eruptions that inject a tremendous volume of sulfur aerosols into the stratosphere can lead to lower surface temperatures and promote depletion of the Earth's ozone layer. Because carbon dioxide gas is heavier than air, the gas may flow into in low-lying areas and collect in the soil. The concentration of carbon dioxide gas in these areas can be lethal to people, animals, and vegetation. A few historic eruptions have released sufficient fluorine-compounds to deform or kill animals that grazed on vegetation coated with volcanic ash; fluorine compounds tend to become concentrated on fine-grained ash particles, which can be ingested by animals.

Sulfur Dioxide (SO_2)

The effects of SO_2 on people and the environment vary widely depending on (1) the amount of gas a volcano emits into the atmosphere; (2) whether the gas is injected into the troposphere or stratosphere; and (3) the regional or global wind and weather pattern that disperses the gas. Sulfur dioxide (SO_2) is a colorless gas with a pungent odor that irritates skin and the tissues and mucous membranes of the eyes, nose, and throat. Sulfur dioxide chiefly affects upper respiratory tract and bronchi. The World Health Organization recommends a concentration of no greater than 0.5 ppm over 24 hours for maximum exposure. A concentration of 6-12 ppm can cause immediate irritation of the nose and throat; 20 ppm can cause eye irritation; 10,000 ppm will irritate moist skin within minutes.

Emission rates of SO_2 from an active volcano range from <20 tonnes/day to >10 million tonnes/day according to the style of volcanic activity and type and volume of magma involved. For example, the large explosive eruption of Mount Pinatubo on 15 June 1991 expelled 3-5 km^3 of dacite magma and injected about 20 million metric tons of SO_2 into the stratosphere. The sulfur aerosols resulted in a 0.5-0.6°C cooling of the Earth's surface in the Northern Hemisphere. The sulfate aerosols also accelerated chemical reactions that, together with the increased stratospheric chlorine levels from human-made chlorofluorocarbon (CFC) pollution, destroyed ozone and led to some of the lowest ozone levels ever observed in the atmosphere.

At Kilauea Volcano, the recent effusive eruption of about 0.0005 km^3/day (500,000 m^3) of basalt magma releases about 2,000 tonnes of SO_2 into the lower troposphere. Downwind from the vent, acid rain and air pollution is a persistent health problem when the volcano is erupting.

- SO_2 causes air pollutionVolcanic smog. Eruptions of Kilauea Volcano release large quantities of sulfur dioxide gas into the atmosphere that can lead to volcanic air pollution on the Island of Hawai`i. Sulfur dioxide gas reacts chemically with sunlight, oxygen, dust particles, and water to form volcanic smog known as vog.
- **SO_2 effects Earth's surface temperature Global cooling and ozone depletion.** Measurements from recent eruptions such as Mount St. Helens, Washington (1980), El Chichon, Mexico (1982), and Mount Pinatubo, Philippines (1991), clearly show the importance of sulfur aerosols in modifying climate, warming the stratosphere, and cooling the troposphere. Research has also shown that the liquid drops of sulfuric acid promote the destruction of the Earth's ozone layer.

Hydrogen Sulfide (H_2S)

Hydrogen sulfide (H_2S) is a colorless, flammable gas with a strong offensive odor. It is sometimes referred to as sewer gas. At low concentrations it can irritate the eyes and acts as a depressant; at high concentrations it can cause irritation of the upper respiratory tract and, during long exposure, pulmonary edema. A 30-minute exposure to 500 ppm results in headache, dizziness, excitement, staggering gait, and diarrhea, followed sometimes by bronchitis or bronchopneumonia.

Carbon Dioxide (CO_2)

Volcanoes release more than 130 million tonnes of CO_2 into the atmosphere every year. This colorless, odorless gas usually does not pose a direct hazard to life because it typically becomes diluted to low concentrations very quickly whether it is released continuously from the ground or during episodic eruptions. But in certain circumstances, CO_2 may become concentrated at levels lethal to people and animals. Carbon dioxide gas is heavier than air and the gas can flow into in low-lying areas; breathing air with more than 30% CO_2can quickly induce unconsciousness and cause death. In volcanic or other areas where CO_2 emissions occur, it is important to avoid small depressions and low areas that might be CO_2 traps. The boundary between air and lethal gas can be extremely sharp; even a single step upslope may be adequate to escape death.

CO_2 trapped in depressions can be lethal to people and animals. When a burning piece of cloth is lowered into a hole that has a high concentration of CO_2, the fire goes out. Such a condition can be lethal to people and animals.

Air with 5% CO_2 causes perceptible increased respiration; 6-10% results in shortness of breath, headaches, dizziness, sweating, and general restlessness; 10-15% causes impaired coordination and abrupt muscle contractions; 20-30% causes loss of consciousness and convulsions; over 30% can cause death (Hathaway et. al., 1991).

Please see the web article, “Volcanic Gases and Climate Change Overview” for more information on Volcanic versus anthropogenic CO_2emissions.

Here is a historical example of the effects of carbon dioxide gas: Mammoth Mountain in Long Valley Caldera, California kills trees near Mammoth Mountain, California

Hydrogen Chloride (HCL)

Chlorine gas is emitted from volcanoes in the form of hydrochloric acid (HCl). Exposure to the gas irritates mucous membranes of the eyes and respiratory tract. Concentrations over 35 ppm cause irritation of the throat after short exposure; >100 ppm results in pulmonary edema, and often laryngeal spasm. It also causes acid rain downwind from volcanoes because HCl is extremely soluble in condensing water droplets and it is a very “strong acid” (it dissociates extensively to give H^+ ions in the droplets).

Hydrogen Fluoride (HF)

Fluorine is a pale yellow gas that attaches to fine ash particles, coats grass, and pollutes streams and lakes. Exposure to this powerful caustic irritant can cause conjunctivitis, skin irritation, bone degeneration and mottling of teeth. Excess fluorine results in a significant cause of death and injury in livestock during ash eruptions. Even in areas that receive just a millimeter of ash, poisoning can occur where the fluorine content of dried grass exceeds 250 ppm. Animals that eat grass coated with fluorine-tainted ash are poisoned. Small amounts of fluorine can be beneficial, but excess fluorine causes fluorosis, an affliction that eventually kills animals by destroying their bones. It also promotes acid rain effects downwind of volcanoes, like HCl.

Secondary Gas Emissions

Another type of gas release occurs when lava flows reach the ocean. Extreme heat from molten lava boils and vaporizes seawater, leading to a series of chemical reactions. The boiling and reactions produce a large white plume, locally known as lava haze or laze, containing a mixture of hydrochloric acid and concentrated seawater.

- Laze plumes are very acidic. Extreme heat from lava entering the sea rapidly boils and vaporizes seawater, leading to a series of chemical reactions. The boiling and reactions produce a large white plume, locally known as lava haze or laze, which contains a mixture of hydrochloric acid (HCl) and concentrated seawater. This is a short-lived local phenomenon that only affects people or vegetation directly under the plume.
  The hydrochloric acid (HCl) comes from the breakdown of seawater-derived chlorides during sudden boiling. Because the lava is largely degassed by the time it reaches the sea, any HCL coming from it is insignificant by comparison. Analyzed samples of the plume show that is is a brine with a salinity of about 2.3 times that of seawater and a pH of 1.5-2.0.
- Key seawater chloride breakdown reactions that produce HCl gas
  - $MgCl_2$ (sea salt) + H_2O (steam) = MgO (periclase) + 2HCl (HCl gas)
  - 2 NaCl (sea salt) + H_2O (steam) = Na_2O (sodium oxide) + 2 HCL (HCl gas)

- $CaCl_2$ (sea salt) + H_2O (steam) = CaO (lime) + 2 HCL (HCl gas)

- **Avoid standing beneath a laze plume.** Dense laze plumes, such as that shown here (Photograph by C.C. Heliker, February 10, 1994) contain as much as 10-15 parts per million of hydrochloric acid. These values drop off sharply as the plume moves away from the lava entry areas. During along-shore or on-shore winds, this plume produces acid rain that may fall on people and land along the coast. This rain (pH 1.5 to 2), often more acidic that lime juice or stomach acid, is very corrosive to the skin and clothing. Visitors to the lava entry areas should avoid standing directly in, under, or downwind of the laze plume.

LAHARS AND THEIR EFFECTS

Lahar is an Indonesian term that describes a hot or cold mixture of water and rock fragments flowing down the slopes of a volcano and (or) river valleys. When moving, a lahar looks like a mass of wet concrete that carries rock debris ranging in size from clay to boulders more than 10 m in diameter. Lahars vary in size and speed. Small lahars less than a few meters wide and several centimeters deep may flow a few meters per second. Large lahars hundreds of meters wide and tens of meters deep can flow several tens of meters per second–much too fast for people to outrun.



Figure 1. Gualí River valley. Photograph by R. Janda on December 18, 1985

As a lahar rushes downstream from a volcano, its size, speed, and the amount of water and rock debris it carries constantly change. The beginning surge of water and rock debris often erodes rocks and vegetation from the side of a volcano and along the river valley it enters. This initial flow can also incorporate water from melting snow and ice (if present) and the river it overruns. By eroding rock debris and incorporating additional water, lahars can easily grow to more than 10 times their initial size. But as a lahar moves farther away from a volcano, it will eventually begin to lose its heavy load of sediment and decrease in size.

Eruptions may trigger one or more lahars directly by quickly melting snow and ice on a volcano or ejecting water from a crater lake. More often, lahars are formed by intense rainfall during or after an eruption–rainwater can easily erode loose volcanic rock and soil on hillsides and in river valleys. Some of the largest lahars begin as landslides of saturated and hydrothermally altered rock on the flank of a volcano or adjacent hillslopes. Landslides are triggered by eruptions, earthquakes, precipitation, or the unceasing pull of gravity on the volcano.

Lahars almost always occur on or near stratovolcanoes because these volcanoes tend to erupt explosively and their tall, steep cones are either snow covered, topped with a crater lake, constructed of weakly consolidated rock debris that is easily eroded, or internally weakened by hot hydrothermal fluids. Lahars are also common from the snow- and ice-covered shield volcanoes in Iceland where eruptions of fluid basalt lava frequently occur beneath huge glaciers.

The scenarios listed below illustrate most of the mechanisms by which lahars are generated. For convenience, we've grouped the mechanisms according to whether a volcano is erupting, has erupted, or is quiet. Each mechanism is illustrated with one or more case studies.

VOLCANO LANDSLIDES AND THEIR EFFECTS

Landslides are large masses of rock and soil that fall, slide, or flow very rapidly under the force of gravity. These mixtures of debris move in a wet or dry state, or both. Landslides commonly originate as massive rockslides or avalanches which disintegrate during movement into fragments ranging in size from small particles to enormous blocks hundreds of meters across. If the moving rock debris is large enough and contains a large content of water and fine material (typically, >3-5 percent of clay-sized particles), the landslide may transform into a lahar and flow downvalley more than 100 km from a volcano!

Volcano landslides range in size from less than 1 km3 to more than 100 km3. The high velocity (>100 km/hr) and great momentum of landslides allows them to run up slopes and to cross valley divides up to several hundred meters high. For example, the landslide at Mount St. Helens on May 18, 1980, had a volume of 2.5 km3, reached speeds of 50-80 m/s (180-288 km/hr), and surged up and over a 400 m tall ridge located about 5 km from the volcano!

Landslides are common on volcanoes because their massive cones (1) typically rise hundreds to thousands of meters above the surrounding terrain; and (2) are often weakened by the very process that created them–the rise and eruption of molten rock. Each time magma moves toward the surface, overlying rocks are shouldered aside as the molten rock makes room for itself, often creating internal shear zones or oversteepening one or more sides of the cone. Magma that remains within the cone releases volcanic gases that partially dissolve in groundwater, resulting in a hot acidic hydrothermal system that weakens rock by altering rock minerals to clay. Furthermore, the tremendous mass of thousands of layers lava and loose fragmented rock debris can lead to internal faults and fault zones that move frequently as the cone “settles” under the downward pull of gravity.

These conditions permit a number of factors to trigger a landslide or to allow part of a volcano’s cone to simply collapse under the influence of gravity:

- intrusion of magma into a volcano
- explosive eruptions (magmatic or phreatic–steam-driven explosions)
- large earthquake directly beneath a volcano or nearby (typically >M5)
- intense rainfall that saturates a volcano or adjacent tephra-covered hillslopes with water, especially before or during a large earthquake.

A landslide typically destroys everything in its path and may generate a variety of related activity. Historically, landslides have caused explosive eruptions, buried river valleys with tens of meters of rock debris, generated lahars, triggered waves and tsunami, and created deep horseshoe-shaped craters.

By removing a large part of a volcano’s cone, a landslide may abruptly decrease pressure on the shallow magmatic and hydrothermal systems, which can generate explosions ranging from a small steam explosion to large steam- and magma-driven directed blasts. A large landslide often buries valleys with tens to hundreds of meters of rock debris, forming a chaotic landscape marked by dozens of small hills and closed depressions. If the deposit is thick enough, it may dam tributary streams to form lakes in the subsequent days to months; the lakes may eventually drain catastrophically and generate lahars and floods downstream.

Landslides also generate some of the largest and most deadly lahars, either by transforming directly into a lahar or, after it stops moving, from dewatering of the deposit. Historically, however, the most deadly volcano landslide occurred in 1792 when sliding debris from Mt. Mayuyama near Unzen Volcano in Japan slammed into the Ariaka Sea and generated a wave on the opposite side that killed nearly 15,000 people.

On a volcano, landslides typically carve deep gashes into its cone or create large horseshoe-shaped craters hundreds of meters deep and more than a kilometer in width.

Volcanic landslides can do the following:

- Trigger volcanic explosions
- Generate lahars that travel far downstream
- Cause waves and tsunamis in a lake or ocean
- Bury river valleys with rock debris
- Dam tributary streams to form lakes
- Create a crater or scar on the volcano

LAVA FLOWS AND THEIR EFFECTS

Lava flows are streams of molten rock that pour or ooze from an erupting vent. Lava is erupted during either nonexplosive activity or explosive lava fountains. Lava flows destroy everything in their path, but most move slowly enough that people can move out of the way. The speed at which lava moves across the ground depends on several factors, including (1) type of lava erupted and its viscosity; (2) steepness of the ground over which it travels; (3) whether the lava flows as a broad sheet, through a confined channel, or down a lava tube; and (4) rate of lava production at the vent.

Fluid basalt flows can extend tens of kilometers from an erupting vent. The leading edges of basalt flows can travel as fast as 10 km/hour on steep slopes but they typically advance less than 1 km/hour on gentle slopes. But when basalt lava flows are confined within a channel or lava tube on a steep slope, the main body of the flow can reach velocities >30 km/hour.

Viscous andesite flows move only a few kilometers per hour and rarely extend more than 8 km from their vents. Viscous dacite and rhyolite flows often form steep-sided mounds called lava domes over an erupting vent. Lava domes often grow by the extrusion of many individual flows >30 m thick over a period of several months or years. Such flows will overlap one another and typically move less than a few meters per hour.

Everything in the path of an advancing lava flow will be knocked over, surrounded, or buried by lava, or ignited by the extremely hot temperature of lava. When lava erupts beneath a glacier or flows over snow and ice, meltwater from the ice and snow can result in far-reaching lahars. If lava enters a body of water or water enters a lava tube, the water may boil violently and cause an explosive shower of molten spatter over a wide area. Methane gas, produced as lava buries vegetation, can migrate in subsurface voids and explode when heated. Thick viscous lava flows, especially those that build a dome, can collapse to form fast-moving pyroclastic flows.



Figure 2. `A`a lava flow moves through an intersection in the Royal Garderns subdivision on the south flank of Kilauea Volcano, Hawai`i. Photograph by J.D. Griggs in 1984.

Deaths caused directly by lava flows are uncommon because most move slowly enough that people can move out the way easily and flows usually don't travel far from the vent. Death and injury can result when onlookers approach an advancing lava flow too closely or their retreat is cut off by other flows. Deaths attributed to lava flows are often due to related causes, such as explosions when lava interacts with water, the collapse of an active lava delta, asphyxiation due to accompanying toxic gases, pyroclastic flows from a collapsing dome, and lahars from meltwater.

Other natural phenomena such as hurricanes, tornadoes, tsunami, fires, and earthquakes often destroy buildings, agricultural crops, and homes, but the owner(s) can usually rebuild or repair structures and their businesses in the same location. Lava flows, however, can bury homes and agricultural land under tens of meters of hardened black rock; landmarks and property lines become obscured by a vast, new hummocky landscape. People are rarely able to use land buried by lava flows or sell it for more than a small fraction of its previous worth.

Lava erupted from Kilauea Volcano covers part of Highway 130 on the southeast coast of the Island of Hawai`i (see figure 3). By

the end of 1998, lava from the Pu'u' 'O'o-Kupaianaha eruption covered about 13 km of the highway to depths as great as 25 m. Between 1983 and 1998, lava flows covered an area of 99.7 km^2 (38.5 mi^2).



Figure 3. Lava buries or surrounds everything.

Because lava flows can completely block roads and highways that may serve as the only evacuation route for people threatened by an advancing flow, it is vital for communities that could be inundated with lava to develop emergency-response plans.

One of the chief threats of lava flows to property owners is that the flows may burn buildings and homes even if the flow doesn't reach the structure. This house caught fire from the intense heat of an advancing `a`a flow (note red glow of flow left of the house).

Basalt has the highest temperature of any lava, typically between about 1170-1100°C (~2140-2000°F). The other lava types (andesite, dacite, and rhyolite) form cooler flows with temperatures between about 1000-800°C (~1800-1500°F); some flows can still move slowly at temperatures as low as about 600°C (~1100°F).

Lava melts snow and ice to form jökulhlaups and lahars. By this time, the area of subsidence had grown to about 9 km long and 2-3 km wide. The eruption continued for about another 10 days, and meltwater from the glacier flowed into the Grímsvötn caldera. On October 1, water level in the caldera's subglacial lake was about 1410 m; by October 16, the water level had risen to 1504 m, an increase of 94 m! According to scientists monitoring the activity, lava erupting from the fissure was piled up on the ground beneath the glacier, "forming a mountain ridge which in places is expected to be 200 m high."



Figure 4. View of eruption crater and ash-covered Vatnajökull glacier about 36 hours after the eruption had broken through the ice. Photograph courtesy of Magnús Tumi Guðmundsson. Science Institute, University of Iceland. October 1, 1996, 12:30 p.m.

On October 16, scientists stated that the meltwater, which had been accumulating under the ice shelf in the Grímsvötn caldera lake, could begin draining at any time to trigger a jökulhlaup (glacial outburst flood). On November 5 the expected jökulhlaup began.

Collapsing lava flows trigger pyroclastic flows. The fast-moving pyroclastic flow was caused by the collapse of a thick lava flow that was extruding from the summit area and oozing down the volcano's steep upper cone. When the lava flow collapsed, the hot lava broke apart into fragments ranging in size from boulders to tiny ash particles and swept down the volcano under the influence of gravity to form the pyroclastic flow; the flow reached a maximum distance of 4.5 km from the summit.

PYROCLASTIC FLOWS AND THEIR EFFECTS

About Pyroclastic Flows

Pyroclastic flows are high-density mixtures of hot, dry rock fragments and hot gases that move away from the vent that erupted them at high speeds. They may result from the explosive eruption of molten or solid rock fragments, or both. They may also result from the nonexplosive eruption of lava when parts of dome or a thick lava flow collapses down a steep slope. Most pyroclastic flows consist of two parts: a basal flow of coarse fragments that moves along the ground, and a turbulent cloud of ash that rises above the basal flow. Ash may fall from this cloud over a wide area downwind from the pyroclastic flow.



Figure 5. Pyroclastic Flows destroy by direct impact.

Figure 5 shows a remnant of a building in Francisco Leon that was destroyed by pyroclastic flows and surges during the eruption of El Chichon volcano in southeastern Mexico between March 29 and April 4, 1982. Francisco Leon was located about 5 km SSE of the volcano. The reinforcement rods in the concrete wall are bent in the direction of flow (right to left).

Several pyroclastic surges swept down all sides of the volcano, reaching as far as 2 to 8 km from the volcano; pyroclastic flows represent only about 30 percent of the total combined mass of surges and flows. In addition to Francisco Leon, eight other villages were destroyed, claiming the lives of up to 2,000 people.



Figure 6. Pyroclastic Flows bury sites with hot rock debris.

Pyroclastic flows erupted by Mount Pinatubo on June 15, 1991, buried the Marella River valley (SW of Pinatubo) with pumice, ash, and other volcanic rocks to depths of between 50 and 200 m (as shown in figure 6). This eruption was one of the largest in the 20th century, depositing about 5.5 km^3 of rock debris over nearly 400 km^2. The pyroclastic flows traveled as far as 12 to 16 km from the volcano in all directions. Unlike river valleys, the steep slopes around the volcano were veneered with very thin, discontinuous pyroclastic-flow deposits.



Figure 7. Pyroclastic Flows melt snow and ice to form lahars.

A series of pyroclastic flows from Redoubt Volcano in Alaska between December 1989 and April 1990 rapidly melted snow and ice that generated lahars in Drift River (valley in figure 7). The lahars swept 40 km to Cook Inlet. Most of the pyroclastic flows were caused by the repeated collapse of a lava dome growing high on the volcano's north flank.

This view across the upper Drift River valley is to the SW; the north flank is on the right side of the volcano, but the dome is not visible. As each pyroclastic flow swept down the volcano's snow- and glacier-covered north flank, the hot lava-dome fragments eroded and mixed with the snow and ice to form a torrent of water that swept into Drift River. The sudden surges of water eroded loose sediment on the valley floor and transformed into lahars.

In this part of the Drift River valley, many of the lahars covered the entire valley floor, but they were generally no more than a few meters thick. The lahars provided an excellent opportunity to test a new lahar detection system.



Figure 8. Pyroclastic Flows burn forests, crops, and buildings.

A small but highly fluidized pyroclastic flow traveled down the narrow Belham stream channel as far as 5 to 6 km from a lava dome growing at the summit of Soufriere Hills volcano in Montserrat (shown in figure 8). The basal part of the pyroclastic flow was confined to the channel bottom, but the overriding hot ash cloud burned and killed vegetation along the channel. The pyroclastic flow was triggered by a partial collapse of the dome. With initial temperatures higher than 900°C, the rock debris and gas carried by a pyroclastic flow or surge easily remain hot enough to burn or singe combustible material even when they travel more than

20 km from a vent.

Effects of Pyroclastic Flows

A pyroclastic flow will destroy nearly everything in its path. With rock fragments ranging in size from ash to boulders traveling across the ground at speeds typically greater than 80 km per hour, pyroclastic flows knock down, shatter, bury or carry away nearly all objects and structures in their way. The extreme temperatures of rocks and gas inside pyroclastic flows, generally between 200°C and 700°C, can cause combustible material to burn, especially petroleum products, wood, vegetation, and houses.

Pyroclastic flows vary considerably in size and speed, but even relatively small flows that move less than 5 km from a volcano can destroy buildings, forests, and farmland. And on the margins of pyroclastic flows, death and serious injury to people and animals may result from burns and inhalation of hot ash and gases.

Pyroclastic flows generally follow valleys or other low-lying areas and, depending on the volume of rock debris carried by the flow, they can deposit layers of loose rock fragments to depths ranging from less than one meter to more than 200 m. Such loose layers of ash and volcanic rock debris in valleys and on hillslopes can lead to lahars indirectly by:

1. Damming or blocking tributary streams, which may cause water to form a lake behind the blockage, overtop and erode the blockage, and mix with the rock fragments as it rushes downstream (for example, see this case study at Pinatubo Volcano, Philippines)
2. Increasing the rate of stream runoff and erosion during subsequent rainstorms. Hot pyroclastic flows and surges can also directly generate lahars by eroding and mixing with snow and ice on a volcano's flanks, thereby sending a sudden torrent of water surging down adjacent valleys (see case study from Nevado del Ruiz volcano, Colombia).

TEPHRA AND THEIR EFFECTS

Tephra is a general term for fragments of volcanic rock and lava regardless of size that are blasted into the air by explosions or carried upward by hot gases in eruption columns or lava fountains. Such fragments range in size from less than 2 mm (ash) to more than 1 m in diameter. Large-sized tephra typically falls back to the ground on or close to the volcano and progressively smaller fragments are carried away from the vent by wind. Volcanic ash, the smallest tephra fragments, can travel hundreds to thousands of kilometers downwind from a volcano.

Tephra consists of a wide range of rock particles (size, shape, density, and chemical composition), including combinations of pumice, glass shards, crystals from different types of minerals, and shattered rocks of all types (igneous, sedimentary, and metamorphic). A great variety of terms are used to describe the range of rock fragments thrown into the air by volcanoes. The terms classify the fragments according to size, shape, or the way in which they form and travel.

Mount St. Helens Tephra: block	Mount St. Helens Tephra: ash & pumice	Kilauea Teph
		

Volcanic Ash

How far will it fall downwind from an erupting volcano?

Ash usually covers a much larger area and disrupts the lives of far more people than the other more lethal types of volcano hazards. Unfortunately, the size of ash particles that fall to the ground and the thickness of ashfall downwind from an erupting volcano are difficult to predict in advance. Not only is there a wide range in the size of an eruption that might occur and the amount of tephra injected into the atmosphere, but the direction and strength of the prevailing wind can vary widely.

Case Histories: Tephra Distribution Downwind from Eruption

- Tephra Falls of the 1991 Eruptions of Mount Pinatubo
  online report from Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines.
- Tephra fall from Mount St. Helens, Washington, on May 18, 1980
  graph, ash thickness and particle size downwind from volcano

Potential Effects of Volcanic Ash

Volcanic ash is highly disruptive to economic activity because it covers just about everything, infiltrates most openings, and is highly abrasive. Airborne ash can obscure sunlight to cause temporary darkness and reduce visibility to zero. Ash is slippery, especially when wet; roads, highways, and airport runways may become impassable. Automobile and jet engines may stall from ash-clogged air filters and moving parts can be damaged from abrasion, including bearings, brakes, and transmissions.

More effects include the following:

- Daylight turns into darkness.
- Roofs may collapse from added weight.
- Machinery and vehicles will be abraded.
- Farmland will be covered.
- Roads will be slippery, blocked, or blocked.
- Power systems may shut down.
- Waste-water systems may clog.
- Gutters may fill and collapse.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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9.10: Putting It Together

SUMMARY

In this section, you learned the following:

1. What the different types of volcanoes are
2. How the different types of volcanoes form and erupt
3. The different products of volcanic activity including pyroclastic flows, lahars, and the different types of lava
4. The hazards associated with volcanic eruptions

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10: MASS MOVEMENT

Landslides and avalanches may not be something we really think about unless we live in an area prone to them, but mass wasting can occur just about anywhere. If you recall from when we learned about the rock cycle, erosion is a powerful and continuous process.

10.1: Why It Matters

10.2: Classifying Mass Movements

10.3: Erosion and Deposition by Gravity

10.4: Driving and Resisting Forces

10.5: Landslide Types and Processes

10.6: Putting It Together

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10.1: Why It Matters

DEFINE AND INTERPRET THE CAUSES, TYPES, EFFECTS, AND HAZARDS OF MASS MOVEMENT AND LAND SUBSIDENCE

Introduction

Mass movement can be devastating and costly. About 10 years ago, a friend was looking to purchase a new home in San Diego. She found a great neighborhood being built on the side of a mountain overlooking the town. They loved the area, the view and the home so they purchased the home site. The cost was $1.5 million.

Since this was not the first home she purchased, she knew the questions to ask and the various test that needed to be performed. One of the inspectors made note of elevated methane in the area. They thought it was temporary and would not cause any problems. However, as more people purchased homes in the area, the problem became more prominent. She contacted a geologist and asked what it could be. The geologist was from the area and was familiar with the location. They did a little research and ruled out numerous possible causes. They were stumped until one day a core sample revealed the neighborhood was being built on an old landslide area. The buried trees and vegetation were decomposing, which was causing them to give off various gases including methane. Building on the site was stopped and never proceeded due to the conditions. The time, effort, and money spent was wasted. While the homeowners did get their money back, the property owner was completed bankrupted.

Landslides and avalanches may not be something we really think about unless we live in an area prone to them, but mass wasting can occur just about anywhere. If you recall from when we learned about the rock cycle, erosion is a powerful and continuous process.

Watch this video of a fantastic earthflow in Italy:

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Wasn't that amazing?

Mass wasting can be very fast or slow. What do you make of this picture?



Do you notice anything strange about the trees? Would you want to live in an area like this?

Let's see what mass wasting is and what it can tell us about the video and picture.

Learning Outcomes

- Identify, classify, and describe types of mass movement
- Identify and interpret driving and resisting forces on various slopes composed of various geologic materials, including geologic and human caused changes that can increase or reduce mass movement

Ok, let's get started!

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10.2: Classifying Mass Movements

IDENTIFY, CLASSIFY, AND DESCRIBE TYPES OF MASS MOVEMENT

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Erosion and Deposition by Gravity

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10.3: Erosion and Deposition by Gravity

INTRODUCTION

Gravity shapes the Earth's surface by moving weathered material from a higher place to a lower one. This occurs in a variety of ways and at a variety of rates including sudden, dramatic events as well as slow steady movements that happen over long periods of time. The force of gravity is constant and it is changing the Earth's surface right now.

TYPES OF MOVEMENT CAUSED BY GRAVITY

Movements caused by gravity are together referred to as **mass wasting** or **mass movement**. Weathered material may fall away from a cliff because there is nothing to keep it in place. Rocks that fall to the base of a cliff make a **talus slope** (figure 1). Sometimes as one rock falls, it hits another rock, which hits another rock, and begins a landslide.



Figure 1. Pieces of rock regularly fall to the base of cliffs to form talus slopes

Landslides and Avalanches

Landslides and **avalanches** are the most dramatic, sudden, and dangerous examples of earth materials moved by gravity. Landslides are sudden falls of rock, whereas avalanches are sudden falls of snow.

- Here is a video of a snow avalanche.

When large amounts of rock suddenly break loose from a cliff or mountainside, they move quickly and with tremendous force (figure 2). Air trapped under the falling rocks 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 2. (a) Landslides are called rock slides by geologists. (b) A snow avalanche moves quickly down slope, burying everything in its path.

Landslides are exceptionally destructive. Homes may be destroyed as hillsides collapse. Landslides can even bury entire villages. Landslides may create lakes when the rocky material dams a stream. If a landslide flows into a lake or bay, they can trigger a tsunami (figure 3).



Figure 3. The 1958 landslide into Lituya Bay, Alaska, created a 524m tsunami that knocked down trees at elevations higher than the Empire State Building (light gray).

Landslides often occur on steep slopes in dry or semi-arid climates. The California coastline, with its steep cliffs and years of drought punctuated by seasons of abundant rainfall, is prone to landslides. At-risk communities have developed landslide warning systems. Around San Francisco Bay, the National Weather Service and the U.S. Geological Survey use rain gauges to monitor soil moisture. If soil becomes saturated, the weather service issues a warning. Earthquakes, which may occur on California's abundant faults, can also trigger landslides.

- Here is a video of rapid downslope movement of material.

KQED: Landslide Detectives

Hillside properties in the San Francisco Bay Area and elsewhere may be prone to damage from landslides. Geologists are studying

the warning signs and progress of local landslides to help reduce risks and give people adequate warnings of these looming threats. You can learn more here.

Mudflows and Lahars

Added water creates natural hazards produced by gravity (figure 4). On hillsides with soils rich in clay, little rain, and not much vegetation to hold the soil in place, a time of high precipitation will create a **mudflow**. Mudflows follow river channels, washing out bridges, trees, and homes that are in their path.



Figure 4. The white areas on green hillsides mark scars from numerous mudflows.

- This video shows a debris flow.

A lahar is mudflow that flows down a composite volcano (figure 5). Ash mixes with snow and ice melted by the eruption to produce hot, fast-moving flows. The lahar caused by the eruption of Nevado del Ruiz in Columbia in 1985 killed more than 23,000 people.



Figure 5. A lahar is a mudflow that forms from volcanic ash and debris.

Slump and Creep

Less dramatic types of downslope movement move earth materials slowly down a hillside. **Slump** moves materials as a large block along a curved surface (figure 6). Slumps often happen when a slope is undercut, with no support for the overlying materials, or when too much weight is added to an unstable slope.



Figure 6. Slump material moves as a whole unit, leaving behind a crescent shaped scar.

Creep is the extremely gradual movement of soil downhill. Curves in tree trunks indicate creep because the base of the tree is moving downslope while the top is trying to grow straight up (figure 7). Tilted telephone or power company poles are also signs of creep.



Figure 7. Trees with curved trunks are often signs that the hillside is slowly creeping downhill.

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.

Water

A little bit of water helps to hold grains of sand or soil together. For example, you can build a larger sand castle with slightly wet sand than with dry sand. However too much water causes the sand to flow quickly away. Rapid snow melt or rainfall adds extra water to the soil, which increases the weight of the slope and makes sediment grains lose contact with each other, allowing flow.

Rock Type

Layers of weak rock, such as clay, also allow more landslides. Wet clay is very slippery, which provides an easy surface for materials to slide over.

Undercutting

If people dig into the base of a slope to create a road or a homesite, the slope may become unstable and move downhill. This is particularly dangerous when the underlying rock layers slope towards the area (figure 8).

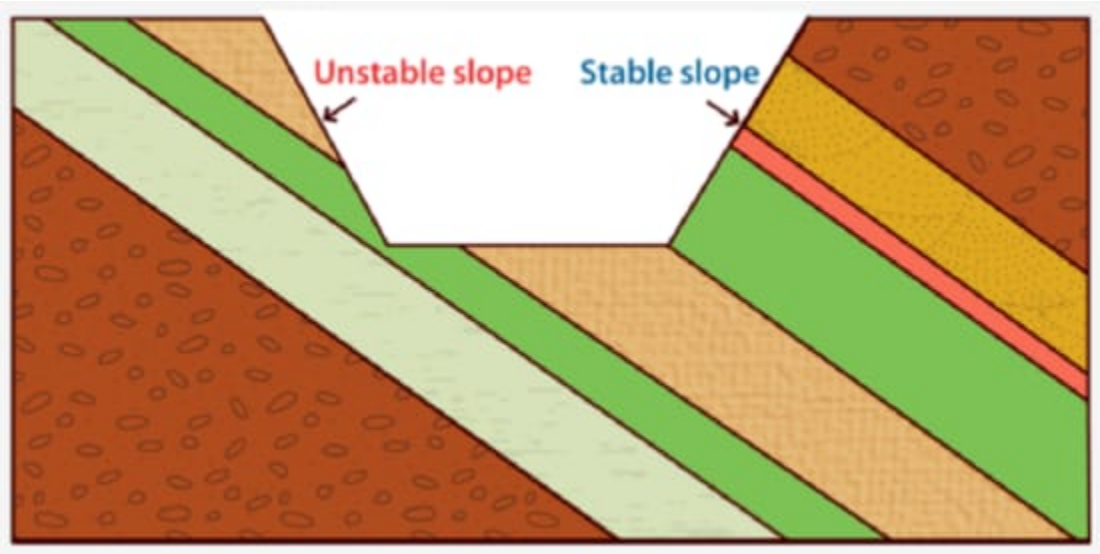


Figure 8. The slope of underlying materials must be considered when making road cuts.

- Ocean waves undercut cliffs and cause landslides on beaches as in this video.

When construction workers cut into slopes for homes or roads, they must stabilize the slope to help prevent a landslide (figure 9). Trees roots or even grasses can bind soil together. It is also a good idea to provide drainage so that the slope does not become saturated with water.



Figure 9. A rock wall stabilizes a slope that has been cut away to make a road.

Ground Shaking

An earthquake, volcanic eruption, or even just a truck going by can shake unstable ground loose and cause a slide. Skiers and hikers may disturb the snow they travel over and set off an avalanche.

A very good introduction to the topic, “Landslide 101,” is a video seen on National Geographic Videos, Environment Video, Natural Disasters, Landslides, and more.

PREVENTION AND AWARENESS

Landslides cause $1 billion to $2 billion damage in the United States each year and are responsible for traumatic and sudden loss of life and homes in many areas of the world. To be safe from landslides:

- Be aware of your surroundings and notice changes in the natural world.
- Look for cracks or bulges in hillsides, tilting of decks or patios, or leaning poles or fences when rainfall is heavy. Sticking windows and doors can indicate ground movement as soil pushes slowly against a house and knocks windows and doors out of alignment.
- Look for landslide scars because landslides are most likely to happen where they have occurred before.
- Plant vegetation and trees on the hillside around your home to help hold soil in place.
- Help to keep a slope stable by building retaining walls. Installing good drainage in a hillside may keep the soil from getting saturated.

LESSON SUMMARY

- Gravity moves earth materials from higher elevations to lower elevations.
- Landslides, avalanches, and mudflows are examples of dangerous erosion by gravity.
- Slump and creep move material slowly downslope.
- Plants, retaining walls, and good drainage are ways to help prevent landslides.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?

- What questions do you have about this content?

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10.4: Driving and Resisting Forces

IDENTIFY AND INTERPRET DRIVING AND RESISTING FORCES ON VARIOUS SLOPES COMPOSED OF VARIOUS GEOLOGIC MATERIALS, INCLUDING GEOLOGIC AND HUMAN CAUSED CHANGES THAT CAN INCREASE OR REDUCE MASS MOVEMENT.

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: Landslide Types and Processes

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10.5: Landslide Types and Processes

Landslides in the United States occur in all 50 States. The primary regions of landslide occurrence and potential are the coastal and mountainous areas of California, Oregon, and Washington, the States comprising the intermountain west, and the mountainous and hilly regions of the Eastern United States. Alaska and Hawaii also experience all types of landslides.

Landslides in the United States cause approximately $3.5 billion (year 2001 dollars) in damage, and kill between 25 and 50 people annually. Casualties in the United States are primarily caused by rockfalls, rock slides, and debris flows. Worldwide, landslides occur and cause thousands of casualties and billions in monetary losses annually.



Figure 1. La Conchita, coastal area of southern California. Photo by R.L. Schuster, U.S. Geological Survey.

The information in this publication provides an introductory primer on understanding basic scientific facts about landslides—the different types of landslides, how they are initiated, and some basic information about how they can begin to be managed as a hazard.

In La Conchita, there was a landslide and earthflow in the spring of 1995 (see figure 1). People were evacuated and the houses nearest the slide were completely destroyed. This is a typical type of landslide.

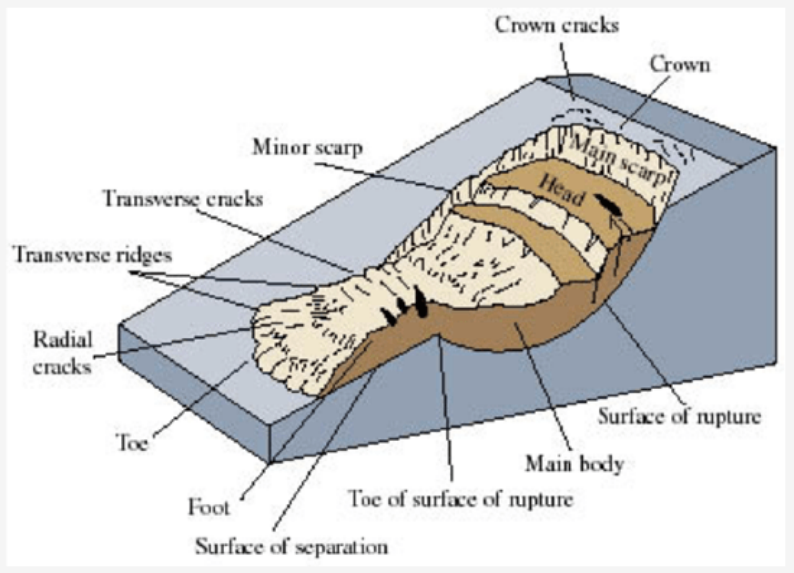


Figure 2. An idealized slump-earth flow showing commonly used nomenclature for labeling the parts of a landslide.

TYPES OF LANDSLIDES

The term “landslide” describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing. Figure 1 shows a graphic illustration of a landslide, with the commonly accepted terminology describing its features.

The various types of landslides can be differentiated by the kinds of material involved and the mode of movement. A classification system based on these parameters is shown in table 1. Other classification systems incorporate additional variables, such as the rate of movement and the water, air, or ice content of the landslide material.

Table 1. Types of landslides. Abbreviated version of Varnes’ classification of slope movements (Varnes, 1978).

Type of Movement		Type of Material		
		Bedrock	**Engineering Soils**	
			Predominantly coarse	***Predominantly fine***
Falls		Rock fall	Debris fall	Earth fall
Topples		Rock topple	Debris topple	Earth topple
Slides	***Rotational***	Rock slide	Debris slide	Earth slide
	Transitional			
Lateral Spreads		Rock spread	Debris spread	Earth spread
Flows		Rock flow (deep creep)	Debris flow (slow creep)	Earth flow (slow creep)
Complex		Combination or two or more principal types of movement		

Although landslides are primarily associated with mountainous regions, they can also occur in areas of generally low relief. In low-relief areas, landslides occur as cut-and-fill failures (roadway and building excavations), river bluff failures, lateral spreading landslides, collapse of mine-waste piles (especially coal), and a wide variety of slope failures associated with quarries and open-pit mines. The most common types of landslides are described as follows and are illustrated in figure 3.

Slides

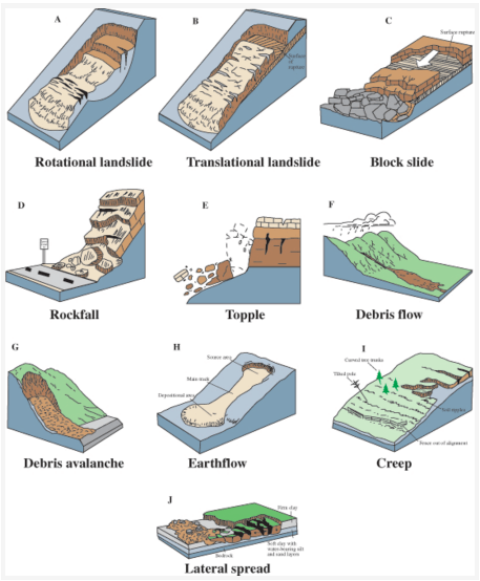


Figure 3. These schematics illustrate the major types of landslide movement.

Although many types of mass movements are included in the general term “landslide,” the more restrictive use of the term refers only to mass movements, where there is a distinct zone of weakness that separates the slide material from more stable underlying material. The two major types of slides are rotational slides and translational slides. Rotational slide: This is a slide in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide (fig. 3A). Translational slide: In this type of slide, the landslide mass moves along a roughly planar surface with little rotation or backward tilting (fig. 3B). A block slide is a translational slide in which the moving mass consists of a single unit or a few closely related units that move downslope as a relatively coherent mass (fig. 3C).

Falls

Falls are abrupt movements of masses of geologic materials, such as rocks and boulders, that become detached from steep slopes or cliffs (fig. 3D). Separation occurs along discontinuities such as fractures, joints, and bedding planes, and movement occurs by free-fall, bouncing, and rolling. Falls are strongly influenced by gravity, mechanical weathering, and the presence of interstitial water.

Topples

Toppling failures are distinguished by the forward rotation of a unit or units about some pivotal point, below or low in the unit, under the actions of gravity and forces exerted by adjacent units or by fluids in cracks (fig. 3E).

Flows

There are five basic categories of flows that differ from one another in fundamental ways.

1. Debris flow: A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as a slurry that flows downslope (fig. 3F). Debris flows include <50% fines. Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt, that erodes and mobilizes loose soil or rock on steep slopes. Debris flows also commonly mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt- and sand-sized material. Debris-flow source areas are often associated with steep gullies, and debris-flow deposits are usually indicated by the presence of debris fans at the mouths of gullies. Fires that denude slopes of vegetation intensify the susceptibility of slopes to debris flows.
2. Debris avalanche: This is a variety of very rapid to extremely rapid debris flow (fig. 3G).
3. Earthflow: Earthflows have a characteristic “hourglass” shape (fig. 3H). The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongate and usually occurs in fine-grained materials or clay-bearing rocks

on moderate slopes and under saturated conditions. However, dry flows of granular material are also possible.

4. Mudflow: A mudflow is an earthflow consisting of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt-, and clay-sized particles. In some instances, for example in many newspaper reports, mudflows and debris flows are commonly referred to as “mudslides.”
5. Creep: Creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure. There are generally three types of creep: (1) seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature; (2) continuous, where shear stress continuously exceeds the strength of the material; and (3) progressive, where slopes are reaching the point of failure as other types of mass movements. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges (fig. 3I).

Lateral Spreads

Lateral spreads are distinctive because they usually occur on very gentle slopes or flat terrain (fig. 3J). The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state. Failure is usually triggered by rapid ground motion, such as that experienced during an earthquake, but can also be artificially induced. When coherent material, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing and extension and may then subside, translate, rotate, disintegrate, or liquefy and flow. Lateral spreading in fine-grained materials on shallow slopes is usually progressive. The failure starts suddenly in a small area and spreads rapidly. Often the initial failure is a slump, but in some materials movement occurs for no apparent reason. Combination of two or more of the above types is known as a complex landslide.

LANDSLIDE CAUSES

1. Geological causes
    1. Weak or sensitive materials
    2. Weathered materials
    3. Sheared, jointed, or fissured materials
    4. Adversely oriented discontinuity (bedding, schistosity, fault, unconformity, contact, and so forth)
    5. Contrast in permeability and/or stiffness of materials
2. Morphological causes
    1. Tectonic or volcanic uplift
    2. Glacial rebound
    3. Fluvial, wave, or glacial erosion of slope toe or lateral margins
    4. Subterranean erosion (solution, piping)
    5. Deposition loading slope or its crest
    6. Vegetation removal (by fire, drought)
    7. Thawing
    8. Freeze-and-thaw weathering
    9. Shrink-and-swell weathering
3. Human causes
    1. Excavation of slope or its toe
    2. Loading of slope or its crest
    3. Drawdown (of reservoirs)
    4. Deforestation
    5. Irrigation
    6. Mining
    7. Artificial vibration
    8. Water leakage from utilities

Although there are multiple types of causes of landslides, the three that cause most of the damaging landslides around the world are these:

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10.6: Putting It Together

SUMMARY

In this section we were able to learn what implication erosion has on a grand scale. We learned the following:

1. The definition of mass wasting
2. The various types of mass wasting
3. The forces behind mass wasting
4. What humans are doing to aggravate the occurrence of mass wasting

SYNTHESIS

In the opening section, we saw a video of an earthflow in Italy and the damage it caused. Can you imagine that coming down a mountain side towards a major city like this?



Figure 1. Damage from the debris flow on the Caraballeda fan. The main channel (at left) avulsed to a new course that led it through the houses to the right. These avulsion deposits are up to 6 meters (20 ft) thick and total about 1.8 million cubic meters of boulders and other material.

What about this?



Figure 2. The Mameyes mudflow disaster, in barrio Tibes, Ponce, Puerto Rico, was caused by heavy rainfall from Tropical Storm Isabel in 1985. The mudflow destroyed more than 100 homes and claimed an estimated 300 lives.

Back to the picture from the opening—did you notice anything odd about the trees in the picture? They were definitely shaped strangely at the base. Their trunks were curved. These trees are the result of mass wasting, specifically creep. Creep is the slowest form of mass wasting, but imagine what would happen if you had a house there!

Once again, we have seen strong forces we are dealing with in geology. By understanding how the various types of mass wasting occur, geologists can save not only money but lives as well.

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11: HYDROLOGY

This section focuses on hydrology. It goes without saying how important water is to all life on the planet. We simply cannot survive without it. Water is what sets the Earth apart from the other planets in our solar system. While the oceans cover roughly 74% of the Earth's surface and are the driving force behind the hydrologic cycle, it is the availability of freshwater that is of most concern today.

11.1: Why It Matters

11.2: Water Cycle

11.3: The Water Cycle

11.4: Streams

11.5: Water Erosion and Deposition

11.6: Streams

11.7: Groundwater

11.8: Groundwater

11.9: Back to Basics on Groundwater

11.10: Aquifers

11.11: Wells

11.12: Aquifers

11.13: Karst Topography, Geysers, and Springs

11.14: Karst Topography

11.15: Geysers, Fumaroles, and Hot Springs

11.16: Springs

11.17: Putting It Together

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11.1: Why It Matters

UNDERSTAND ROLES, PROCESSES, AND EFFECTS OF STREAMS AND GROUNDWATER

This section focuses on hydrology. It goes without saying how important water is to all life on the planet. We simply cannot survive without it. Water is what sets the Earth apart from the other planets in our solar system. While the oceans cover roughly 74% of the Earth's surface and are the driving force behind the hydrologic cycle, it is the availability of freshwater that is of most concern today.

Currently, California is experiencing severe drought while the Midwest is currently undergoing extreme flooding. While these variations are a normal part of the complex dynamic of climate, they impact us in major ways. California is currently scrambling to find a solution as it is currently estimated that in just over a year they will no longer have enough freshwater to meet their needs. With flooding in the Midwest, the loss of life and property damage is steadily increasing. Droughts and floods are a normal part of the hydrologic cycle, the issue is how to be prepared for them and how to best adapt to them in order to survive.

Freshwater consists of glaciers, groundwater, surface water (such as ponds and lakes) as well as water stored in the biosphere and the atmosphere. The vast majority of freshwater is used in agriculture for irrigation purposes. Again, without this freshwater our food production would suffer. Most people associate mining with metals, fuel resources and gems. However, would it surprise you to learn that we actually mine water? Mining means withdrawing or removing something from within the Earth. Groundwater is found within the Earth and is our second largest store of freshwater. Currently, groundwater use in the US is centered on the Ogallala Aquifer.

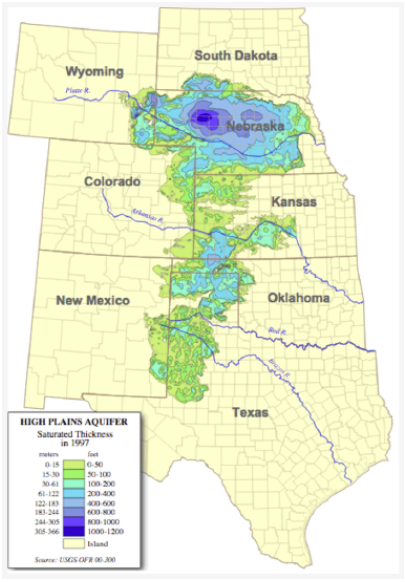


Figure 1. Saturated thickness of the Ogallala Aquifer in 1997 after several decades of intensive withdrawals. The breadth and depth of the aquifer generally decrease from north to south.

The Ogallala Aquifer is located in the central portion of the United States. It is located beneath 8 states: Texas, Oklahoma, Colorado, Kansas, Nebraska, New Mexico, South Dakota and Wyoming. It is approximately 174,000 square miles in area and is more than 10,000,000 years old (Kromm, n.d.). It is the freshwater source for over 13,600,000 acres of farming and ranch lands. This aquifer formed, in part, due to melting glaciers and took over 64,000 years to fill (Overmann, n.d.). It is the largest aquifer in North America and one of the largest freshwater sources in the world. Initially, farmers only had to drill down anywhere from 25 to 50 feet before they would hit the water table. However, in the 1940's this began to change. With the technology boom associated with the war and the post war period, numerous devices such as high capacity pumps allowed easier and greater access to the aquifer. In some places, farmers now have to drill over 500 feet before they hit the water table. The Ogallala was originally over

500 feet in thickness but now that has diminished and varies by location. The issue with this particular aquifer is that is being used at a much greater rate than it is recharged. In fact, the Ogallala is considered to be a “fossil aquifer” which means once it is gone, it is gone. What does this mean for us? How does this translate into affecting you or your family?

Here is a short video that shows you some of the ways farmers are adapting the rapid depletion of the aquifer.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Learning Outcomes

- Describe and model processes involved throughout Earth’s hydrologic cycle
- Identify and describe channel types and sedimentary loads formed and carried by streams
- Describe how groundwater is affected by porosity and permeability of geologic materials and by hydraulic gradient
- Compare and contrast types of aquifers and potential well use within various types of aquifers
- Define and describe karst topography, geysers, and springs

Ok, let’s get started!

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11.2: Water Cycle

DESCRIBE AND MODEL PROCESSES INVOLVED THROUGHOUT EARTH'S HYDROLOGIC CYCLE

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by this Open Educational Resource. Review and reflect the content as you prepare to complete the assessment for this module.

- Reading: The Water Cycle

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11.3: The Water Cycle

Water is simply two atoms of hydrogen and one atom of oxygen bonded together. Despite its simplicity, water has remarkable properties. Water expands when it freezes, has high surface tension (because of the polar nature of the molecules, they tend to stick together), and others. Without water, life might not be able to exist on Earth and it certainly would not have the tremendous complexity and diversity that we see.

Distribution of Earth's Water

Earth's oceans contain 97% of the planet's water, so just 3% is fresh water, water with low concentrations of salts (figure 1). Most **fresh water** is trapped as ice in the vast glaciers and ice sheets of Greenland. A storage location for water such as an ocean, glacier, pond, or even the atmosphere is known as a **reservoir**. A water molecule may pass through a reservoir very quickly or may remain for much longer. The amount of time a molecule stays in a reservoir is known as its **residence time**.

How is the 3% of fresh water divided into different reservoirs? How much of that water is useful for living creatures? How much for people?

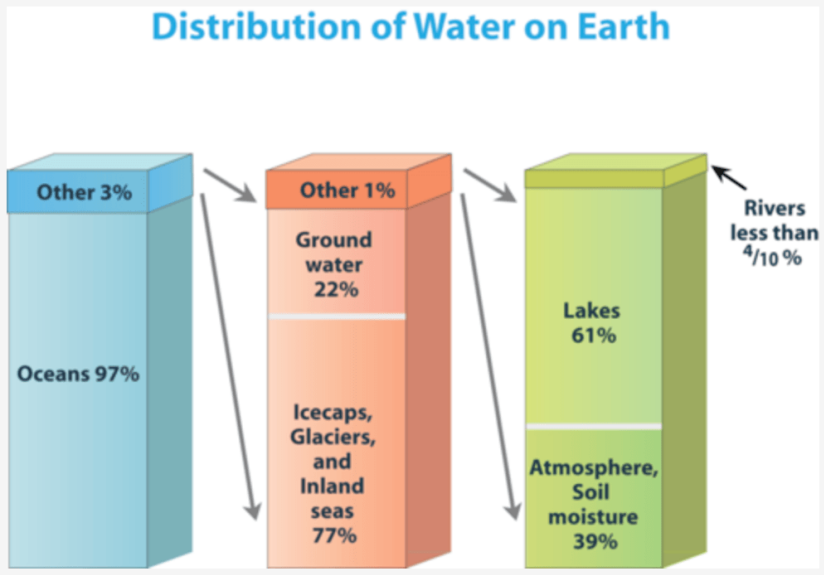


***Figure 1**. The distribution of Earth's water.*

The Hydrologic Cycle

Because of the unique properties of water, water molecules can cycle through almost anywhere on Earth. The water molecule found in your glass of water today could have erupted from a volcano early in Earth history. In the intervening billions of years, the molecule probably spent time in a glacier or far below the ground. The molecule surely was high up in the atmosphere and maybe deep in the belly of a dinosaur. Where will that water molecule go next?

Three States of Water

Water is the only substance on Earth that is present in all three states of matter – as a solid, liquid or gas. (And Earth is the only planet where water is present in all three states.) Because of the ranges in temperature in specific locations around the planet, all three phases may be present in a single location or in a region. The three phases are solid (ice or snow), liquid (water), and gas (**water vapor**). See ice, water, and clouds (figure 2).



Figure 2. *(a) Ice floating in the sea. Can you find all three phases of water in this image? (b) Liquid water. (c) Water vapor is invisible, but clouds that form when water vapor condenses are not.*

The Water Cycle

Because Earth's water is present in all three states, it can get into a variety of environments around the planet. The movement of water around Earth's surface is the **hydrologic (water) cycle** (figure 3).

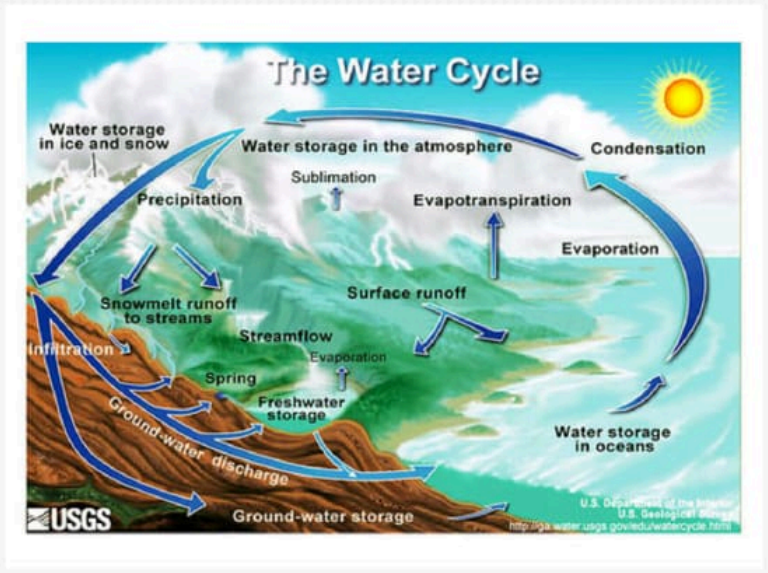


Figure 3*. Because it is a cycle, the water cycle has no beginning and no end.*

The Sun, many millions of kilometers away, provides the energy that drives the water cycle. Our nearest star directly impacts the water cycle by supplying the energy needed for evaporation. Most of Earth's water is stored in the oceans where it can remain for hundreds or thousands of years. Water changes from a liquid to a gas by **evaporation** to become water vapor. The Sun's energy can evaporate water from the ocean surface or from lakes, streams, or puddles on land. Only the water molecules evaporate; the salts remain in the ocean or a fresh water reservoir.

The water vapor remains in the atmosphere until it undergoes **condensation** to become tiny droplets of liquid. The droplets gather in clouds, which are blown about the globe by wind. As the water droplets in the clouds collide and grow, they fall from the sky as precipitation. **Precipitation** can be rain, sleet, hail, or snow. Sometimes precipitation falls back into the ocean and sometimes it falls onto the land surface.

For a little fun, watch this video. This water cycle song focuses on the role of the sun in moving H_2O from one reservoir to another. The movement of all sorts of matter between reservoirs depends on Earth's internal or external sources of energy:

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

This animation shows the annual cycle of monthly mean precipitation around the world.

When water falls from the sky as rain it may enter streams and rivers that flow downward to oceans and lakes. Water that falls as snow may sit on a mountain for several months. Snow may become part of the ice in a glacier, where it may remain for hundreds or thousands of years. Snow and ice may go directly back into the air by **sublimation**, the process in which a solid changes directly into a gas without first becoming a liquid. Although you probably have not seen water vapor sublimating from a glacier, you may have seen dry ice sublimate in air.

Snow and ice slowly melt over time to become liquid water, which provides a steady flow of fresh water to streams, rivers, and lakes below. A water droplet falling as rain could also become part of a stream or a lake. At the surface, the water may eventually evaporate and reenter the atmosphere.

A significant amount of water infiltrates into the ground. Soil moisture is an important reservoir for water (figure 4). Water trapped in soil is important for plants to grow.

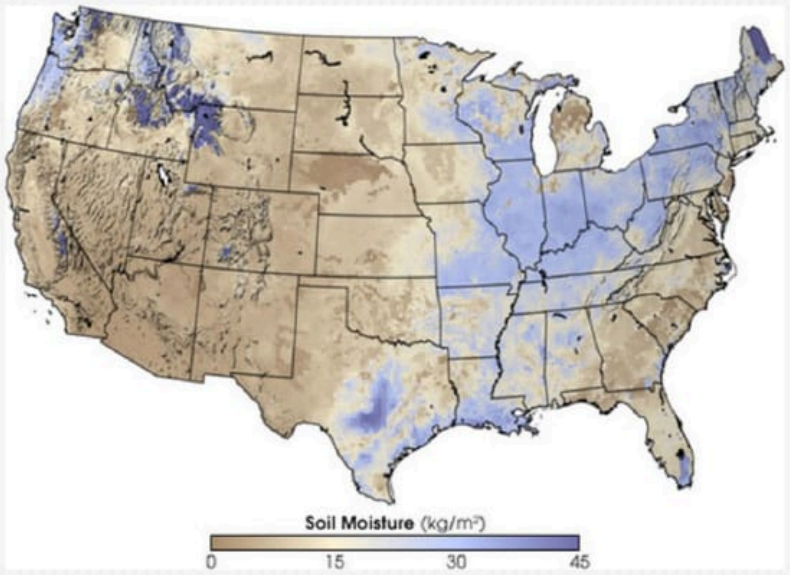


Figure 4. *The moisture content of soil in the United States varies greatly.*

Water may seep through dirt and rock below the soil through pores infiltrating the ground to go into Earth's groundwater system. Groundwater enters aquifers that may store fresh water for centuries. Alternatively, the water may come to the surface through springs or find its way back to the oceans.

Plants and animals depend on water to live and they also play a role in the water cycle. Plants take up water from the soil and release large amounts of water vapor into the air through their leaves (figure 5), a process known as **transpiration**.

An online guide to the hydrologic cycle from the University of Illinois is found here.



Figure 5. Clouds form above the Amazon Rainforest even in the dry season because of moisture from plant transpiration.

People also depend on water as a natural resource. Not content to get water directly from streams or ponds, humans create canals, aqueducts, dams, and wells to collect water and direct it to where they want it (figure 6).



Figure 6. The Pont du Gard aqueduct in France was constructed during the Roman Empire.

Table 1. Water Use in the United States and Globally

Use	United States	Global
Agriculture	34%	70%
Domestic (drinking, bathing)	12%	10%
Industry	5%	20%
Power plant cooling	49%	small

It is important to note that water molecules cycle around. If climate cools and glaciers and ice caps grow, there is less water for the oceans and sea level will fall. The reverse can also happen.

KQED: Tracking Raindrops

How the water cycle works and how rising global temperatures will affect the water cycle, especially in California, are the topics of this Quest video. Learn more here.

SUMMARY

- Although Earth's surface is mostly water covered, only 3% is fresh water.
- Water on Earth is found in all three phases: solid, liquid, and gas.
- Water travels between phases and reservoirs as part of the hydrologic (water) cycle.
- The major processes of the water cycle include evaporation, transpiration, condensation, precipitation, and return to the oceans via runoff and groundwater supplies.

QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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11.4: Streams

IDENTIFY AND DESCRIBE CHANNEL TYPES AND SEDIMENTARY LOADS FORMED AND CARRIED BY STREAMS

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Water Erosion and Deposition
- Reading: Streams

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11.5: Water Erosion and Deposition

INTRODUCTION

Streams—any running water from a rivulet to a raging river—complete the hydrologic cycle by returning precipitation that falls on land to the oceans (figure 1). Some of this water moves over the surface and some moves through the ground as **groundwater.** Flowing water does the work of both erosion and deposition.



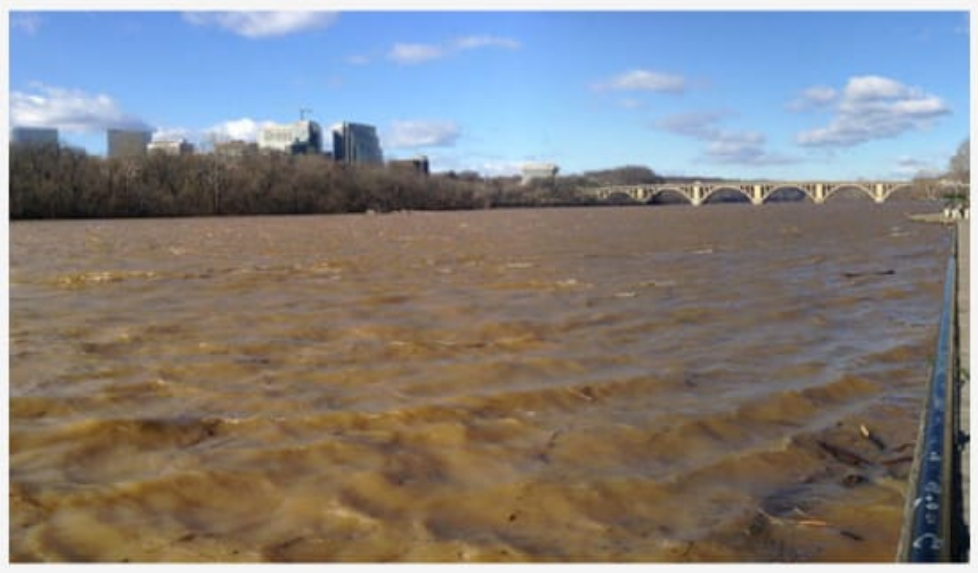
Figure 1. As streams flow towards the ocean, they carry weathered materials.

EROSION AND DEPOSITION BY STREAMS

Erosion By Streams

Flowing streams pick up and transport weathered materials by eroding sediments from their banks. Streams also carry ions and ionic compounds that dissolve easily in the water. Sediments are carried as:

- Dissolved load: Dissolved load is composed of ions in solution. These ions are usually carried in the water all the way to the ocean.
- Suspended load: Sediments carried as solids as the stream flows are suspended load. The size of particles that can be carried is determined by the stream's velocity (figure 2). Faster streams can carry larger particles. Streams that carry larger particles have greater **competence**. Streams with a steep **gradient** (slope) have a faster velocity and greater competence.



- **Bed load**: Particles that are too large to be carried as suspended load are bumped and pushed along the stream bed as bed load. Bed load sediments do not move continuously. This intermittent movement is called **saltation**. Streams with high velocities and steep gradients do a great deal of down cutting into the stream bed, which is primarily accomplished by movement of particles that make up the bed load.
- Here is a video of bedload transport.

Stages of Streams

As a stream flows from higher elevations, like in the mountains, towards lower elevations, like the ocean, the work of the stream changes. At a stream's **headwaters**, often high in the mountains, gradients are steep (figure 3). The stream moves fast and does lots of work eroding the stream bed.



Figure 3. This stream begins as snow melt from the mountains.

As a stream moves into lower areas, the gradient is not as steep. Now the stream does more work eroding the edges of its banks. Many streams develop curves in their channels called **meanders** (figure 4).



Figure 4. (a) At a meander, a stream actively erodes its outer banks and deposits material along the inside curves. This causes these meanders to migrate laterally over time. (b) This stream has deposited larger materials such as gravel and pebbles along the inside curve of a meander. (c) This image is a topographic map. The San Juan River eroded the land surface as the Colorado Plateau uplifted. The river's meanders were preserved as a feature called incised meanders.

As the river moves onto flatter ground, the stream erodes the outer edges of its banks to carve a **floodplain**, which is a flat level area surrounding the stream channel (figure 5).



Figure 5. The Vistula River in Poland flows onto its floodplain.

Base level is where a stream meets a large body of standing water, usually the ocean, but sometimes a lake or pond. Streams work to down cut in their stream beds until they reach base level. The higher the elevation, the farther the stream is from where it will reach base level and the more cutting it has to do.

Stream Deposition

As a stream gets closer to base level, its gradient lowers and it deposits more material than it erodes. On flatter ground, streams deposit material on the inside of meanders. Placer mineral deposits, described in the Earth's Minerals chapter, are often deposited there. A stream's floodplain is much broader and shallower than the stream's channel. When a stream flows onto its floodplain, its velocity slows and it deposits much of its load. These sediments are rich in nutrients and make excellent farmland (figure 6).

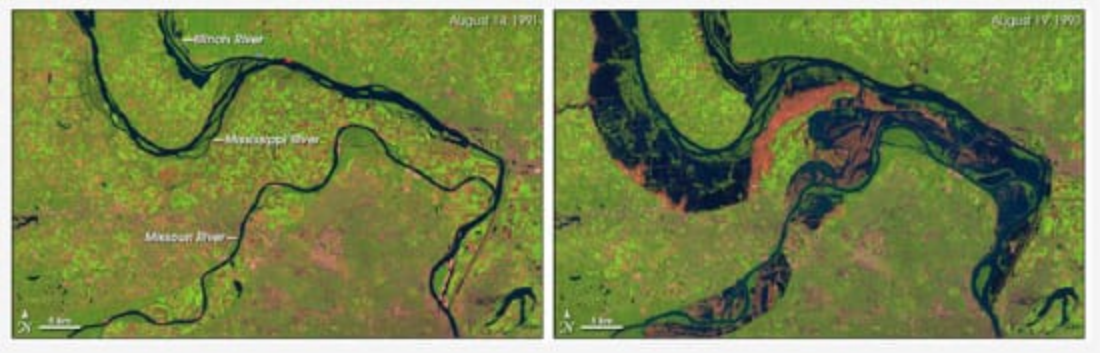


Figure 6. The Mississippi floodplain is heavily farmed. Flooding can wipe out farms and towns, but the stream also deposits nutrient-rich sediments that enrich the floodplain.

A stream at flood stage carries lots of sediments. When its gradient decreases, the stream overflows its banks and broadens its channel. The decrease in gradient causes the stream to deposit its sediments, the largest first. These large sediments build a higher area around the edges of the stream channel, creating **natural levees** (figure 7).

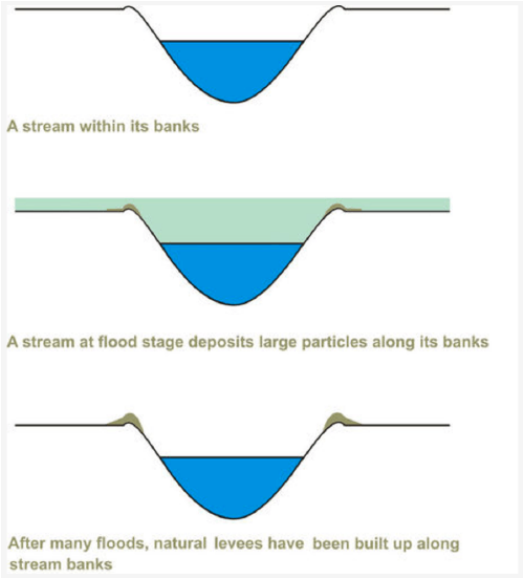


Figure 7. After many floods, a stream builds natural levees along its banks.

When a river enters standing water, its velocity slows to a stop. The stream moves back and forth across the region and drops its sediments in a wide triangular-shaped deposit called a **delta** (figure 8).



Figure 8. (a) The Nile River delta has a classic triangular shape, like the capital Greek letter delta. (b) Sediment in the Yellow River delta. The main stream channel splits into many smaller distributaries.

If a stream falls down a steep slope onto a broad flat valley, an **alluvial fan** develops (figure 9). Alluvial fans generally form in arid regions.



Figure 9. An alluvial fan in Iran. The mountains are in the lower right corner of the photograph.

GROUND WATER EROSION AND DEPOSITION

Rainwater absorbs carbon dioxide (CO_2) as it falls. The CO_2 combines with water to form carbonic acid. The slightly acidic water sinks into the ground and moves through pore spaces in soil and cracks and fractures in rock. The flow of water underground is **ground water.**

Ground water is a strong erosional force, as it works to dissolve away solid rock. Carbonic acid is especially good at dissolving the rock limestone.

Cave Formation

Working slowly over many years, ground water travels along small cracks. The water dissolves and carries away the solid rock gradually enlarging the cracks. Eventually a cave may form (figure 10).

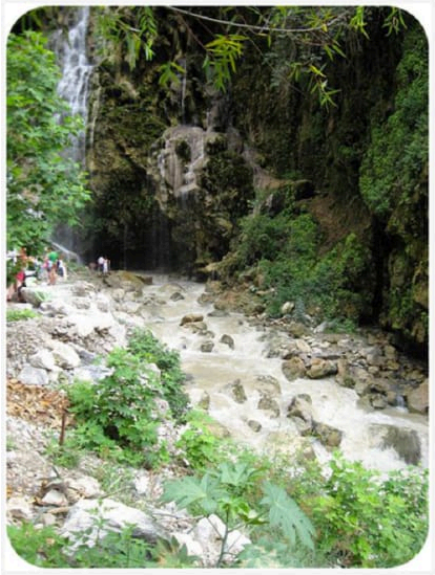


Figure 10. Caverns many football fields long and as high as many meters tall form where ground water erodes away rock.

Ground water carries the dissolved minerals in solution. The minerals may then be deposited, for example, as **stalagmites** or **stalactites** (figure 11).



Figure 11. (a) Stalactites form as calcium carbonate drips from the ceiling of a cave, forming beautiful icicle-like formations. The word stalactite has a c and it forms from the ceiling. (b) Stalagmites form as calcium carbonate drips from the ceiling to the floor of a cave and then grow upwards. The g in stalagmite means 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 rock, formed from calcium carbonate, **travertine**. Ground water saturated with calcium carbonate precipitates as the mineral calcite or aragonite. Mineral springs that produce travertine can be hot, warm or even cold (figure 12).



Figure 12. Travertine is a beautiful form of limestone.

You can explore a fantastic cave, Kartchner Caverns, in Arizona, by watching this video.

If the roof of a cave collapses, a **sinkhole** could form. Some sinkholes are large enough to swallow up a home or several homes in a neighborhood (figure 13).



Figure 13. This sinkhole formed in Florida.

LESSON SUMMARY

- 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 erodes deeply when it is far from its base level, the place where it enters standing water.
- Streams form bends, called meanders. Broad, flat areas are known as floodplains.
- A delta or an alluvial fan might form where the stream drops its sediment load.
- Caves form underground as ground water gradually dissolves away rock.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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11.6: Streams

INTRODUCTION

Streams have a major role in geology. Streams sculpt and shape the earth's surface by eroding, transporting, and depositing sediment. By eroding sediment from uplifted areas and creating landforms made of deposited sediment in lower areas, streams shape the earth's surface more than glaciers do, more than waves on a beach do, and far more than wind does.

WHAT ARE STREAMS?

A stream is flow of water, driven by gravity, in a natural channel, on land. A small brook in a meadow and the Amazon River are both streams. It is interesting to watch water on a recently bulldozed construction site with a slope. At first the water saturates the ground and begins to flow downhill across the surface of the slope in a thin sheet. Soon, the water excavates small channels, known as rills, in the dirt. Rills coalesce to form larger channels. A network of streams, including tributaries, has formed. If not prevented, the channels may continue to deepen and erode soil from the construction site.

Over longer intervals of time the same processes we've imagined on the construction site have built systems of streams and stream valleys on the surface of the earth. Most valleys on earth are the product of streams. Streams erode dirt and rocks, transport the sediment, and redeposit it in new locations, shaping the earth's surface into a system of stream valleys.

Streams flow downhill due to the force of gravity. The higher the hill, the more gravitational energy there is to drive the stream. Where the slopes are steepest and the hills the highest, the streams will be the most energetic and the rate of erosion will be fastest.

DRAINAGE AREA

The drainage area of a stream encompasses all the land from which surface runoff flows into that stream. A stream drainage area is also called a watershed. Boundaries between stream drainage areas are called drainage divides. What stream drainage do you live in?

STREAM ORDER

It is common for one stream to flow into another. The smaller of the two streams is a tributary of the larger stream. A stream with no tributaries is a first order stream. A stream with only first-order tributaries is a second order stream. A stream that has any second-order tributaries and none higher is a third-order stream, and so on. The Mississippi River is a tenth order stream, one of the highest order streams on earth. As more and more tributaries join together a larger stream network is formed and the master stream, the highest order stream in the system has a discharge that is the sum of all the tributary discharges. When flooding occurs, higher order streams take longer to build up to flood stage than lower order streams and longer for the flood to subside.

DRAINAGE PATTERNS

A stream system that includes multiple tributaries exhibits a distinct drainage pattern as seen on a map. The drainage pattern depends on the rock types and geologic structures underlying the stream system. Some types of rock are harder and more resistant to erosion than others. If the geology underlying a stream system is fairly uniform—rocks equally resistant to erosion in all directions—a dendritic drainage pattern will develop, as shown in figure 1. A dendritic drainage pattern is the most common type.

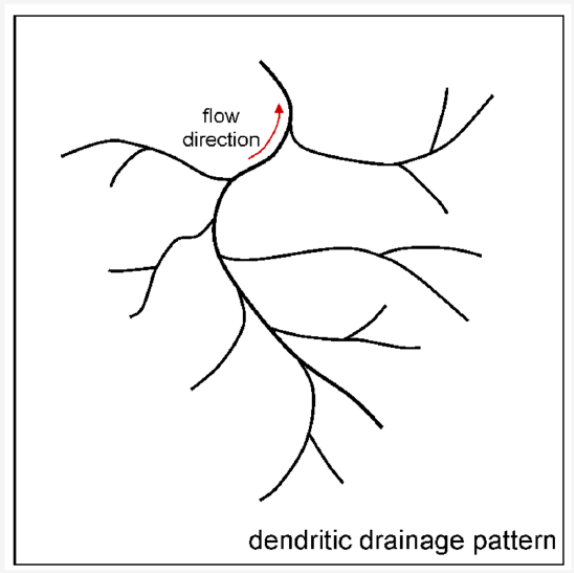


Figure 1

If a region is underlain by layered formations of rock that have been folded, and the layers have different degrees of resistance to erosion, the stream valleys will tend to follow the layers of less resistant rock, and the layers of harder rock will become ridges. This results in a trellis drainage pattern, as show in figure 2.

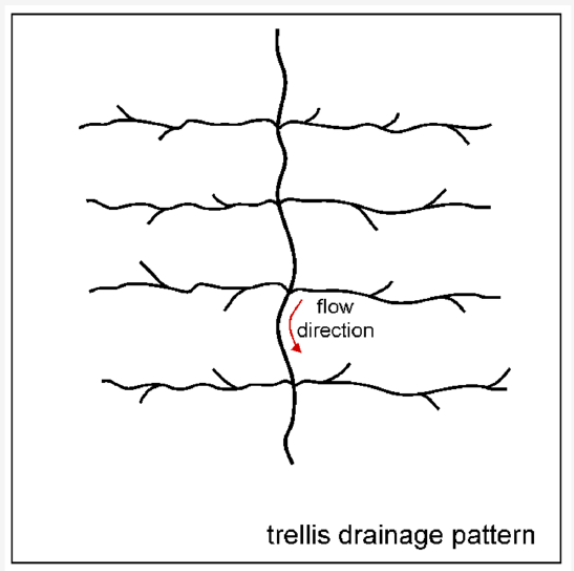


Figure 2.

In some places the geology consists of a single type of rock that is resistant to erosion but the rock contains sets of parallel joints where it erodes more easily. The sets of joints typically intersect each other at high angles. As stream valleys develop in the joint system a rectangular drainage pattern develops, as shown in figure 3. The stream valleys will bend sharply where they switch from following one joint set to another.

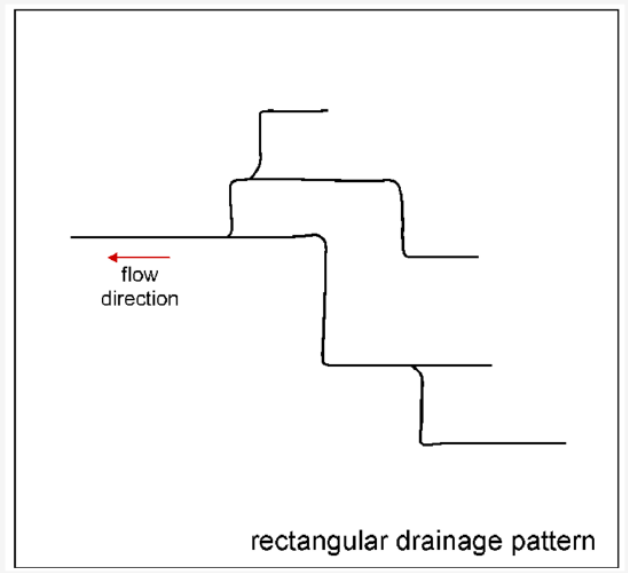


Figure 3.

Streams will radiate in all directions from the center of a broad, high-elevation area, such as a composite cone. This is known as a radial drainage pattern.

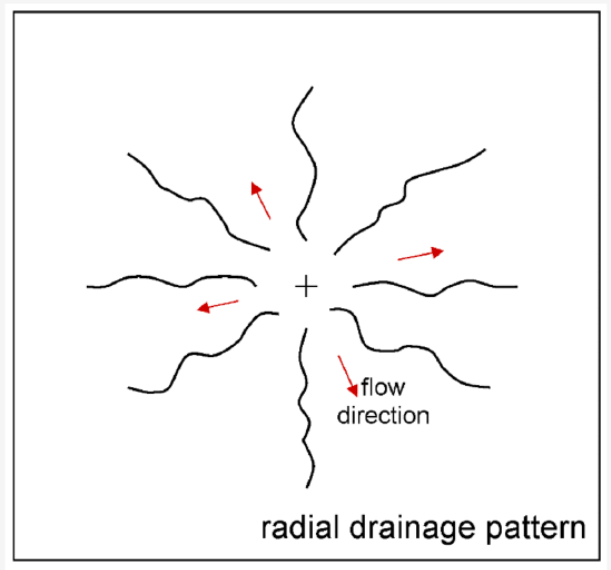


Figure 4.

GRADED PROFILE

Because streams erode more and remove more sediment where the stream gradient is higher, and deposit more sediment where the stream gradient is lower, a stream will develop a graded profile as shown. The graded profile shows how the elevation of the stream changes along the length of the stream, from its beginning at the highest elevation to its base level where it ends at the lowest elevation it reaches.

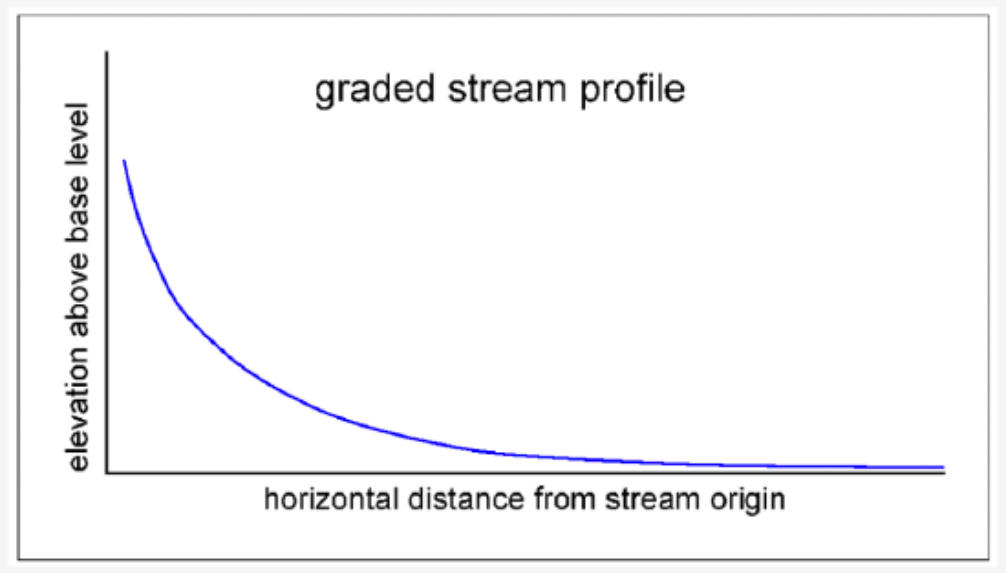


Figure 5.

A graded profile starts with a steep slope at the beginning of the stream and tapers to a gentle slope at the base level of the stream. Imagine a hiker following a stream up to its beginning and tracking her progress on a topographic map. She starts out where the stream valley is low and wide and the gradient is gentle so the hiking is easy. As the day goes on, the going gets steeper as she approaches the stream source. Checking the topographic map, she sees that the contour lines are much closer together than they were earlier in the day and farther down the valley. As she approaches the small lake on the side of the mountain where the stream begins, the slope is so steep that nearly loses her footing. She has experienced for herself a typical stream profile that steepens from near the base-level to the origin of the stream.

Lakes and waterfalls are temporary features in a stream drainage. If a lake forms the stream feeding it will slow down and deposit sediment until the lake has been filled with sediment. Where a waterfall forms the energy of the stream going over the waterfall is high will erode the base of the waterfall, causing the waterfall to retreat upstream until a graded profile is established.

STREAM DISCHARGE

The amount of water flowing through a stream and speed at which it is moving is expressed as the discharge of the stream. Discharge is measured by multiplying the cross-sectional area of a stream by the average speed of water through that cross-section. Multiplying the area of the cross-section by the average speed of the water results in units of volume/time. For example, if a stream has a cross-sectional area of 150 square feet (ft^2) and is moving at an average speed of 10 feet per second (ft/s), multiplying the area and the speed results in a discharge of 1,500 cubic feet per second (ft^3/s).

SEDIMENT LOAD

The water flowing in streams erodes, transports, and deposits sediment. Most rocks and minerals are much denser than water. Sufficient energy in the stream is required to dislodge rocks from the earth and move them. The faster a stream flows, the more energy it has and the larger pieces of sediment it can transport. The *competence* of a stream refers to the maximum size of the pieces of sediment it can move. Faster-moving water has greater competence and can move larger pieces of sediment.

The *capacity* of a stream is the total amount of sediment it can move. Capacity depends on how fast the stream is moving and its total discharge. As a stream slows down, its competence and capacity are reduced. The stream starts to deposit sediment, beginning with the largest pieces. Several factors cause a stream to slow down, including the stream channel widening, the stream overflowing its banks and spreading into a floodplain, the stream gradient (downhill slope) diminishing, and the stream emptying into a larger, slower moving body of water.

Streams transport clastic sediment in two ways depending on the size of the particles. The coarser sediment is called bed load and consists of particles too large to be suspended in the moving current of water for an extended length of time. The bed load

particles, the largest particles of sediment transported by a stream, spend most of their time on the bottom of the stream channel, rolling, sliding, or bouncing downstream in fits and starts. The finer sediment is called suspended load and consists of particles small enough to be suspended in the moving current of water. Suspended load moves at about the same rate as the flowing water. In a muddy river, the mud is suspended load.

FLOODPLAINS

Streams build floodplains through a combination of erosion and deposition at lower gradient stretches of stream valleys. Although a floodplain has a general downhill slope consistent with the overall stream gradient, a floodplain is relatively flat.

Floodplains are filled with sediments spread by the stream. These sediments are known as alluvium. Because alluvium is loose material that is easy for the stream to erode and redeposit, the location of a stream channel in a floodplain changes frequently.

Meanders

A stream running down a slope, even the gentle slope of a floodplain, will seldom follow a straight path for very long. Depending on the distribution of sediments and turbulence of the stream, one side of the channel may erode more easily than the other. The stream will migrate toward the area undergoing erosion, developing a curve in that direction. Once the stream channel has begun to curve, the energy of the water is concentrated on the outside of the curve.

The diagram shows a stretch of stream channel with a significant bend, also known as meander. The blue line shows how erosive energy is concentrated along the outside of each bend in the stream. As erosion occurs on the outside bank of a meander, deposition occurs on the inside bank where the water slows and drops sediment.

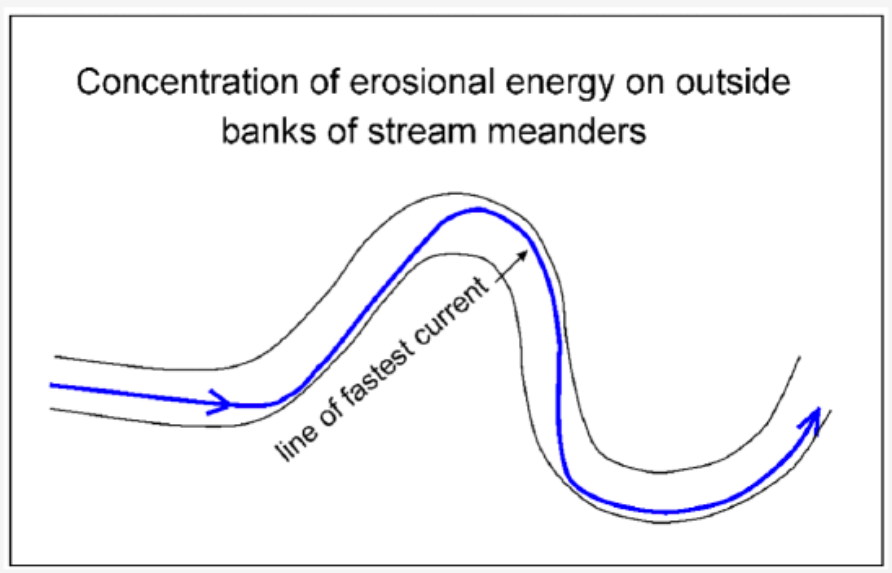


Figure 6.

The diagram below shows two well-developed meanders that have formed in a stream. Along each meander, the outer stream bank that is being cut into by erosion is called a cut bank. The inner bank, which has grown by accretion of deposited sediment, is called a point bar.

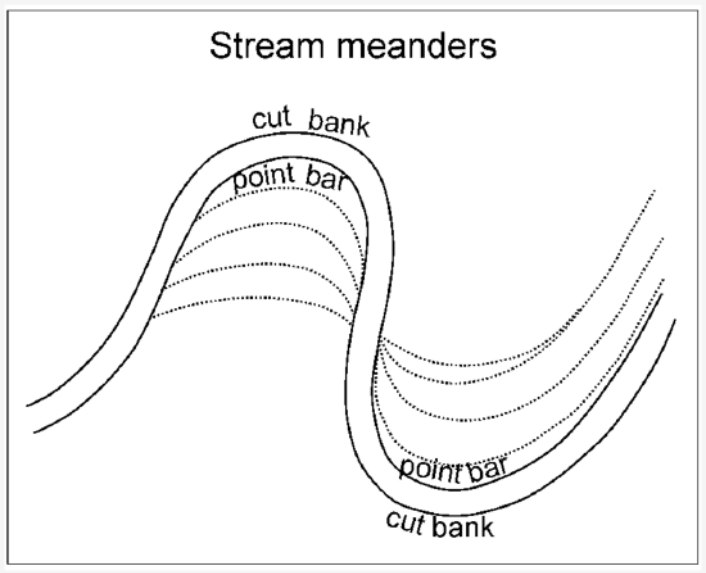


Figure 7.

In a stream, meanders enlarge and migrate downstream because the stream continually erodes its cut banks and grows its point bars. The diagram below shows the enlargement and downstream migration of a meander in a stream channel. As the meander is enlarged, its neck gets narrower. Eventually, the stream may cut through the neck of the meander, either as a result of gradual erosion and channel migration, or abruptly during high water and flooding. Once the stream has cut through the neck of the meander, the openings get filled with sediment dropped by water that slows down as it enters from the main stream. The sediment deposits will separate the cut off meander from the river channel and turn it into an oxbow lake. As the years go by, the oxbow lake will eventually be completely filled in with sediment because it is a low spot on the floodplain where any water that enters, such as during flooding, will come to a standstill and deposit its sediment load.

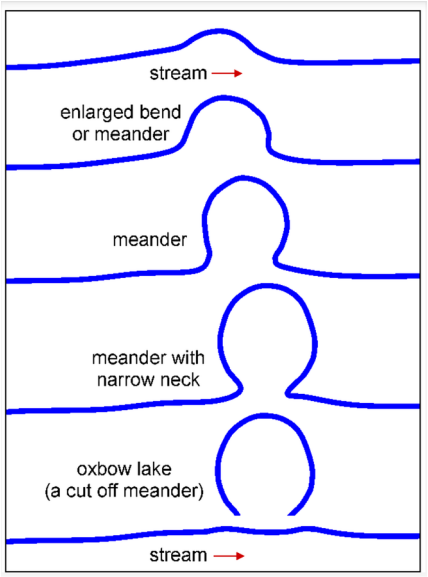


Figure 8.

Entrenched Meanders

Typical meandering stream channels flow through broad flood plains full of alluvial sediment. However, in some situations meanders may cut directly into bedrock. A meander that has cut into bedrock is known as an incised or entrenched meander. In contrast to meanders in alluvium that erode and migrate rapidly or get cut off at the neck abruptly, entrenched meanders are relatively fixed. This is because entrenched meanders are walled in by bedrock on both sides and have little floodplain to easily erode and redeposit.

Entrenched meanders form as a result of tectonic uplift of the stream drainage area. The uplift increases the gravity-driven energy of the stream causing it to incise rapidly down through the flood plain alluvium into the bedrock beneath. Entrenched meanders are striking landscape features because they are unusual and they provide strong evidence of tectonic activity in a region. Classic examples of entrenched meanders include the Goosenecks of the San Juan River, which are incised in the Colorado Plateau east of the Grand Canyon, and a stretch of the Yakima River with entrenched meanders, which are incised in a recently uplifted ridge of basalt in the Columbia Plateau of eastern Washington state.

Braided Streams

Rather than a single channel, some streams have multiple channels that weave in and out of each other forming what is known as a braided stream. Braided streams are associated with excessive amounts of sediment entering a stream system. Valleys draining alpine glaciers are common settings for braided streams. The glaciers deposit more sediment into the meltwater stream system than a stream of that discharge has capacity to transport in a single channel system. Braided stream systems are indicators that there is an additional source of sediment in the system besides the stream itself. Sources of excess sediment that lead to braided streams include glaciers, eruptions of pyroclastic material by volcanoes and landslides.

FLOODING AND FLOOD FREQUENCY

Streams flood. Flooding is a normal part of stream behavior. The rate at which streams erode, transport, and deposit sediments greatly increases during flooding. A flood occurs when the water depth in a stream exceeds the depth of the stream channel and spreads beyond the stream channel onto the surrounding land. When a stream completely fills its channel it is said to be at bankfull stage. When a stream surpasses bankfull stage it is said to be in flood. When the flood spreads widely enough to cause property damage, a stream is said to be at flood stage.

Different streams have different flood behaviors. Some rivers tend to have an annual flood associated with a rainy season or snowmelt season in the higher part of the drainage area. Some streams only flood sporadically, often with years between floods. In the United States all the larger streams have their flow measured at gaging stations that are installed and monitored by the US Geological Survey. Records of stream flow must be kept for at least 30 years to be statistically valid. The likelihood of a flood of a specified magnitude occurring on a stream in a given year can be calculated from the stream flow data. The magnitude of a flood that has a 1 out of 100 chance of happening in a given year—also known as the 100-year flood—is calculated for a stream from it record of stream flow. The 100-year flood magnitude, and maps that show what would be covered by a 100-year flood, are key elements in granting permits for land use and building construction in floodplains.

Low order streams may flood rapidly during or immediately after heavy rainfall. Such rapid floods are called flash floods. Flash floods are often unpredictable. If a river drains through a canyon from a high elevation area, people may be walking along a stream in the canyon in the sunshine and not realize that a thunderstorm is occurring at the stream's source. They may be surprised by a flash flood sweeping through the canyon. A slow building flood on a higher order stream can usually be predicted because major streams are monitored and it takes longer for water from heavy rainfall or rapidly melting snow to move through the higher order stream system. Floods on the highest order streams, such as the Mississippi River, may take several weeks to crest and subside.

Changes to the land in the drainage area of a stream, such as the addition of buildings and roads, can change how a stream floods. Buildings and pavement that cover the ground prevent infiltration and cause increased surface run off. Increased stream runoff means smaller amount of rain will cause the stream to reach flood stage than before the alterations to the land. The stream will flood more frequently. For the same amount and rate of rainfall that caused flooding prior to building, the stream will reach flood stage quicker and the flood will be deeper. The diagram below shows the flood response of a stream to a given amount of rainfall before and after the stream drainage area was urbanized by removal of forest and addition of buildings and roads. After urbanization, the stream reaches its peak flood level quicker and rises to a higher level than before urbanization. Unless countermeasures are engineered and installed, an urbanized area will flood more frequently and severely than the same area when it was forested.

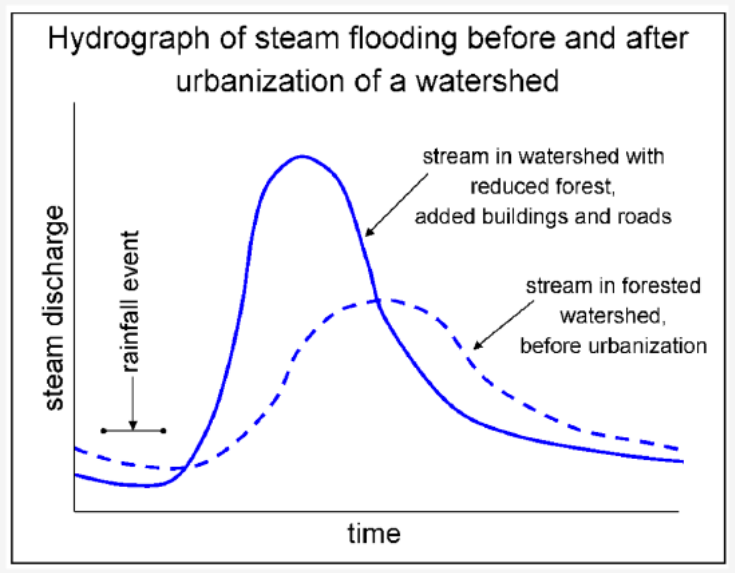


Figure 9.

ALLUVIAL FANS

At the location where a stream reaches its base level, it slows down and deposits nearly all of the sediment it is carrying. A stream that comes down a canyon and enters a flat valley or plain builds a fan shaped deposit of sediment known as an alluvial fan. Alluvial fans are built mostly during flash floods. Alluvial fans are easy to recognize in arid areas but they form in wetter climates as well.



Figure 10.

The diagram in figure 11 shows in cross-section how an alluvial fan develops over time as sediment is eroded from higher elevation and deposited on the adjacent lower elevation plain.

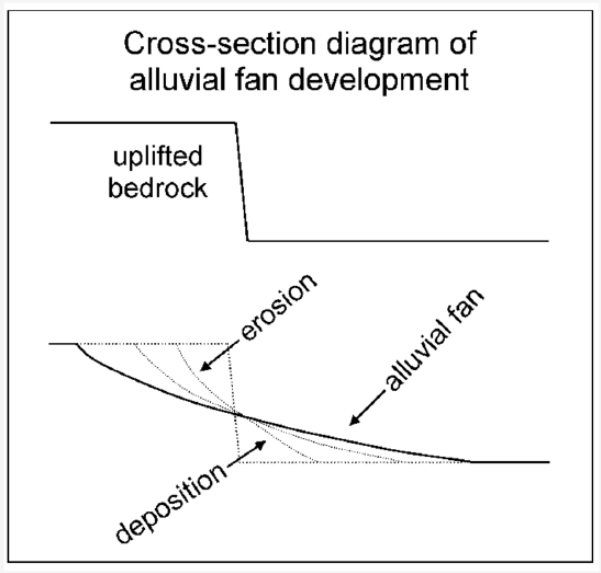


Figure 11.

DELTAS

Deltas are important landforms to civilization. They provide fertile soils, flat land, and water for agriculture, as well as river channels for transportation.

A delta is a landform composed of sediment deposited where a stream enters a larger, slower moving body of water, such as an ocean, a lake, or a larger river. The term delta comes from the triangular shape of the Greek letter delta (Δ). Ancient Greek geographers recognized the triangular shape of the land created by the Nile River where it emptied into the Mediterranean Sea and gave the name delta to that landform. The Nile River delta is one of several types of deltas that are defined by the predominate processes that shape them. The Nile delta is a wave-dominated delta. Waves of the Mediterranean Sea have pushed and distributed sediment along the coast, flattening the seaward side of delta.

The Mississippi River delta is an example of a stream dominated delta. Deposition of sediments has built the delta into the Gulf of Mexico faster than waves or tides could redistribute the sediment. As commonly occurs in a delta, the Mississippi River splits in the downstream direction into several branches that discharge across the delta into the Gulf of Mexico. These branches are known as distributaries. The mouth of each distributary has built part of the delta farther out into the Gulf of Mexico forming what is known as a bird's foot delta, another name for a stream dominated delta based on the way it looks on a map.

The Ganges River delta is a tide dominated delta formed from sediment eroded from the Himalaya Mountains, the largest mountain range in the world. The mouth of the Ganges River is at the northern end of the Bay of Bengal, a large embayment of the Indian Ocean. The shape of this large bay has a magnifying effect on the tides. The combination of strong tides and the consistently high discharge from a river caring a large sediment load create a branching pattern of distributaries, in effect a braided stream system across the delta.

Deltas are lowlands that lie barely above sea level and are at high risk of being submerged under water. There are several ways in which deltas can be inundated by rising water. Floods coming down the river can cover a delta. Marine deltas can be subject to storm surges when extreme winds raise sea level along the coast and push ocean water inland. In the last several decades a new risk of submergence has arisen for marine deltas. Many marine deltas are undergoing gradual submergence as global sea level rises.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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11.7: Groundwater

DESCRIBE HOW GROUNDWATER IS AFFECTED BY POROSITY AND PERMEABILITY OF GEOLOGIC MATERIALS AND BY HYDRAULIC GRADIENT

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Groundwater
- Reading: Back to Basics on Groundwater

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11.8: Groundwater

INTRODUCTION

Although this may seem surprising, water beneath the ground is commonplace. Usually groundwater travels slowly and silently beneath the surface, but in some locations it bubbles to the surface at springs. The products of erosion and deposition by groundwater were described in the Erosion and Deposition chapter.

GROUNDWATER

Groundwater is the largest reservoir of liquid fresh water on Earth and is found in **aquifers**, porous rock and sediment with water in between. Water is attracted to the soil particles and **capillary action**, which describes how water moves through a porous media, moves water from wet soil to dry areas.

Aquifers are found at different depths. Some are just below the surface and some are found much deeper below the land surface. A region may have more than one aquifer beneath it and even most deserts are above aquifers. The source region for an aquifer beneath a desert is likely to be far from where the aquifer is located; for example, it may be in a mountain area.

The amount of water that is available to enter groundwater in a region is influenced by the local climate, the slope of the land, the type of rock found at the surface, the vegetation cover, land use in the area, and water retention, which is the amount of water that remains in the ground. More water goes into the ground where there is a lot of rain, flat land, porous rock, exposed soil, and where water is not already filling the soil and rock.

The residence time of water in a groundwater aquifer can be from minutes to thousands of years. Groundwater is often called “fossil water” because it has remained in the ground for so long, often since the end of the ice ages.

AQUIFERS

Features of an Aquifer

To be a good aquifer, the rock in the aquifer must have good:

- porosity: small spaces between grains
- permeability: connections between pores

This animation shows porosity and permeability. The water droplets are found in the pores between the sediment grains, which is porosity. When the water can travel between ores, that’s permeability.

To reach an aquifer, surface water infiltrates downward into the ground through tiny spaces or pores in the rock. The water travels down through the permeable rock until it reaches a layer that does not have pores; this rock is **impermeable** (figure 1). This impermeable rock layer forms the base of the aquifer. The upper surface where the groundwater reaches is the **water table**.

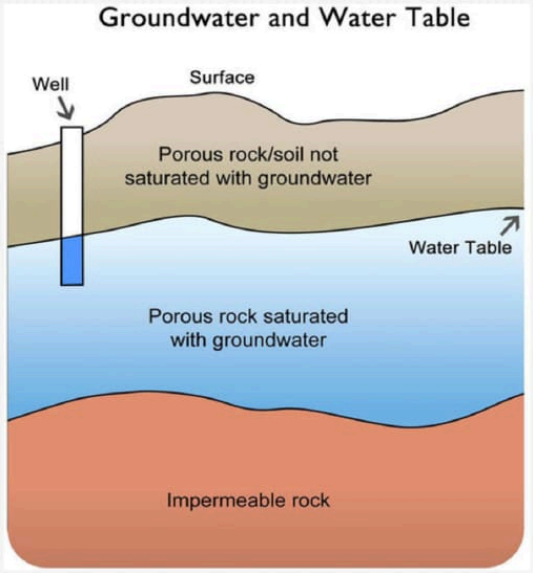


Figure 1. Groundwater is found beneath the solid surface. Notice that the water table roughly mirrors the slope of the land's surface. A well penetrates the water table.

The Water Table

For a groundwater aquifer to contain the same amount of water, the amount of recharge must equal the amount of discharge. What are the likely sources of recharge? What are the likely sources of discharge?

In wet regions, streams are fed by groundwater; the surface of the stream is the top of the water table (figure 2). In dry regions, water seeps down from the stream into the aquifer. These streams are often dry much of the year. Water leaves a groundwater reservoir in streams or springs. People take water from aquifers, too.

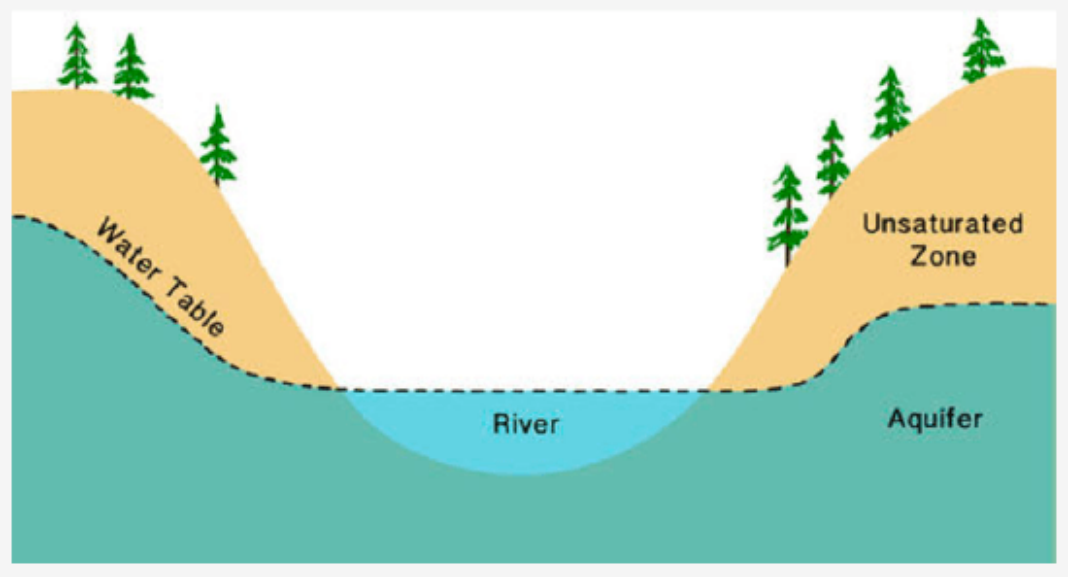


Figure 2. The top of the stream is the top of the water table. The stream feeds the aquifer.

What happens to the water table when there is a lot of rainfall? What happens when there is a drought? Although groundwater levels do not rise and fall as rapidly as at the surface, over time the water table will rise during wet periods and fall during droughts.

One of the most interesting, but extremely atypical types of aquifers is found in Florida. Although aquifers are very rarely underground rivers, in Florida water has dissolved the limestone so that streams travel underground and above ground (figure 3).

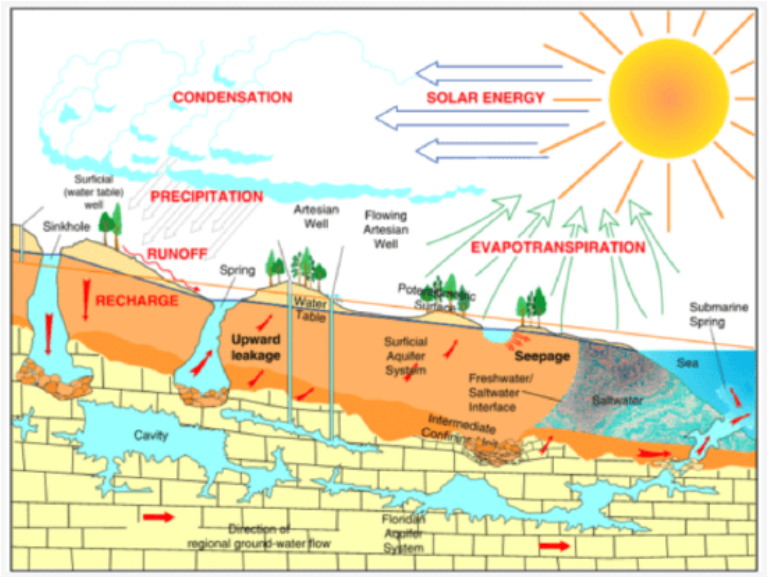


Figure 3. In Florida, groundwater is sometimes not underground.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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11.9: Back to Basics on Groundwater

When many people hear the word groundwater they imagine a raging underground torrent of water flowing along a pathway called an aquifer. Well, sorry to disappoint you, but you could not be more wrong about how groundwater exists and flows. In this post we will discuss the very basics of groundwater science (hydrogeology) and flow.



Figure 1. A spring coming out of the shale near Red Creek. Yes, that water is black! (Photo: Matt Herod)

WHAT IS GROUNDWATER?

As the name implies groundwater is simply water that exists underground. It is the opposite of surface water, which exists on the surface of the Earth such as lakes, rivers and oceans. Groundwater is an extremely important resource for industry, drinking water and other applications, however, it is generally quite poorly understood. The branch of geology that researches groundwater is called hydrogeology and is still a relatively new sector of the geological sciences.

As I have already mentioned groundwater exists underground. However, there are still lots of misconceptions about how people envision groundwater. Many see large underground lakes and rivers, and while those do exist, they represent an infinitesimally small percentage of all groundwater. Generally speaking groundwater exists in the pore spaces between grains of soil and rocks. Imagine a water filled sponge. All of the holes in that sponge are water-filled. By squeezing that sponge we force the water out, similarly, by pumping an aquifer we force the water out of pore spaces.

There are lots of terms in hydrogeology, most of which are very simple, but essential. Here are a few of the big ones and their meanings.

Porosity

Porosity is an intrinsic property of every material. It refers to the amount of empty space within a given material. In a soil or rock the porosity (empty space) exists between the grains of minerals. In a material like gravel the grains are large and there is lots of empty space between them since they don't fit together very well. However, in a material like a gravel, sand and clay mixture the porosity is much less as the smaller grains fill the spaces. The amount of water a material can hold is directly related to the porosity since water will try and fill the empty spaces in a material. We measure porosity by the percentage of empty space that exists within a particular porous media.

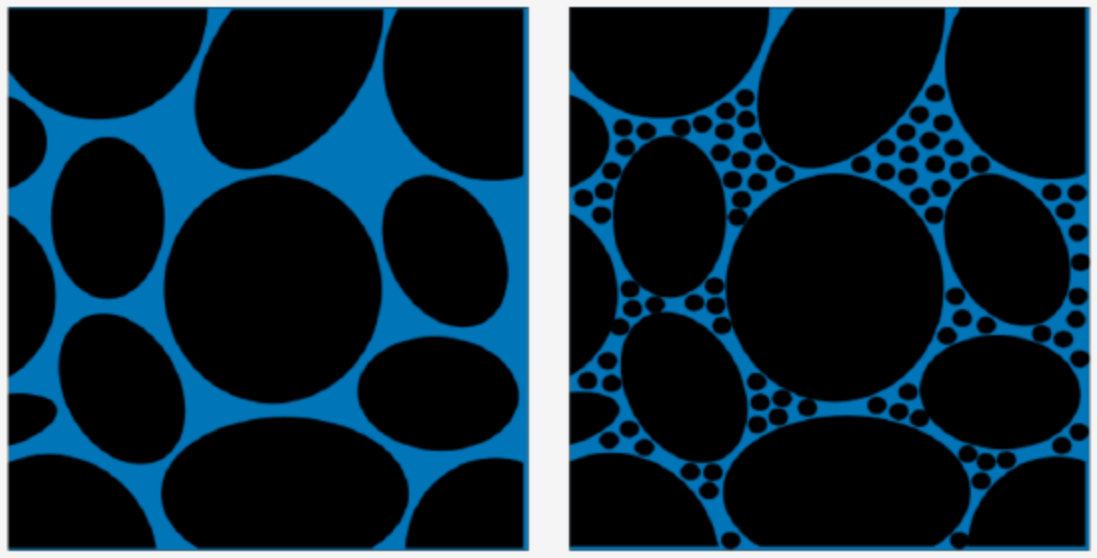


Figure 2. Porosity in two different media. The image on the left is analagous to gravel whereas on the right smaller particles are filling some of the pores and displacing water. Therefore, the water content of the material on the right is less. (Source: Wikipedia)

Permeability

Permeability is another intrinsic property of all materials and is closely related to porosity. Permeability refers to how connected pore spaces are to one another. If the material has high permeability than pore spaces are connected to one another allowing water to flow from one to another, however, if there is low permeability then the pore spaces are isolated and water is trapped within them. For example, in a gravel all of the pores well connected one another allowing water to flow through it, however, in a clay most of the pore spaces are blocked, meaning water cannot flow through it easily.

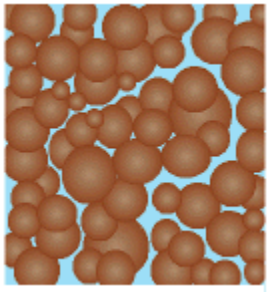


Figure 3. Video showing how connected pores have high permeability and can transport water easily. Note that some pores are isolated and cannot transport water trapped within them.

Aquifer

An aquifer is a term for a type of soil or rock that can hold and transfer water that is completely saturated with water. That means that all it is simply a layer of soil or rock that has a reasonably high porosity and permeability that allows it to contain water and transfer it from pore to pore relatively quickly and all of the pore spaces are filled with water. Good examples of aquifers are glacial till or sandy soils which have both high porosity and high permeability. Aquifers allows us to recover groundwater by pumping quickly and easily. However, overpumping can easily reduce the amount of water in an aquifer and cause it to dry up. Aquifers are replenished when surface water infiltrates through the ground and refills the pore spaces in the aquifer. This process is called recharge. It is especially important to ensure that recharge is clean and uncontaminated or the entire aquifer could become polluted. There are two main types of aquifer. An unconfined aquifer is one that does not have an aquitard above it but usually does below it. The other type is a confined aquifer that has an aquitard above and below it.

Aquitard

An aquitard is basically the opposite of an aquifer with one key exception. Aquitards have very low permeability and do not transfer water well at all. In fact, in the ground they often act as a barrier to water flow and separate two aquifers. The one key exception is that aquitards can have high porosity and hold lots of water however, due to the their low permeability they are unable to transmit it from pore to pore and therefore water cannot flow within an aquitard very well. A good example of an aquitard is a layer of clay. Clay often has high porosity but almost no permeability meaning it is essentially a barrier which water cannot flow through and the water within it is trapped. However, there is still limited water flow within aquitards due to other processes that I won't get into now.

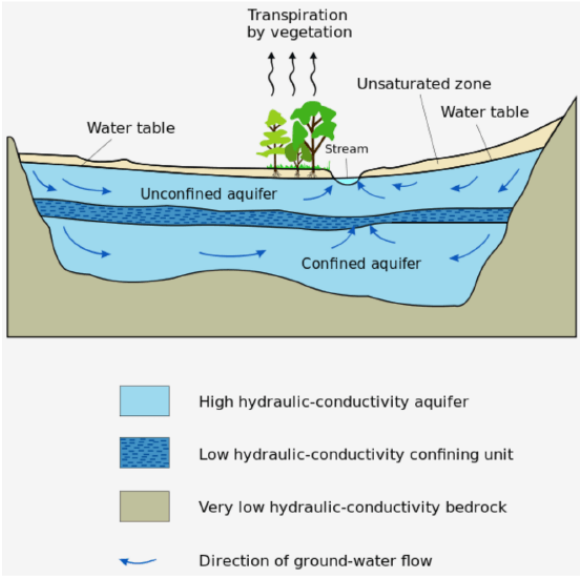


Figure 4.

Water Table

The water table is a term that hydrogeologists use to describe an imaginary surface that usually exists underground. Below the water table all pore spaces are completely filled with water and above it they are filled with air. The water table is the boundary between these two zones called the saturated and unsaturated (vadose) zone. In order to imagine the water table it helps to imagine a layer that exists underground rather than a line as the water table is a surface that extends in every direction. The top of the water table is determined by water pressure. When water pressure in the pore spaces is the same as air pressure we are at the water table. The water table is subject to rise and fall depending on pumping of water out of the aquifer or other changes. Finally, if the water table and the surface of the Earth intersect we have a spring.

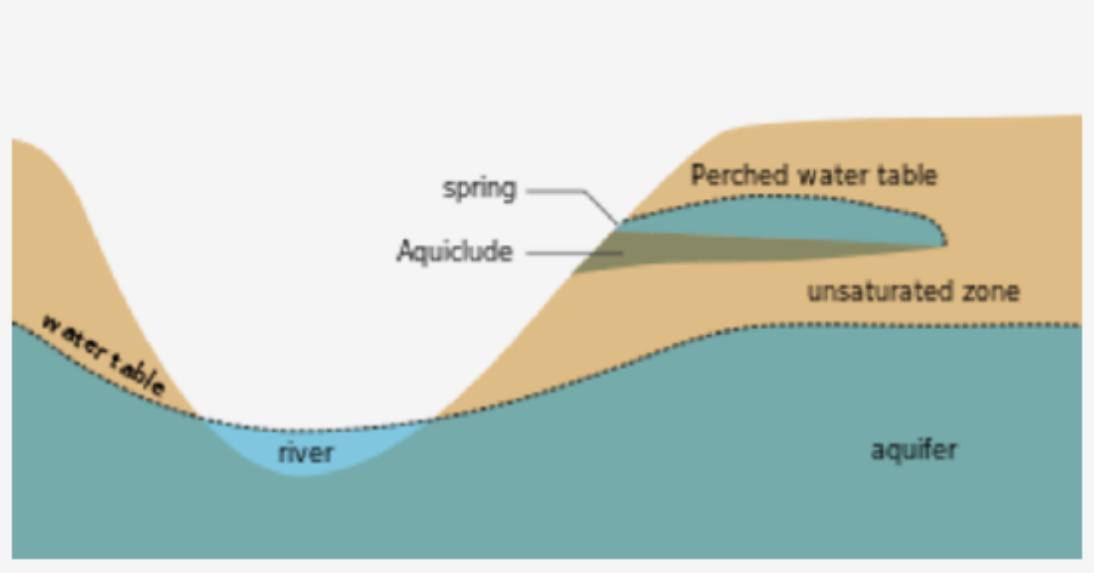


Figure 5. Cross section of what the water table looks like as a line. Remember it is actually a surface that extends in every direction. Note that the water in the well only rises to the surface of the water table because air pressure and water pressure are equal at the water table. (Source: Wikipedia)

GROUNDWATER FLOW

The study of hydrogeology is a very mathy one. There are lots of complicated equations, Greek letters, and funny squiggles. However, you don't need an advanced degree in math to understand the basics, but it helps to know a little bit. Basically all ground water flow can be described by a single simple equation. Sure, there have been lots of modifications made to fit specific conditions and circumstances, but it all comes back to the same basic principles outlined in a single equation. That equation is called Darcy's Law (cue dramatic music).



Figure 6. Henry Darcy: the father of hydrogeology

Darcy's law states that the velocity water flows is dependant on the material which it flows through and the hydraulic gradient, which is the difference in water level between two points of measurement divided by the distance between them. In mathematical terms it looks like this: $Q = -K(\frac{h_1 - h_2}{l})$

- **Q** is the discharge or the amount of water that flows out of a given material over a set amount of time.

- ***K*** is called the hydraulic conductivity and is a property of every material that tells us the speed any liquid moves through a given material. It is directly related to the porosity and permeability of the the material and the density of the liquid in question. For water we don't need to worry about the density though, just the porosity and permeability.
- $\left(\frac{h_1-h_2}{l}\right)$ is usually represented by the letter *i* and is called the hydraulic gradient. It is the difference in water level between the two points of measurement divided by the distance between them.

Here is a graphical representation of the properties that make up Darcy's law:

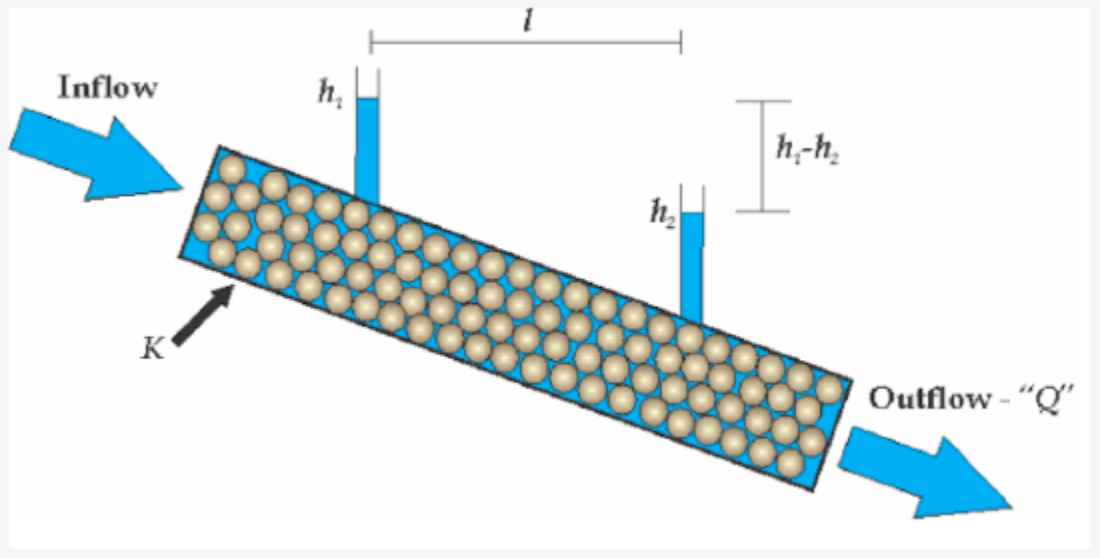


Figure 7. Graphical representation of Darcy's Law in a hypothetical porous medium with two points of measurement (h_1 and h_2) and a hydraulic conductivity of K. (Matt Herod – 2011)

So now we understand some of the basic principles governing groundwater flow, but we haven't discussed why it would flow from one place to another. We all take it for granted that groundwater is not stationary and moves, but why is that? The answer is shockingly simple, and lies in the fact that everything in nature is in a constant struggle to find balance.

Water flows from areas of high energy to low energy in an attempt to distribute that energy evenly throughout the water table. In this case energy is not a synonym for electricity, but energy in all forms, such as pressure or concentration differences. In the case of the water table the driving force is usually differences in pressure and elevation along the surface of the water table which lead to water flow. In hydrogeological terms these energy differences are referred to as hydraulic head, which can be measured at any point in the water table. It is helpful to imagine the weather when we think of groundwater flow. We all know that wind moves from areas of high air pressure to low air pressure bringing weather changes and temperature fronts in with it. Groundwater behaves the same and moves from places with high hydraulic head to low hydraulic head the same as the wind.

Obviously there is much more to discuss in the field of hydrogeology. The big topics being this like contamination or freshwater resources. However, in order to discuss those topics properly it is crucial to have a solid grasp on groundwater terms and basics. Please feel free to to comment if you have any suggestions for future posts on groundwater. Thanks for reading.

REFLECTION QUESTIONS

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11.10: Aquifers

COMPARE AND CONTRAST TYPES OF AQUIFERS AND POTENTIAL WELL USE WITHIN VARIOUS TYPES OF AQUIFERS

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Wells
- Reading: Aquifers

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11.11: Wells

There's a good chance that the average Joe who had to dig a well in ancient Egypt probably did the work with his hands, a shovel, and a bucket. He would have kept digging until he reached the water table and water filled the bottom of the hole. Some wells are still dug by hand today, but more modern methods are available. It's still a dirty job, though!

Wells are extremely important to all societies. In many places wells provide a reliable and ample supply of water for home uses, irrigation, and industries. Where surface water is scarce, such as in deserts,people couldn't survive and thrive without groundwater.

TYPES OF WELLS

Digging a well by hand is becoming outdated today (would YOU want to do it?). Modern wells are more often drilled by a truck-mounted drill rig. Still, there are many ways to put in a well—here are some of the common methods.

Dug Wells

Hacking at the ground with a pick and shovel is one way to dig a well. If the ground is soft and the water table is shallow,then dug wells can work. Historically, dug wells were excavated by hand shovel to below the water table until incoming water exceeded the digger's bailing rate . The well was lined with stones, brick, tile, or other material to prevent collapse, and was covered with a cap of wood, stone, or concrete. They cannot be dug much deeper than the water table — just as you cannot dig a hole very deep when you are at the beach... it keeps filling up with water!

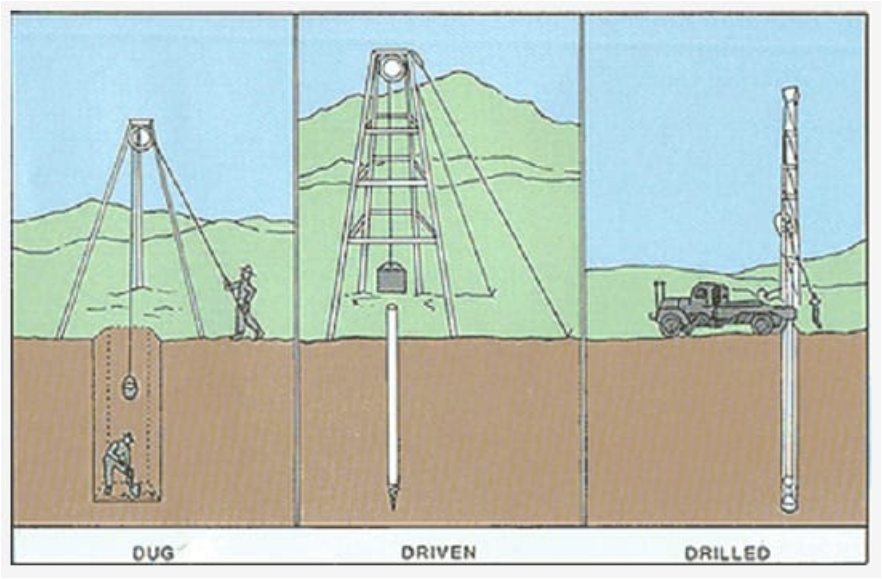


Figure 1. Well Types

Driven Wells

Driven wells are still common today. They are built by driving a small-diameter pipe into soft earth, such as sand or gravel. A screen is usually attached to the bottom of the pipe to filter out sand and other particles. Problems? They can only tap shallow water, and because the source of the water is so close to the surface, contamination from surface pollutants can occur.

Drilled Wells

Most modern wells are drilled, which requires a fairly complicated and expensive drill rig. Drill rigs are often mounted on big

trucks. They use rotary drill bits that chew away at the rock, percussion bits that smash the rock, or, if the ground is soft,large auger bits. Drilled wells can be drilled more than 1,000 feet deep. Often a pump is placed at the bottom to push water up to the surface.

WATER LEVELS IN WELLS

Ground-water users would find life easier if the water level in the aquifer that supplied their well always stayed the same. Seasonal variations in rainfall and the occasional drought affect the “height” of the underground water level. If a well is pumped at a faster rate than the aquifer around it is recharged by precipitation or other underground flow, then water levels around the well can be lowered. The water level in a well can also be lowered if other wells near it are withdrawing too much water. When water levels drop below the levels of the pump intakes, then wells will begin to pump air—they will “go dry.”

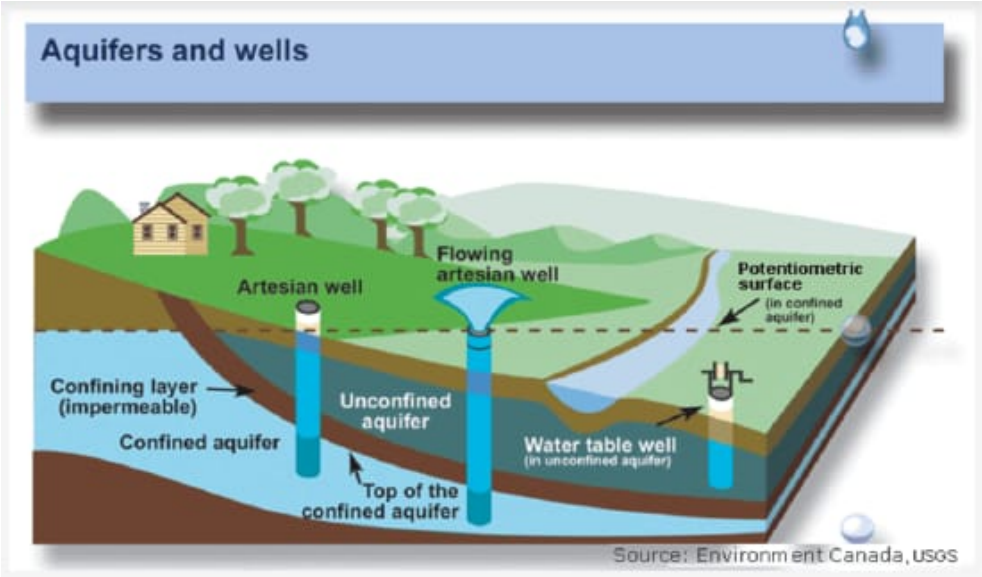


Figure 2. Aquifers and Wells

REFLECTION QUESTIONS

- What skill does this content help you develop?
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11.12: Aquifers

I hope you appreciate my spending an hour in the blazing sun to dig this hole at the beach. It is a great way to illustrate the concept of how, below a certain depth, the ground, if it is permeable enough to hold water, is saturated with water. The upper surface of this zone of saturation is called the water table. The saturated zone beneath the water table is called an aquifer, and aquifers are huge storehouses of water. What you are looking at in this picture is a “well” that exposes the water table, with an aquifer beneath it. Of course, I am cheating here, as at the beach, the level of the water table is always at the same level as the ocean, which is just below the surface of the beach.



Groundwater is one of our most valuable resource—even though you probably never see it or even realize it is there. As you may have read, most of the void spaces in the rocks below the water table are filled with water. But rocks have different porosity and permeability characteristics, which means that water does not move around the same way in all rocks below ground.

When a water-bearing rock readily transmits water to wells and springs, it is called an aquifer. Wells can be drilled into the aquifers and water can be pumped out. Precipitation eventually adds water (recharge) into the porous rock of the aquifer. The rate of recharge is not the same for all aquifers, though, and that must be considered when pumping water from a well. Pumping too much water too fast draws down the water in the aquifer and eventually causes a well to yield less and less water and even run dry. In fact, pumping your well too fast can even cause your neighbor’s well to run dry if you both are pumping from the same aquifer.

In the diagram below, you can see how the ground below the water table (the blue area) is saturated with water. The “unsaturated zone” above the water table (the greenish area) still contains water (after all, plants’ roots live in this area), but it is not totally saturated with water. You can see this in the two drawings at the bottom of the diagram, which show a close-up of how water is stored in between underground rock particles.

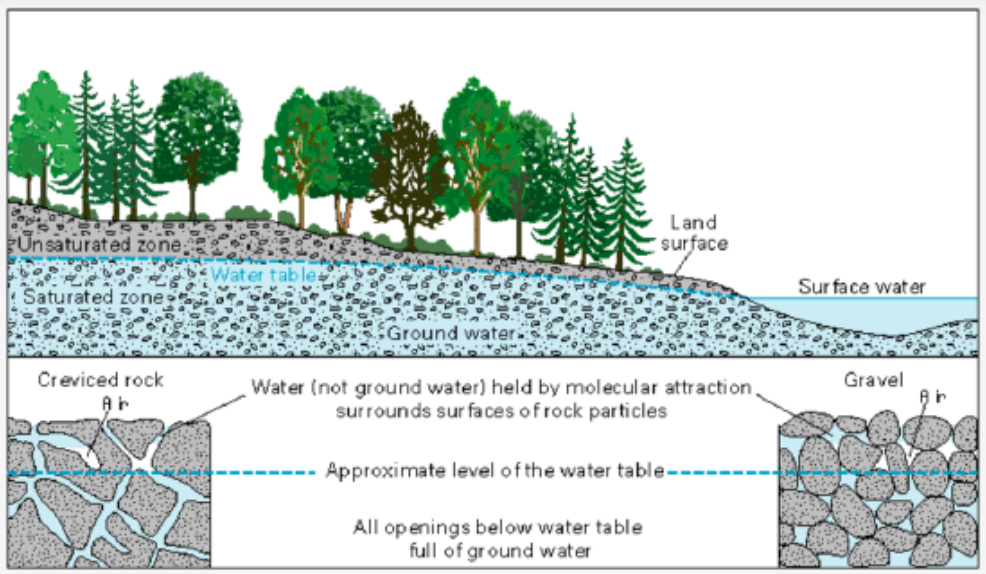


Figure 2.

Sometimes the porous rock layers become tilted in the earth. There might be a confining layer of less porous rock both above and below the porous layer. This is an example of a confined aquifer. In this case, the rocks surrounding the aquifer confines the pressure in the porous rock and its water. If a well is drilled into this “pressurized” aquifer, the internal pressure might (depending on the ability of the rock to transport water) be enough to push the water up the well and up to the surface without the aid of a pump, sometimes completely out of the well. This type of well is called artesian. The pressure of water from an artesian well can be quite dramatic.

A relationship does not necessarily exist between the water-bearing capacity of rocks and the depth at which they are found. A very dense granite that will yield little or no water to a well may be exposed at the land surface. Conversely, a porous sandstone, such as the Dakota Sandstone mentioned previously, may lie hundreds or thousands of feet below the land surface and may yield hundreds of gallons per minute of water. Rocks that yield freshwater have been found at depths of more than 6,000 feet, and salty water has come from oil wells at depths of more than 30,000 feet. On the average, however, the porosity and permeability of rocks decrease as their depth below land surface increases; the pores and cracks in rocks at great depths are closed or greatly reduced in size because of the weight of overlying rocks.

WATER MOVEMENT IN AQUIFERS

Water movement in aquifers is highly dependent of the permeability of the aquifer material. Permeable material contains interconnected cracks or spaces that are both numerous enough and large enough to allow water to move freely. In some permeable materials groundwater may move several metres in a day; in other places, it moves only a few centimeters in a century. Groundwater moves very slowly through relatively impermeable materials such as clay and shale.

After entering an aquifer, water moves slowly toward lower lying places and eventually is discharged from the aquifer from springs, seeps into streams, or is withdrawn from the ground by wells. Groundwater in aquifers between layers of poorly permeable rock, such as clay or shale, may be confined under pressure. If such a confined aquifer is tapped by a well, water will rise above the top of the aquifer and may even flow from the well onto the land surface. Water confined in this way is said to be under artesian pressure, and the aquifer is called an artesian aquifer.

VISUALIZING ARTESIAN PRESSURE

Here’s a little experiment to show you how artesian pressure works. Fill a plastic sandwich baggie with water, put a straw in through the opening, tape the opening around the straw closed, do *not* point the straw towards your teacher or parents, and then squeeze the baggie. Artesian water is pushed out through the straw.

REFLECTION QUESTIONS

- What skill does this content help you develop?
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11.13: Karst Topography, Geysers, and Springs

DEFINE AND DESCRIBE KARST TOPOGRAPHY, GEYSERS, AND SPRINGS

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Karst Topography
- Reading: Geysers, Fumaroles, and Hot Springs
- Reading: Springs

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11.14: Karst Topography

INTRODUCTION

Throughout the world **karst** landscapes vary from rolling hills dotted with sinkholes, as found in portions of the central United States, to jagged hills and pinnacle karst found in the tropics. The development of all karst landforms requires the presence of rock which is capable of being dissolved by surface water or **ground water**.

The term karst describes a distinctive topography that indicates **dissolution** (also called chemical solution) of underlying soluble rocks by surface water or ground water. Although commonly associated with **carbonate rocks** (limestone and dolomite) other highly soluble rocks such as evaporates (gypsum and rock salt) can be sculpted into karst terrain.

Understanding caves and karst is important because ten percent of the Earth's surface is occupied by karst landscape and as much as a quarter of the world's population depends upon water supplied from karst areas. Though most abundant in humid regions where carbonate rock is present, karst terrain occurs in temperate, tropical, alpine and polar environments. Karst features range in scale from microscopic (chemical precipitates) to entire drainage systems and ecosystems which cover hundreds of square miles, and broad karst plateaus.

Although karst processes sculpt beautiful landscapes, karst systems are very vulnerable to ground water pollution due to the relatively rapid rate of water flow and the lack of a natural filtration system. This puts local drinking water supplies at risk of being contaminated. In the mid 1980's, flooding of caves in the highly populated area of Bowling Green, Kentucky, caused industrial waste to leak into the vast system of underground fissures polluting the ground water in local wells. Due to urban expansion millions of dollars is spent annually in the United States to repair damage to roads, buildings and other structures which are built on unstable karst surfaces.

KARST TOPOGRAPHY

The degree of development of karst landforms varies greatly from region to region. Large drainage systems in karst areas are likely to have both **fluvial** (surface) and karst (underground) drainage components. As stated in the introduction, the term **karst** describes a distinctive topography that indicates **dissolution** of underlying rocks by surface water or ground water.

Water falls as rain or snow and soaks into the soil. The water becomes weakly acidic because it reacts chemically with carbon dioxide that occurs naturally in the atmosphere and the soil. This acid is named carbonic acid and is the same compound that makes carbonated beverages taste tangy. Rainwater seeps downward through the soil and through fractures in the rock responding to the force of gravity. The carbonic acid in the moving ground water dissolves the bedrock along the surfaces of joints, fractures and bedding planes, eventually forming cave passages and caverns.

Limestone is a sedimentary rock consisting primarily of calcium carbonate in the form of the mineral calcite. Rainwater dissolves the limestone by the following reaction: Calcite + Carbonic acid = Calcium ions dissolved in ground water + Bicarbonate ions dissolved in ground water.

Cracks and joints that interconnect in the soil and bedrock allow the water to reach a zone below the surface of the land where all the fractures and void spaces are completely filled (also known as saturated) with water. This water-rich zone is called the saturated zone and its upper surface is called the **water table.** The volume of void space (space filled with air or water) in soil or bedrock is termed **porosity.** The larger the proportion of voids in a given volume of soil or rock the greater the porosity. When these voids are interconnected, water or air (or other fluids) can migrate from void to void. Thus the soil or bedrock is said to be **permeable** because fluids (air and water) can easily move through them. Permeable bedrock makes a good aquifer, a rock layer that holds and conducts water. If the ground water that flows through the underlying permeable bedrock is acidic and the bedrock is soluble, a distinctive type of topography, karst topography, can be created.

The first part of our animation shows evolution of karst landforms created by downward movement of water accompanied by dissolution of rock and mass transport of sediments in stream channels. In tropical areas with thick massive limestones, a remarkable and distinctive landscape of jagged hills and narrow gorges completely dominates the landscape. Movement of solution along fractures and joints etches the bedrock and leaves limestone blocks as isolated spires or pinnacles. Pinnacles

range from small features a few inches tall to intermediate forms a few feet tall to large pinnacles hundreds of feet tall. Besides the etching of pinnacles and residual hills, sheets of flowing water move down sloping surfaces creating a variety of etched surface features. Our computer animation shows the dominant landforms, such as pinnacles, cones, and towers, commonly found in the tropical karst environment of northern Puerto Rico.

Our paper model represents another type of karst landscape, that of a rolling limestone plain such as is found in south-central Kentucky, northern Florida, and the Highland Rim of central Tennessee where **doline** karst is the dominate feature. Doline karst is the most widely distributed type of karst landscape. The landscape is dotted with **sinkholes** (dolines) which can vary widely in number and size. For the Sinkhole Plain in central Kentucky, there are approximately 5.4 sinkholes per square kilometer over a 153 square kilometer area. For north Florida there are almost 8 sinkholes per square kilometer over a 427 square kilometer area (White, 1988, table 4.1, page 100).

Karst topography dominated by sinkholes or dolines usually has several distinct surface features. Our paper model shows features normally associated with karst topography. Sinkholes (also known as dolines) are surface depressions formed by either: 1) the dissolution of bedrock forming a bowl-shaped depression, or 2) the collapse of shallow caves that were formed by dissolution of the bedrock. These sinkholes or shallow basins may fill with water forming lakes or ponds. Springs are locations where ground water emerges at the surface of the earth. **Disappearing streams** are streams which terminate abruptly by flowing or seeping into the ground. Disappearing streams are evidence of disrupted surface drainage and thus indicate the presence of an underground drainage system. **Cave entrances** are natural openings in the earth large enough to allow a person to enter. Caves may reflect a complex underground drainage system.

A Brief List of the Longest Caves in the United States

Name	Location	Distance Mapped*
Mammoth Cave—Flint Ridge System	Kentucky	500 km
Jewel Cave	South Dakota	118 km
Wind Cave	South Dakota	73 km
Friars Hole System	West Virginia	68 km
Fisher Ridge Cave System	Kentucky	64 km
* Numbers are rounded to nearest kilometer		

WHAT DO CAVES CONTAIN?

Moving water may transport earth materials into and through caves physically or chemically. Caves contain interesting features as a result of the physical and chemical processes that form them. Among these features are **breakdown** blocks of rock formed by collapse of cave ceilings. Also seen are sediments containing boulders, sand, silt, and clay deposited from water flowing in and through cave passages and conduits. **Speleogens** are irregular or distinctive shapes of carbonate rock etched from bedrock by dripping or running water. Speleogens can form where bedrock is not uniform in chemical composition. Consequently, the less soluble rock dissolves slower than adjacent more soluble rock through time. The less soluble rock tends to stand in relief and projects from walls and ceilings of caves.

Away from their entrances, caves usually provide a relatively constant temperature and humidity over a long period of time. Thus, caves provide an ideal environment for chemical deposition of minerals. As water laden with dissolved carbonate seeps into the air-filled cave passage, it may lose excess carbon dioxide to the cave atmosphere, or the water itself may evaporate, causing the dripwater to precipitate secondary carbonate or other minerals from solution, creating cave formations or **speleothems** including cone-shaped **stalactites**, **stalagmites**, **flowstone** or rimstone, or other interesting shapes. Caves in karst areas often have stalactites (icicle-like masses of chemical limestone) that hang from cave ceilings and stout stalagmites protruding from the cave floor. Stalactites and stalagmites can be a few inches to several feet long. Sometimes the drip water will flow down the walls and over the cave floor creating flowstone or rimstone deposits. Where drip water seeps from a joint and then drips over the edges of ledges, deposits of great complexity known as draperies are formed. The color of dripstones and flowstones comes from organic and/or iron oxide compounds brought in from the surface, giving the speleothems an orange brown color or from the presence of oxides and hydroxides of iron and manganese which give the speleothems a deep brown or black color.

WHAT LIVES UNDERGROUND?

Some scientists are interested in cave ecology and how cave animals interact with cave **microclimates.** Animals found in caves include everything from surface dwelling animals like raccoons that occasionally use the cave, to animals that have adapted exclusively to life in the cave **(troglobites)**. Troglobites cannot survive outside caves. These may include such diverse animals as eyeless fish and crayfish, cave beetles, flatworms, and other unusual types of insects. Many of these animals have lost body pigmentation and are white or transparent in color. Although the cave environment appears to be stable, change can and does occur. The temperature of the cave varies due to air movement near the entrances and the temperature of water entering the cave. In reality, some caves have their own weather systems which create wind due to temperature and pressure differences between the entrance and interior passageways.

Many animals, such as bats, cave crickets, and pack rats, regularly visit, raise their young, or hibernate in caves. These animals are called **trogloxenes** . Caves may support large numbers of different types of bats. Bats may be among the most beneficial animals to people and the ecosystem as insect-eaters and plant pollinators. The little brown bat can eat 600 mosquitoes in an hour thus performing the work of a “natural insecticide,” helping control crop pests and other insects. The Mammoth Cave-Flint Ridge System in Kentucky, which is the most extensive cave system in the world, has a biodiversity of 43 mammals, 15 reptiles, 19 amphibians and 3 fish. In 1981, the United Nations designated Mammoth Cave National Park as a World Heritage Site. Follow this link for an excellent summary of the Mammoth Cave area and other caves found in the U. S. National Park System.

In 1988 the United States passed the Federal Cave Resource Protection Act which preserves and protects all significant caves found on federal land for future generations of Americans.

WHAT’S IN IT FOR ME?

Knowing where karst features are located could help city and town planners, as well as individual landowners, to make decisions on where to build houses and other structures. This information could save cities thousand of dollars in repairs to buildings that are built on unstable karst terrain.

Karst springs supply drinking water to millions of people. Knowledge of karst terrain and the movement of water in underground drainage systems is important for maintaining good quality and safe drinking water. Pollution of ground water is a major problem in karst terrain.

Caves provide a venue for recreation. Although most of the caves located in National Parks are protected, there are over 200 commercial show caves nationwide which are open to the public. Recreational caving has become a popular hobby. The National Speleological Society has about 20,000 active affiliates nationwide.

Deposits preserved in caves can tell geologists about past climates. Fossils and artifacts found in caves help geologists and archaeologists unravel the prehistory of an area.

Caves support a unique community of bacteria, fungi and animals not seen on the surface of the Earth.

QUESTIONS

- Why is there often a wind at the mouth of a cave?
- Do large caves form in dry environments above the water table?
- Do dripstone features such as stalactites and stalagmites form in caves that are below or above the water table? Why or why not?
- Is the water table always level?
- Should a person explore a cave alone?
- Should a person build a house near a sinkhole?
- Should a person collect stalactites and stalagmites?
- Should a person collect cave-dwelling animals?

REFLECTION QUESTIONS

- What skill does this content help you develop?

- What are the key topics covered in this content?
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11.15: Geysers, Fumaroles, and Hot Springs

Geysers, fumaroles (also called *solfataras*), and hot springs are generally found in regions of young volcanic activity. Surface water percolates downward through the rocks below the Earth's surface to high-temperature regions surrounding a magma reservoir, either active or recently solidified but still hot. There the water is heated, becomes less dense, and rises back to the surface along fissures and cracks. Sometimes these features are called "dying volcanoes" because they seem to represent the last stage of volcanic activity as the magma, at depth, cools and hardens.



Figure 1. Old Faithful Geyser, Yellowstone National Park, Wyoming.

Erupting geysers provide spectacular displays of underground energy suddenly unleashed, but their mechanisms are not completely understood. Large amounts of hot water are presumed to fill underground cavities. The water, upon further heating, is violently ejected when a portion of it suddenly flashes into steam. This cycle can be repeated with remarkable regularity, as for example, at Old Faithful Geyser in Yellowstone National Park, which erupts on an average of about once every 65 minutes.

Fumaroles, which emit mixtures of steam and other gases, are fed by conduits that pass through the water table before reaching the surface of the ground. Hydrogen sulfide (H2S), one of the typical gases issuing from fumaroles, readily oxidizes to sulfuric acid and native sulfur. This accounts for the intense chemical activity and brightly colored rocks in many thermal areas.



Figure 2. Black Growler steam vents (fumaroles), Norris Basin, Yellowstone National Park, Wyoming.

Hot springs occur in many thermal areas where the surface of the Earth intersects the water table. The temperature and rate of discharge of hot springs depend on factors such as the rate at which water circulates through the system of underground channelways, the amount of heat supplied at depth, and the extent of dilution of the heated water by cool ground water near the surface.



Figure 3. Mammoth Hot Springs, Yellowstone National Park, Wyoming.

REFLECTION QUESTIONS

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11.16: Springs

Groundwater meets the surface in a stream, as shown above, or a **spring** (figure 1). A spring may be constant, or may only flow at certain times of year.

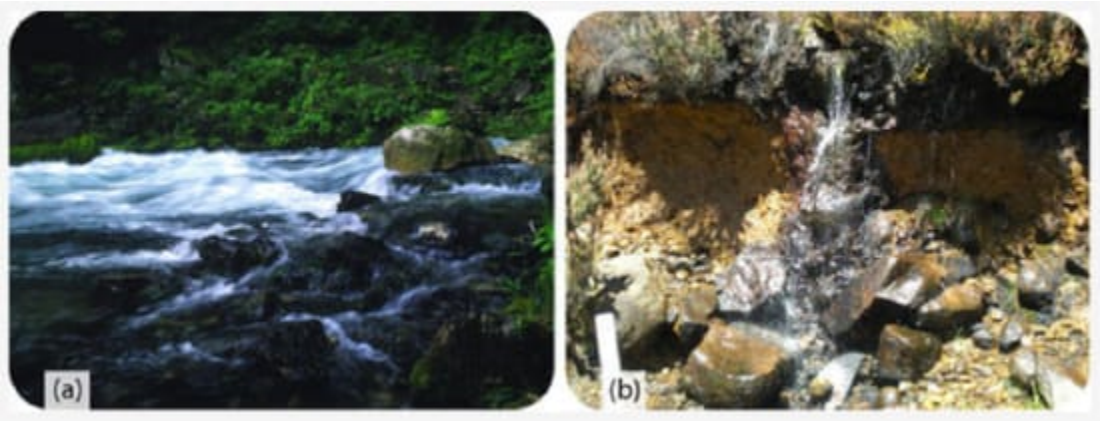


Figure 1. (a) Big Spring in Missouri lets out 12,000 liters of water per second. (b) Other springs are just tiny outlets like this one.

Towns in many locations depend on water from springs. Springs can be an extremely important source of water in locations where surface water is scarce (figure 2).

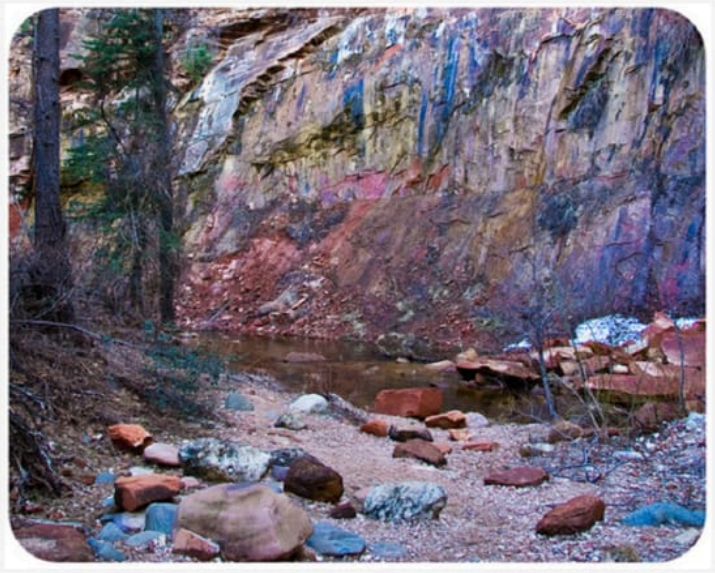


Figure 2. In the dry Arizona desert, Oak Creek and many other streams are spring fed.

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11.17: Putting It Together

SUMMARY

The hydrologic cycle is anything but a simple straight forward loop. As you saw in the lesson, it is a very complex and ever changing dynamic. In this section you learned:

1. What the hydrologic cycle is and the various steps within the cycle
2. How important the hydrologic cycle is to life on earth
3. About streams and stream loads
4. What an aquifer is and the various types of aquifers
5. Why permeability and porosity are an important component of aquifers
6. The issues associated with groundwater withdrawal
7. The various types of features groundwater can produce

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12: GEOLOGICAL IMPLICATIONS

This section takes into consideration everything we have discussed so far. We will take a glance back at the formation of rocks and minerals, concentrating on mineral and energy resources. These resources focus mainly on our fossil fuels—oil, natural gas and coal. However, we use a variety of other material as well. Most of the resources we use are done so indirectly. For example, each person will use over 450,000 pounds of coal in their lifetime. While you may not go to the store and purchase coal to use like you would gasoline for your car, you do it in other indirect ways—for instance, most electricity in the US is generated by coal burning.



- Topic hierarchy

12.1: Why It Matters

12.2: Geological Formation

12.3: Ore Genesis

12.4: Petroleum

12.5: Natural Gas

12.6: Coal

12.7: Extraction Methods

12.8: Mining and Mineral Use

12.9: Mining

12.10: Open-Pit Mining

12.11: Geologic Materials as Energy Sources

12.12: Earth's Energy

12.13: Use and Conservation of Resources

12.14: Putting It Together

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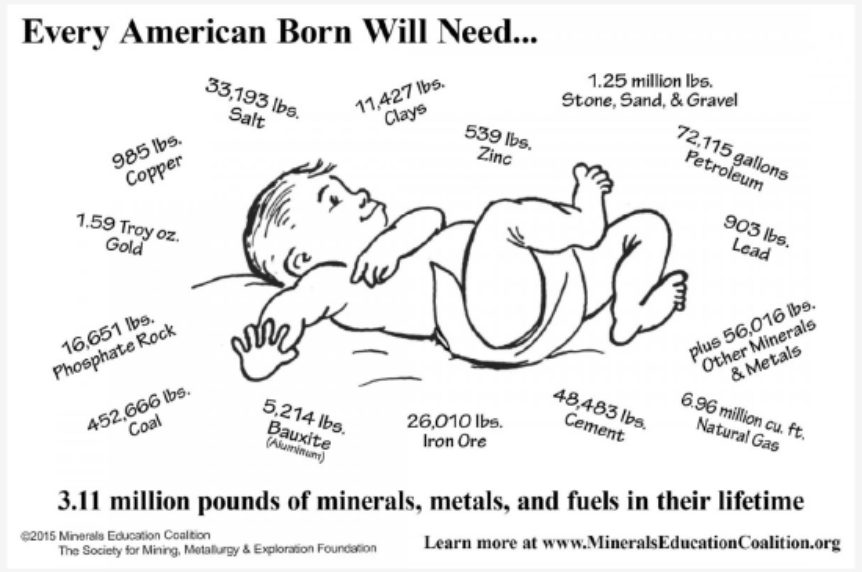
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12.1: Why It Matters

RESEARCH AND DISCUSS GEOLOGICAL, ECONOMIC, AND ENVIRONMENTAL IMPLICATIONS TO HUMAN AND NATURAL SYSTEMS RELATING TO MULTIPLE COMPETENCIES ACHIEVED THROUGHOUT THE COURSE

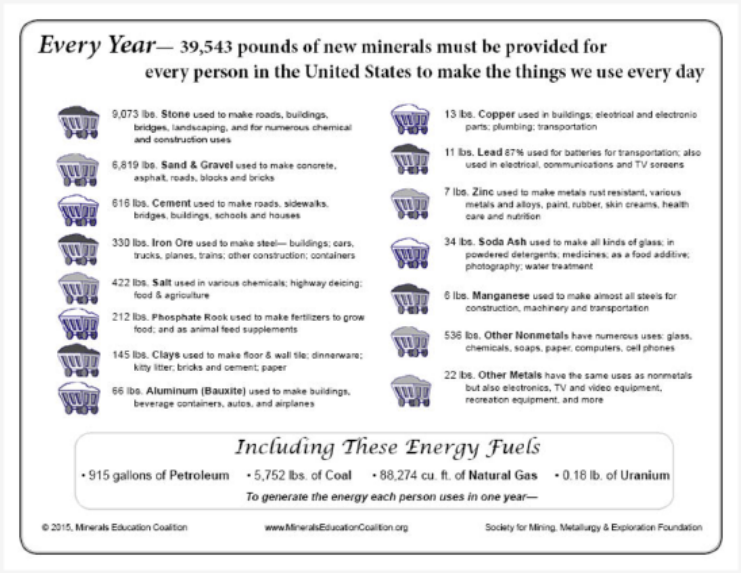
Introduction

This section takes into consideration everything we have discussed so far. We will take a glance back at the formation of rocks and minerals, concentrating on mineral and energy resources. These resources focus mainly on our fossil fuels—oil, natural gas and coal. However, we use a variety of other material as well. Most of the resources we use are done so indirectly. For example, each person will use over 450,000 pounds of coal in their lifetime. While you may not go to the store and purchase coal to use like you would gasoline for your car, you do it in other indirect ways—for instance, most electricity in the US is generated by coal burning. The following graphic illustrates the type and amount of resources each American will need and use throughout their lives.



Every American born in 2015 will need 3.11 million pounds of minerals, metals, and fuels in their lifetime. This includes 1.25 million pounds of stone, sand, and gravel; 72,115 gallons of petroleum, 903 pounds of lead, 539 pounds of zinc, 11,427 pounds of clays, 33,193 pounds of salt, 985 pounds of copper, 1.59 troy ounces of Gold, 16,651 pounds of phosphate rock, 425,666 pounds of coal, 5,214 pounds of bauxite (aluminum), 26,010 pounds of iron ore, 48,483 pounds of cement, 6.96 million cubic feet of natural gas, and 56,016 pounds of other minerals and metals.

This chart provides us with some staggering statistics on the amount of resources we use:



Were you surprised see some of the items listed? How about the quantities—3.11 million pounds of resources per person?!

One item not shown on the figure is tantalum. If you have a cell phone, tablet, computer, camera or gaming system you own some tantalum. This resource is used because it has many desirable properties including high heat capacity, ductile and the ability to conduct electricity (Tantalum, 2015). However, tantalum is considered to be a “conflict resource.” This means that it is mined in an area where a dispute or conflict is occurring. It could also mean that the resource is used to perpetuate the conflict. In the case of tantalum, it is mined in an area of the Congo where it is believed to have played a role in helping finance war in the area. This conflict is believed to have caused the death of 5,400,000 since 1998 (Tantalum, 2015)!

These resources are collected in a variety of ways from drilling to mining. Depending on the resource and its location, different mining methods may be used. And these resources are mined on every continent (except Antarctica).

Unfortunately not all of our resources will be around forever. Our nonrenewable resources are in jeopardy of depletion. Alternative or renewable resources will play a bigger role in meeting our energy needs in the future.

Learning Outcomes

- Learn common processes of geologic formation of rock and mineral resources
- Describe some of the extraction methods and how extraction impacts society and our environment
- Describe geologic materials as current or potential energy resources and categorize sources as renewable or nonrenewable

Ok, let’s get started!

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12.2: Geological Formation

LEARN COMMON PROCESSES OF GEOLOGIC FORMATION OF ROCK AND MINERAL RESOURCES

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Ore Genesis
- Reading: Petroleum
- Reading: Natural Gas
- Reading: Coal

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12.3: Ore Genesis

The various theories of **ore genesis** explain how the various types of mineral deposits form within the Earth's crust. Ore genesis theories are dependent on the mineral or commodity.

Ore genesis theories generally involve three components: source, transport or conduit, and trap. This also applies to the petroleum industry, which was first to use this methodology.

- Source is required because metal must come from somewhere, and be liberated by some process
- Transport is required first to move the metal bearing fluids or solid minerals into the right position, and refers to the act of physically moving the metal, as well as chemical or physical phenomenon which encourage movement
- Trapping is required to concentrate the metal via some physical, chemical or geological mechanism into a concentration which forms mineable ore

The biggest deposits are formed when the source is large, the transport mechanism is efficient, and the trap is active and ready at the right time.

ORE GENESIS PROCESSES

Endogenous

Magmatic Processes

- Fractional crystallization: separates ore and non-ore minerals according to their crystallization temperature. As early crystallizing minerals form, they incorporate certain elements, some of which are metals. These crystals may settle onto the bottom of the intrusion, concentrating ore minerals there. Chromite and magnetite are ore minerals that form in this way.
- Liquid immiscibility: sulfide ores containing copper, nickel or platinum may form from this process. As a magma changes, parts of it may separate from the main body of magma. Two liquids that will not mix are called immiscible; oil and water are an example. In magmas, sulfides may separate and sink below the silicate-rich part of the intrusion or be injected into the rock surrounding it. These deposits are found in mafic and ultramafic rocks.

Hydrothermal Processes

These processes are the physicochemical phenomena and reactions caused by movement of hydrothermal water within the crust, often as a consequence of magmatic intrusion or tectonic upheavals. The foundations of hydrothermal processes are the source-transport-trap mechanism.

Sources of hydrothermal solutions include seawater and meteoric water circulating through fractured rock, formational brines (water trapped within sediments at deposition) and metamorphic fluids created by dehydration of hydrous minerals during metamorphism.

Metal sources may include a plethora of rocks. However most metals of economic importance are carried as trace elements within rock-forming minerals, and so may be liberated by hydrothermal processes. This happens because of:

- incompatibility of the metal with its host mineral, for example zinc in calcite, which favours aqueous fluids in contact with the host mineral during diagenesis.
- solubility of the host mineral within nascent hydrothermal solutions in the source rocks, for example mineral salts (halite), carbonates (cerussite), phosphates (monazite and thorianite) and sulfates (barite)
- elevated temperatures causing decomposition reactions of minerals

Transport by hydrothermal solutions usually requires a salt or other soluble species which can form a metal-bearing complex. These metal-bearing complexes facilitate transport of metals within aqueous solutions, generally as hydroxides, but also by processes similar to chelation.

This process is especially well understood in gold metallogeny where various thiosulfate, chloride and other gold-carrying chemical complexes (notably tellurium-chloride/sulfate or antimony-chloride/sulfate). The majority of metal deposits formed by hydrothermal processes include sulfide minerals, indicating sulfur is an important metal-carrying complex.

Sulfide deposition: Sulfide deposition within the *trap* zone occurs when metal-carrying sulfate, sulfide or other complexes become chemically unstable due to one or more of the following processes;

- falling temperature, which renders the complex unstable or metal insoluble
- loss of pressure, which has the same effect
- reaction with chemically reactive wall rocks, usually of reduced oxidation state, such as iron bearing rocks, mafic or ultramafic rocks or carbonate rocks
- degassing of the hydrothermal fluid into a gas and water system, or boiling, which alters the metal carrying capacity of the solution and even destroys metal-carrying chemical complexes

Metal can also become precipitated when temperature and pressure or oxidation state favour different ionic complexes in the water, for instance the change from sulfide to sulfate, oxygen fugacity, exchange of metals between sulfide and chloride complexes, et cetera.

Metamorphic Processes

Lateral secretion: Ore deposits formed by lateral secretion are formed by metamorphic reactions during shearing, which liberate mineral constituents such as quartz, sulfides, gold, carbonates and oxides from deforming rocks and focus these constituents into zones of reduced pressure or dilation such as faults. This may occur without much hydrothermal fluid flow, and this is typical of podiform chromite deposits.

Metamorphic processes also control many physical processes which form the source of hydrothermal fluids, outlined above.

Surficial Processes (Exogenous)

Surficial processes are the physical and chemical phenomena which cause concentration of ore material within the regolith, generally by the action of the environment. This includes placerdeposits, laterite deposits and residual or eluvial deposits. The physical processes of ore deposit formation in the surficial realm include;

- erosion
- deposition by sedimentary processes, including winnowing, density separation (e.g.; gold placers)
- weathering via oxidation or chemical attack of a rock, either liberating rock fragments or creating chemically deposited clays, laterites or supergene enrichment
- Deposition in low-energy environments in beach environments

CLASSIFICATION OF ORE DEPOSITS

Ore deposits are usually classified by ore formation processes and geological setting. For example, SEDEX deposits, literally meaning “sedimentary exhalative” are a class of ore deposit formed on the sea floor (sedimentary) by exhalation of brines into seawater (exhalative), causing chemical precipitation of ore minerals when the brine cools, mixes with sea water and loses its metal carrying capacity.

Ore deposits rarely fit snugly into the boxes in which geologists wish to place them. Many may be formed by one or more of the basic genesis processes above, creating ambiguous classifications and much argument and conjecture. Often ore deposits are classified after examples of their type, for instance Broken Hill type lead-zinc-silver deposits or Carlin–type gold deposits.

Classification of hydrothermal ore deposits is also achieved by classifying according to the temperature of formation, which roughly also correlates with particular mineralising fluids, mineral associations and structural styles. This scheme, proposed by Waldemar Lindgren (1933) classified hydrothermal deposits as *hypothermal*, *mesothermal*, *epithermal* and *telethermal*.

GENESIS OF COMMON ORES

As they require the conjunction of specific environmental conditions to form, particular mineral deposit types tend to occupy specific geodynamic niches,[1] therefore, this page has been organised by metal commodity. It is also possible to organise theories the other way, namely according to geological criteria of formation. Often ores of the same metal can be formed by multiple processes, and this is described here under each metal or metal complex.

Iron

Iron ores are overwhelmingly derived from ancient sediments known as *banded iron formations* (BIFs). These sediments are composed of iron oxide minerals deposited on the sea floor. Particular environmental conditions are needed to transport enough iron in sea water to form these deposits, such as acidic and oxygen-poor atmospheres within the Proterozoic Era.

Often, more recent weathering is required to convert the usual magnetite minerals into more easily processed hematite. Some iron deposits within the Pilbara of West Australia are *placer deposits*, formed by accumulation of hematite gravels called *pisolites* which form channel-iron deposits. These are preferred because they are cheap to mine.

Lead Zinc Silver

Lead-zinc deposits are generally accompanied by silver, hosted within the lead sulfide mineral galena or within the zinc sulfide mineral sphalerite.

Lead and zinc deposits are formed by discharge of deep sedimentary brine onto the sea floor (termed *sedimentary exhalative* or SEDEX), or by replacement of limestone, in skarn deposits, some associated with submarine volcanoes (called volcanogenic massive sulfide ore deposits or VMS) or in the aureole of subvolcanic intrusions of granite. The vast majority of SEDEX lead and zinc deposits are Proterozoic in age, although there are significant Jurassic examples in Canada and Alaska.

The carbonate replacement type deposit is exemplified by the Mississippi valley type (MVT) ore deposits. MVT and similar styles occur by replacement and degradation of carbonate sequences byhydrocarbons, which are thought important for transporting lead.

Gold

Gold deposits are formed via a very wide variety of geological processes. Deposits are classified as primary, alluvial or placerdeposits, or residual or laterite deposits. Often a deposit will contain a mixture of all three types of ore.

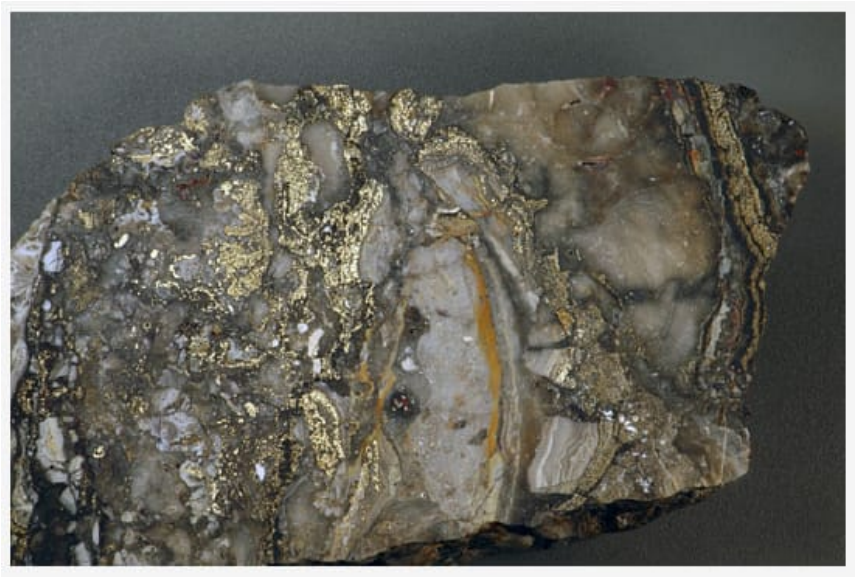


Figure 1. High-grade (bonanza) gold ore, brecciated quartz-adularia rhyolite. Native gold (Au) occurs in this rock as colloform bands, partially replaces breccia clasts, and is also disseminated in the matrix. Published research indicates that Sleeper Mine rocks represent an ancient epithermal gold deposit (hot springs gold deposit), formed by volcanism during Basin & Range extensional tectonics. Sleeper Mine, Humboldt County, Nevada.

Plate tectonics is the underlying mechanism for generating gold deposits. The majority of primary gold deposits fall into two main categories: lode gold deposits or intrusion-related deposits.

Lode gold deposits are generally high-grade, thin, vein and fault hosted. They are primarily made up of quartz veins also known as lodes or *reefs*, which contain either native gold or gold sulfides and tellurides. Lode gold deposits are usually hosted in basalt or in sediments known as turbidite, although when in faults, they may occupy intrusive igneous rocks such as granite.

Lode-gold deposits are intimately associated with orogeny and other plate collision events within geologic history. Most lode gold deposits *sourced* from metamorphic rocks because it is thought that the majority are formed by dehydration of basalt during metamorphism. The gold is transported up faults by hydrothermal waters and deposited when the water cools too much to retain gold in solution.

Intrusive related gold is generally hosted in granites, porphyry or rarely dikes. Intrusive related gold usually also contains copper, and is often associated with tin and tungsten, and rarely molybdenum, antimony and uranium. Intrusive-related gold deposits rely on gold existing in the fluids associated with the magma (White, 2001), and the inevitable discharge of thesehydrothermal fluids into the wall-rocks (Lowenstern, 2001). Skarn deposits are another manifestation of intrusive-related deposits.

Placer deposits are sourced from pre-existing gold deposits and are secondary deposits. Placer deposits are formed by alluvialprocesses within rivers, streams and on beaches. Placer gold deposits form via gravity, with the density of gold causing it to sink into trap sites within the river bed, or where water velocity drops, such as bends in rivers and behind boulders. Often placer deposits are found within sedimentary rocks and can be billions of years old, for instance the Witwatersrand deposits in South Africa. Sedimentary placer deposits are known as ‘leads’ or ‘deep leads’.

Placer deposits are often worked by fossicking, and panning for gold is a popular pastime.

Laterite gold deposits are formed from pre-existing gold deposits (including some placer deposits) during prolonged weathering of the bedrock. Gold is deposited within iron oxides in the weathered rock or regolith, and may be further enriched by reworking by erosion. Some laterite deposits are formed by wind erosion of the bedrock leaving a residuum of native gold metal at surface.

A bacterium, Cupriavidus metallidurans plays a vital role in the formation of gold nuggets, by precipitating metallic gold from a solution of gold (III) tetrachloride, a compound highly toxic to most other microorganisms. Similarly, Delftia acidovorans can form gold nuggets.

Platinum

Platinum and palladium are precious metals generally found in ultramafic rocks. The source of platinum and palladium deposits is ultramafic rocks which have enough sulfur to form a sulfide mineral while the magma is still liquid. This sulfide mineral (usually pentlandite, pyrite, chalcopyrite or pyrrhotite) gains platinum by mixing with the bulk of the magma because platinum is chalcophile and is concentrated in sulfides. Alternatively, platinum occurs in association with chromite either within the chromite mineral itself or within sulfides associated with it.

Sulfide phases only form in ultramafic magmas when the magma reaches sulfur saturation. This is generally thought to be nearly impossible by pure fractional crystallisation, so other processes are usually required in ore genesis models to explain sulfur saturation. These include contamination of the magma with crustal material, especially sulfur-rich wall-rocks or sediments; magma mixing; volatile gain or loss.

Often platinum is associated with nickel, copper, chromium, and cobalt deposits.

Nickel

Nickel deposits are generally found in two forms, either as sulfide or laterite.

Sulfide type nickel deposits are formed in essentially the same manner as platinum deposits. Nickel is a chalcophile element which prefers sulfides, so an ultramafic or mafic rock which has a sulfide phase in the magma may form nickel sulfides. The best nickel deposits are formed where sulfide accumulates in the base of lava tubes or volcanic flows—especially komatiite lavas.

Komatiitic nickel-copper sulfide deposits are considered to be formed by a mixture of sulfide segregation, immiscibility, and thermal erosion of sulfidic sediments. The sediments are considered to be necessary to promote sulfur saturation.

Some subvolcanic sills in the Thompson Belt of Canada host nickel sulfide deposits formed by deposition of sulfides near the feeder vent. Sulfide was accumulated near the vent due to the loss of magma velocity at the vent interface. The massive Voisey's Bay nickel deposit is considered to have formed via a similar process.

The process of forming *nickel laterite* deposits is essentially similar to the formation of gold laterite deposits, except that ultramafic or mafic rocks are required. Generally nickel laterites require very large olivine-bearing ultramafic intrusions. Minerals formed in laterite nickel deposits include gibbsite.

Copper

Copper is found in association with many other metals and deposit styles. Commonly, copper is either formed within sedimentary rocks, or associated with igneous rocks.

The world's major copper deposits are formed within the granitic porphyry copper style. Copper is enriched by processes during crystallisation of the granite and forms as chalcopyrite—a sulfide mineral, which is carried up with the granite.

Sometimes granites erupt to surface as volcanoes, and copper mineralisation forms during this phase when the granite and volcanic rocks cool via hydrothermal circulation.

Sedimentary copper forms within ocean basins in sedimentary rocks. Generally this forms by brine from deeply buried sediments discharging into the deep sea, and precipitating copper and oftenlead and zinc sulfides directly onto the sea floor. This is then buried by further sediment. This is a process similar to SEDEX zinc and lead, although some carbonate-hosted examples exist.

Often copper is associated with gold, lead, zinc and nickel deposits.

Uranium

Uranium deposits are usually *sourced* from radioactive granites, where certain minerals such as monazite are leached during hydrothermal activity or during circulation of groundwater. The uranium is brought into solution by acidic conditions and is deposited when this acidity is neutralised. Generally this occurs in certain carbon-bearing sediments, within an unconformity in sedimentary strata. The majority of the world's nuclear power is sourced from uranium in such deposits.

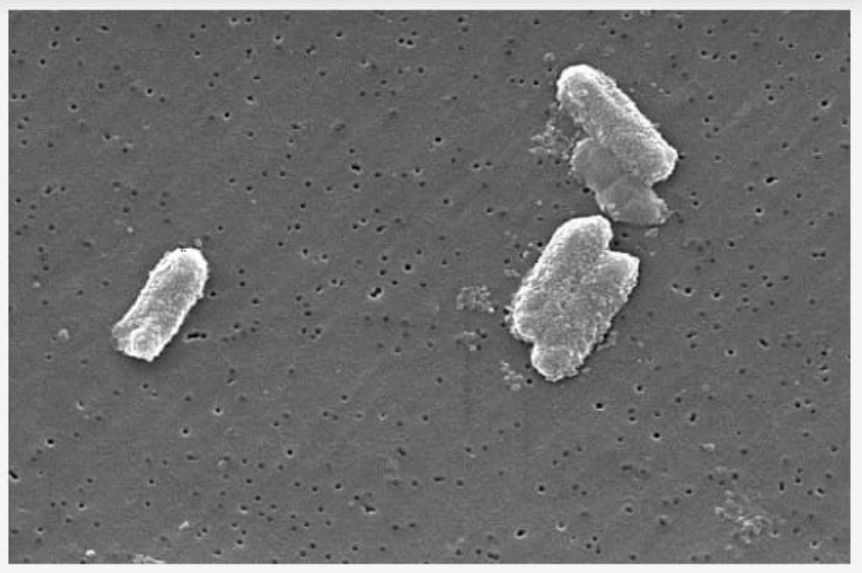


Figure 2. Citrobacter species can have concentrations of uranium in their bodies 300 times higher than in the surrounding environment.

Uranium is also found in nearly all coal at several parts per million, and in all granites. Radon is a common problem during mining of uranium as it is a radioactive gas.

Uranium is also found associated with certain igneous rocks, such as granite and porphyry. The Olympic Dam deposit in Australia is an example of this type of uranium deposit. It contains 70% of Australia's share of 40% of the known global low-cost recoverable uranium inventory.

Titanium and Zirconium

Mineral sands are the predominant type of titanium, zirconium and thorium deposit. They are formed by accumulation of such heavy minerals within beach systems, and are a type of *placer deposits*. The minerals which contain titanium are ilmenite, rutile and leucoxene, zirconium is contained within zircon, and thorium is generally contained within monazite. These minerals are sourced from primarily granite bedrock by erosion and transported to the sea by rivers where they accumulate within beach sands. Rarely, but importantly, gold, tin and platinum deposits can form in beach placer deposits.

Tin, Tungsten, and Molybdenum

These three metals generally form in a certain type of granite, via a similar mechanism to intrusive-related gold and copper. They are considered together because the process of forming these deposits is essentially the same. Skarn type mineralisation related to these granites is a very important type of tin, tungsten and molybdenum deposit. Skarn deposits form by reaction of mineralised fluids from the granite reacting with wall rocks such as limestone. Skarn mineralisation is also important in lead, zinc, copper, gold and occasionally uranium mineralisation.

Greisen granite is another related tin-molybdenum and topaz mineralisation style.

Rare Earth Elements, Niobium, Tantalum, Lithium

The overwhelming majority of rare earth elements, tantalum and lithium are found within pegmatite. Ore genesis theories for these ores are wide and varied, but most involve metamorphism and igneous activity. Lithium is present as spodumene or lepidolite within pegmatite.

Carbonatite intrusions are an important source of these elements. Ore minerals are essentially part of the unusual mineralogy of carbonatite.

Phosphate

Phosphate is used in fertilisers. Immense quantities of *phosphate rock* or phosphorite occur in sedimentary shelf deposits, ranging in age from the Proterozoic to currently forming environments. Phosphate deposits are thought to be sourced from the skeletons of dead sea creatures which accumulated on the seafloor. Similar to iron ore deposits and oil, particular conditions in the ocean and environment are thought to have contributed to these deposits within the geological past.

Phosphate deposits are also formed from alkaline igneous rocks such as nepheline syenites, carbonatites and associated rock types. The phosphate is, in this case, contained within magmaticapatite, monazite or other rare-earth phosphates.

Vanadium

Due to the presence of vanabins, concentration of vanadium found in the blood cells of *Ascidia gemmata* belonging to the suborder Phlebobranchia is 10,000,000 times higher than that in the surrounding seawater. A similar biological process might have played a role in the formation of vanadium ores. Vanadium is also present in fossil fuel deposits such as crude oil, coal, oil shale and oil sands. In crude oil, concentrations up to 1200 ppm have been reported.



Figure 3. Tunicates such as this bluebell tunicate contain vanadium as vanabin.

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12.4: Petroleum

Petroleum is a naturally occurring, yellow-to-black liquid found in geological formations beneath the Earth's surface, which is commonly refined into various types of fuels.



Figure 1. Pumpjack pumping an oil well near Lubbock, Texas

It consists of hydrocarbons of various molecular weights and other organic compounds. The name *petroleum* covers both naturally occurring unprocessed **crude oil** and petroleum products that are made up of refined crude oil. A fossil fuel, petroleum is formed when large quantities of dead organisms, usually zooplankton and algae, are buried underneath sedimentary rock and subjected to intense heat and pressure.

Petroleum is recovered mostly through oil drilling (natural petroleum springs are rare). This comes after the studies of structural geology (at the reservoir scale), sedimentary basin analysis, reservoir characterization (mainly in terms of the porosity and permeability of geologic reservoir structures). It is refined and separated, most easily by distillation, into a large number of consumer products, from gasoline (petrol) and kerosene to asphalt and chemical reagents used to make plastics and pharmaceuticals. Petroleum is used in manufacturing a wide variety of materials, and it is estimated that the world consumes about 90 million barrels each day.

Concern over the depletion of the earth's finite reserves of oil, and the effect this would have on a society dependent on it, is a concept known as peak oil. The use of fossil fuels, such as petroleum, has a negative impact on Earth's biosphere, damaging ecosystems through events such as oil spills and releasing a range of pollutants into the air including ground-level ozone and sulfur dioxide from sulfur impurities in fossil fuels.

COMPOSITION

In its strictest sense, petroleum includes only crude oil, but in common usage it includes all liquid, gaseous, and solid hydrocarbons. Under surface pressure and temperature conditions, lighter hydrocarbons methane, ethane, propane and butane occur as gases, while pentane and heavier ones are in the form of liquids or solids. However, in an underground oil reservoir the proportions of gas, liquid, and solid depend on subsurface conditions and on the phase diagram of the petroleum mixture.

An oil well produces predominantly crude oil, with some natural gas dissolved in it. Because the pressure is lower at the surface than underground, some of the gas will come out of solution and be recovered (or burned) as *associated gas* or *solution gas*. A gas well produces predominantly natural gas. However, because the underground temperature and pressure are higher than at the surface, the gas may contain heavier hydrocarbons such as pentane, hexane, and heptane in the gaseous state. At surface conditions these will condense out of the gas to form natural gas condensate, often shortened to *condensate*. Condensate

resembles gasoline in appearance and is similar in composition to some volatile light crude oils.

The proportion of light hydrocarbons in the petroleum mixture varies greatly among different oil fields, ranging from as much as 97 percent by weight in the lighter oils to as little as 50 percent in the heavier oils and bitumens.

The hydrocarbons in crude oil are mostly alkanes, cycloalkanes and various aromatic hydrocarbons while the other organic compounds contain nitrogen, oxygen and sulfur, and trace amounts of metals such as iron, nickel, copper and vanadium. Many oil reservoirs contain live bacteria. The exact molecular composition varies widely from formation to formation but the proportion of chemical elements vary over fairly narrow limits as follows:

Composition by weight

Element	**Percent range**
Carbon	83 to 85%
Hydrogen	10 to 14%
Nitrogen	0.1 to 2%
Oxygen	0.05 to 1.5%
Sulfur	0.05 to 6.0%
Metals	< 0.1%

Four different types of hydrocarbon molecules appear in crude oil. The relative percentage of each varies from oil to oil, determining the properties of each oil.

Composition by weight

Hydrocarbon	**Average**	**Range**
Alkanes (paraffins)	30%	15 to 60%
Naphthenes	49%	30 to 60%
Aromatics	15%	3 to 30%
Asphaltics	6%	remainder

Crude oil varies greatly in appearance depending on its composition. It is usually black or dark brown (although it may be yellowish, reddish, or even greenish). In the reservoir it is usually found in association with natural gas, which being lighter forms a gas cap over the petroleum, and saline water which, being heavier than most forms of crude oil, generally sinks beneath it. Crude oil may also be found in semi-solid form mixed with sand and water, as in the Athabasca oil sands in Canada, where it is usually referred to as crude bitumen. In Canada, bitumen is considered a sticky, black, tar-like form of crude oil which is so thick and heavy that it must be heated or diluted before it will flow. Venezuela also has large amounts of oil in the Orinoco oil sands, although the hydrocarbons trapped in them are more fluid than in Canada and are usually called extra heavy oil. These oil sands resources are called unconventional oil to distinguish them from oil which can be extracted using traditional oil well methods. Between them, Canada and Venezuela contain an estimated 3.6 trillion barrels (570×10^9 m^3) of bitumen and extra-heavy oil, about twice the volume of the world's reserves of conventional oil.

Petroleum is used mostly, by volume, for producing fuel oil and gasoline, both important *"primary energy"* sources. 84 percent by volume of the hydrocarbons present in petroleum is converted into energy-rich fuels (petroleum-based fuels), including gasoline, diesel, jet, heating, and other fuel oils, and liquefied petroleum gas. The lighter grades of crude oil produce the best yields of these products, but as the world's reserves of light and medium oil are depleted, oil refineries are increasingly having to process heavy oil and bitumen, and use more complex and expensive methods to produce the products required. Because heavier crude oils have too much carbon and not enough hydrogen, these processes generally involve removing carbon from or adding hydrogen to the molecules, and using fluid catalytic cracking to convert the longer, more complex molecules in the oil to the shorter, simpler ones in the fuels.

Due to its high energy density, easy transportability and relative abundance, oil has become the world's most important source of energy since the mid-1950s. Petroleum is also the raw material for many chemical products, including pharmaceuticals, solvents, fertilizers, pesticides, and plastics; the 16 percent not used for energy production is converted into these other materials.

Petroleum is found in porous rock formations in the upper strata of some areas of the Earth's crust. There is also petroleum in oil sands (tar sands). Known oil reserves are typically estimated at around 190 km^3(1.2 trillion (short scale) barrels) without oil sands, or 595 km^3 (3.74 trillion barrels) with oil sands. Consumption is currently around 84 million barrels (13.4×10^6 m^3) per day, or 4.9 km^3 per year. Which in turn yields a remaining oil supply of only about 120 years, if current demand remain static.

FORMATION

Petroleum is a fossil fuel derived from ancient fossilized organic materials, such as zooplankton and algae. Vast quantities of these remains settled to sea or lake bottoms, mixing with sediments and being buried under anoxic conditions. As further layers settled to the sea or lake bed, intense heat and pressure build up in the lower regions. This process caused the organic matter to change, first into a waxy material known as kerogen, which is found in various oil shales around the world, and then with more heat into liquid and gaseous hydrocarbons via a process known as catagenesis. Formation of petroleum occurs from hydrocarbon pyrolysis in a variety of mainly endothermic reactions at high temperature and/or pressure.



Figure 2. Natural petroleum spring in Korňa, Slovakia

There were certain warm nutrient-rich environments such as the Gulf of Mexico and the ancient Tethys Sea where the large amounts of organic material falling to the ocean floor exceeded the rate at which it could decompose. This resulted in large masses of organic material being buried under subsequent deposits such as shale formed from mud. This massive organic deposit later became heated and transformed under pressure into oil.

Geologists often refer to the temperature range in which oil forms as an "oil window"—below the minimum temperature oil remains trapped in the form of kerogen, and above the maximum temperature the oil is converted to natural gas through the process of thermal cracking. Sometimes, oil formed at extreme depths may migrate and become trapped at a much shallower level. The Athabasca Oil Sands are one example of this.

An alternative mechanism was proposed by Russian scientists in the mid-1850s, the Abiogenic petroleum origin, but this is contradicted by the geological and geochemical evidence.

RESERVOIRS

Crude Oil Reservoirs

Three conditions must be present for oil reservoirs to form: a source rock rich in hydrocarbon material buried deep enough for subterranean heat to cook it into oil, a porous and permeable reservoir rock for it to accumulate in, and a cap rock (seal) or other mechanism that prevents it from escaping to the surface. Within these reservoirs, fluids will typically organize themselves like a three-layer cake with a layer of water below the oil layer and a layer of gas above it, although the different layers vary in size

between reservoirs. Because most hydrocarbons are less dense than rock or water, they often migrate upward through adjacent rock layers until either reaching the surface or becoming trapped within porous rocks (known as reservoirs) by impermeable rocks above. However, the process is influenced by underground water flows, causing oil to migrate hundreds of kilometres horizontally or even short distances downward before becoming trapped in a reservoir. When hydrocarbons are concentrated in a trap, an oil field forms, from which the liquid can be extracted by drilling and pumping.

The reactions that produce oil and natural gas are often modeled as first order breakdown reactions, where hydrocarbons are broken down to oil and natural gas by a set of parallel reactions, and oil eventually breaks down to natural gas by another set of reactions. The latter set is regularly used in petrochemical plants and oil refineries.

Wells are drilled into oil reservoirs to extract the crude oil. “Natural lift” production methods that rely on the natural reservoir pressure to force the oil to the surface are usually sufficient for a while after reservoirs are first tapped. In some reservoirs, such as in the Middle East, the natural pressure is sufficient over a long time. The natural pressure in most reservoirs, however, eventually dissipates. Then the oil must be extracted using “artificial lift” means. Over time, these “primary” methods become less effective and “secondary” production methods may be used. A common secondary method is “waterflood” or injection of water into the reservoir to increase pressure and force the oil to the drilled shaft or “wellbore.” Eventually “tertiary” or “enhanced” oil recovery methods may be used to increase the oil’s flow characteristics by injecting steam, carbon dioxide and other gases or chemicals into the reservoir. In the United States, primary production methods account for less than 40 percent of the oil produced on a daily basis, secondary methods account for about half, and tertiary recovery the remaining 10 percent. Extracting oil (or “bitumen”) from oil/tar sand and oil shale deposits requires mining the sand or shale and heating it in a vessel or retort, or using “in-situ” methods of injecting heated liquids into the deposit and then pumping out the oil-saturated liquid.

Unconventional Oil Reservoirs

Oil-eating bacteria biodegrade oil that has escaped to the surface. Oil sands are reservoirs of partially biodegraded oil still in the process of escaping and being biodegraded, but they contain so much migrating oil that, although most of it has escaped, vast amounts are still present—more than can be found in conventional oil reservoirs. The lighter fractions of the crude oil are destroyed first, resulting in reservoirs containing an extremely heavy form of crude oil, called crude bitumen in Canada, or extra-heavy crude oil in Venezuela. These two countries have the world’s largest deposits of oil sands.

On the other hand, oil shales are source rocks that have not been exposed to heat or pressure long enough to convert their trapped hydrocarbons into crude oil. Technically speaking, oil shales are not always shales and do not contain oil, but are fined-grain sedimentary rocks containing an insoluble organic solid called kerogen. The kerogen in the rock can be converted into crude oil using heat and pressure to simulate natural processes. The method has been known for centuries and was patented in 1694 under British Crown Patent No. 330 covering, “A way to extract and make great quantities of pitch, tar, and oil out of a sort of stone.” Although oil shales are found in many countries, the United States has the world’s largest deposits.

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12.5: Natural Gas

Natural gas is a fossil fuel formed when layers of buried plants, gases, and animals are exposed to intense heat and pressure over thousands of years. The energy that the plants originally obtained from the sun is stored in the form of chemical bonds in natural gas. Natural gas is a nonrenewable resource because it cannot be replenished on a human time frame. Natural gas is a hydrocarbon gas mixture consisting primarily of methane, but commonly includes varying amounts of other higher alkanes and sometimes a usually lesser percentage of carbon dioxide, nitrogen, and/or hydrogen sulfide. Natural gas is an energy source often used for heating, cooking, and electricity generation. It is also used as fuel for vehicles and as a chemical feedstock in the manufacture of plastics and other commercially important organic chemicals.

Natural gas is found in deep underground rock formations or associated with other hydrocarbon reservoirs in coal beds and as methane clathrates. Petroleum is another resource and fossil fuel found in close proximity to, and with natural gas. Most natural gas was created over time by two mechanisms: biogenic and thermogenic. Biogenic gas is created by methanogenic organisms in marshes, bogs, landfills, and shallow sediments. Deeper in the earth, at greater temperature and pressure, thermogenic gas is created from buried organic material.

Before natural gas can be used as a fuel, it must be processed to remove impurities, including water, to meet the specifications of marketable natural gas. The by-products of this processing include: ethane, propane, butanes, pentanes, and higher molecular weight hydrocarbons, hydrogen sulfide (which may be converted into pure sulfur), carbon dioxide, water vapor, and sometimes helium and nitrogen.

Natural gas is often informally referred to simply as “gas,” especially when compared to other energy sources such as oil or coal. However, it is not to be confused with gasoline, especially in North America, where the term gasoline is often shortened in colloquial usage to *gas*.

Natural gas was used by the Chinese in about 500 BC. They discovered a way to transport gas seeping from the ground in crude pipelines of bamboo to where it was used to boil salt water to extract the salt, in the Ziliujing District of Sichuan. The world’s first industrial extraction of natural gas started at Fredonia, New York, USA in 1825. By 2009, 66 trillion cubic meters (or 8%) had been used out of the total 850 trillion cubic meters of estimated remaining recoverable reserves of natural gas. Based on an estimated 2015 world consumption rate of about 3.4 trillion cubic meters of gas per year, the total estimated remaining economically recoverable reserves of natural gas would last 250 years at current consumption rates. An annual increase in usage of 2–3% could result in currently recoverable reserves lasting significantly less, perhaps as few as 80 to 100 years.

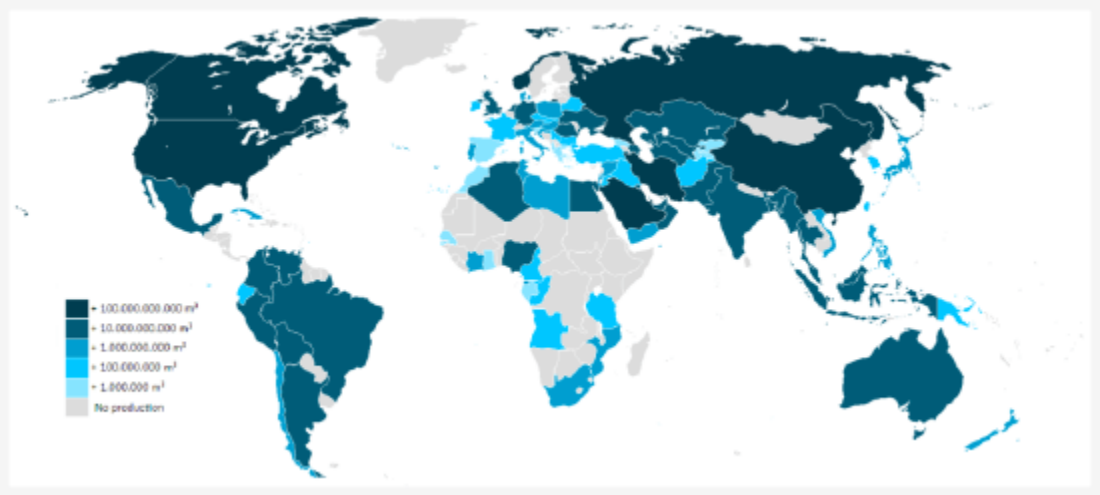


Figure 1. Natural gas extraction by countries in cubic meters per year.

SOURCES

Natural Gas

In the 19th century, natural gas was usually obtained as a by-product of producing oil, since the small, light gas carbon chains came out of solution as the extracted fluids underwent pressure reduction from the reservoir to the surface, similar to uncapping a soft drink bottle where the carbon dioxide effervesces. Unwanted natural gas was a disposal problem in the active oil fields. If there was not a market for natural gas near the wellhead it was virtually valueless since it had to be piped to the end user.



Figure 2. Natural gas drilling rig in Texas.

In the 19th century and early 20th century, such unwanted gas was usually burned off at oil fields. Today, unwanted gas (or stranded gas without a market) associated with oil extraction often is returned to the reservoir with 'injection' wells while awaiting a possible future market or to repressurize the formation, which can enhance extraction rates from other wells. In regions with a high natural gas demand (such as the US), pipelines are constructed when it is economically feasible to transport gas from a wellsite to an end consumer.

In addition to transporting gas via pipelines for use in power generation, other end uses for natural gas include export as liquefied natural gas (LNG) or conversion of natural gas into other liquid products via gas-to-liquids (GTL) technologies. GTL technologies can convert natural gas into liquids products such as gasoline, diesel or jet fuel. A variety of GTL technologies have been developed, including Fischer–Tropsch (F–T), methanol to gasoline (MTG) and STG+. F–T produces a synthetic crude that can be further refined into finished products, while MTG can produce synthetic gasoline from natural gas. STG+ can produce drop-in gasoline, diesel, jet fuel and aromatic chemicals directly from natural gas via a single-loop process. In 2011, Royal Dutch Shell's 140,000 barrel per day F–T plant went into operation in Qatar.

Natural gas can be "associated" (found in oil fields), or "non-associated" (isolated in natural gas fields), and is also found in coal beds (as coalbed methane). It sometimes contains a significant amount of ethane, propane, butane, and pentane—heavier hydrocarbons removed for commercial use prior to the methane being sold as a consumer fuel or chemical plant feedstock. Non-hydrocarbons such as carbon dioxide, nitrogen, helium (rarely), andhydrogen sulfide must also be removed before the natural gas can be transported.

Natural gas extracted from oil wells is called casinghead gas (whether or not truly produced up the annulus and through a casinghead outlet) or associated gas. The natural gas industry is extracting an increasing quantity of gas from challenging resource types: sour gas, tight gas, shale gas, and coalbed methane.

There is some disagreement on which country has the largest proven gas reserves. Sources that consider that Russia has by far the largest proven reserves include the US CIA (47.6 trillion cubic meters), the US Energy Information Administration (47.8 tcm), and OPEC (48.7 tcm). However, BP credits Russia with only 32.9 tcm, which would place it in second place, slightly behind Iran (33.1 to 33.8 tcm, depending on the source). With Gazprom, Russia is frequently the world's largest natural gas extractor. Major

proven resources (in billion cubic meters) are world 187,300 (2013), Iran 33,600 (2013), Russia 32,900 (2013), Qatar 25,100 (2013), Turkmenistan 17,500 (2013) and the United States 8,500 (2013).

It is estimated that there are about 900 trillion cubic meters of "unconventional" gas such as shale gas, of which 180 trillion may be recoverable. In turn, many studies from MIT, Black & Veatchand the DOE predict that natural gas will account for a larger portion of electricity generation and heat in the future.

The world's largest gas field is the offshore South Pars / North Dome Gas-Condensate field, shared between Iran and Qatar. It is estimated to have 51 trillion cubic meters of natural gas and 50 billion barrels of natural gas condensates.

Because natural gas is not a pure product, as the reservoir pressure drops when non-associated gas is extracted from a field under supercritical (pressure/temperature) conditions, the higher molecular weight components may partially condense upon isothermic depressurizing—an effect called retrograde condensation. The liquid thus formed may get trapped as the pores of the gas reservoir get depleted. One method to deal with this problem is to re-inject dried gas free of condensate to maintain the underground pressure and to allow re-evaporation and extraction of condensates. More frequently, the liquid condenses at the surface, and one of the tasks of the gas plant is to collect this condensate. The resulting liquid is called natural gas liquid (NGL) and has commercial value.

Shale Gas

Shale gas is natural gas produced from shale. Because shale has matrix permeability too low to allow gas to flow in economical quantities, shale gas wells depend on fractures to allow the gas to flow. Early shale gas wells depended on natural fractures through which gas flowed; almost all shale gas wells today require fractures artificially created by hydraulic fracturing. Since 2000, shale gas has become a major source of natural gas in the United States and Canada. Following the success in the United States, shale gas exploration is beginning in countries such as Poland, China, and South Africa. With the increase of shale production it has caused the United States to become the number one natural gas producer in the world.

Town Gas

Town gas is a flammable gaseous fuel made by the destructive distillation of coal and contains a variety of calorific gases including hydrogen, carbon monoxide, methane, and other volatile hydrocarbons, together with small quantities of non-calorific gases such as carbon dioxide and nitrogen, and is used in a similar way to natural gas. This is a historical technology, not usually economically competitive with other sources of fuel gas today. But there are still some specific cases where it is the best option and it may be so into the future.

Most town "gashouses" located in the eastern US in the late 19th and early 20th centuries were simple by-product coke ovens that heated bituminous coal in air-tight chambers. The gas driven off from the coal was collected and distributed through networks of pipes to residences and other buildings where it was used for cooking and lighting. (Gas heating did not come into widespread use until the last half of the 20th century.) The coal tar (or asphalt) that collected in the bottoms of the gashouse ovens was often used for roofing and other waterproofing purposes, and when mixed with sand and gravel was used for paving streets.

Biogas

Methanogenic archaea are responsible for all biological sources of methane. Some live in symbiotic relationships with other life forms, including termites, ruminants, and cultivated crops. Other sources of methane, the principal component of natural gas, include landfill gas, biogas, and methane hydrate. When methane-rich gases are produced by the anaerobic decay of non-fossilorganic matter (biomass), these are referred to as biogas (or natural biogas). Sources of biogas include swamps, marshes, and landfills (see landfill gas), as well as agricultural waste materials such as sewage sludge and manure by way of anaerobic digesters, in addition to enteric fermentation, particularly in cattle. Landfill gas is created by decomposition of waste in landfill sites. Excluding water vapor, about half of landfill gas is methane and most of the rest is carbon dioxide, with small amounts of nitrogen, oxygen, and hydrogen, and variable trace amounts of hydrogen sulfide and siloxanes. If the gas is not removed, the pressure may get so high that it works its way to the surface, causing damage to the landfill structure, unpleasant odor, vegetation die-off, and an explosion hazard. The gas can be vented to the atmosphere, flared or burned to produce electricity or heat. Biogas can also be produced by separating organic materials from waste that otherwise goes to landfills. This method is more efficient than just capturing the landfill gas it produces. Anaerobic lagoons produce biogas from manure, while biogas reactors can be used for manure or plant parts. Like landfill gas, biogas is mostly methane and carbon dioxide, with small amounts of nitrogen, oxygen and hydrogen. However, with the exception of pesticides, there are usually lower levels of contaminants.

Landfill gas cannot be distributed through utility natural gas pipelines unless it is cleaned up to less than 3 per cent CO_2, and a few parts per million H_2S, because CO_2 and H_2S corrode the pipelines. The presence of CO_2 will lower the energy level of the gas below requirements for the pipeline. Siloxanes in the gas will form deposits in gas burners and need to be removed prior to entry into any gas distribution or transmission system. Consequently it may be more economical to burn the gas on site or within a short distance of the landfill using a dedicated pipeline. Water vapor is often removed, even if the gas is burned on site. If low temperatures condense water out of the gas, siloxanes can be lowered as well because they tend to condense out with the water vapor. Other non-methane components may also be removed to meet emission standards, to prevent fouling of the equipment or for environmental considerations. Co-firing landfill gas with natural gas improves combustion, which lowers emissions.

Biogas, and especially landfill gas, are already used in some areas, but their use could be greatly expanded. Experimental systems were being proposed for use in parts of Hertfordshire, UK, and Lyon in France. Using materials that would otherwise generate no income, or even cost money to get rid of, improves the profitability and energy balance of biogas production. Gas generated in sewage treatment plants is commonly used to generate electricity. For example, the Hyperion sewage plant in Los Angeles burns 8 million cubic feet (230,000 m^3) of gas per day to generate power New York City utilizes gas to run equipment in the sewage plants, to generate electricity, and in boilers. Using sewage gas to make electricity is not limited to large cities. The city of Bakersfield, California, uses cogeneration at its sewer plants. California has 242 sewage wastewater treatment plants, 74 of which have installed anaerobic digesters. The total biopower generation from the 74 plants is about 66 MW.

Crystallized Natural Gas-Hydrates

Huge quantities of natural gas (primarily methane) exist in the form of hydrates under sediment on offshore continental shelves and on land in arctic regions that experience permafrost, such as those in Siberia. Hydrates require a combination of high pressure and low temperature to form.



Figure 3. The McMahon natural gas processing plant in Taylor, British Columbia, Canada.

In 2010, the cost of extracting natural gas from crystallized natural gas was estimated to 100–200 per cent the cost of extracting natural gas from conventional sources, and even higher from offshore deposits.

In 2013, Japan Oil, Gas and Metals National Corporation (JOGMEC) announced that they had recovered commercially relevant quantities of natural gas from methane hydrate.

DEPLETION

Natural gas production in the U.S. reached a peak in 1973, and went over a second lower peak in 2001, but recently has peaked again and is continuing to rise.

USES

Mid-Stream Natural Gas

Natural gas flowing in the distribution lines and at the natural gas well head are often used to power natural gas powered engines. These engines rotate compressors to facilitate the natural gas transmission. These compressors are required in the mid-stream line to pressurize and to re-pressurize the natural gas in the transmission line as the gas travels. The natural gas transmission lines extend to the natural gas processing plant or unit which removes the higher molecular weighted natural gas hydrocarbons to produce a British thermal unit (BTU) value between 950 and 1050 BTUs. The processed natural gas may then be used for residential, commercial and industrial uses.

Often mid-stream and well head gases require removal of many of the various hydrocarbon species contained within the natural gas. Some of these gases include heptane, pentane, propane and other hydrocarbons with molecular weights above Methane (CH4) to produce a natural gas fuel which is used to operate the natural gas engines for further pressurized transmission. Typically, natural gas compressors require 950 to 1050 BTU per cubic foot to operate at the natural gas engines rotational name plate specifications.

Several methods are used to remove these higher molecular weighted gases for use at the natural gas engine. A few technologies are as follows:

- Joule–Thomson skid
- Cryogenic or chiller system
- Chemical enzymology system

Power Generation

Natural gas is a major source of electricity generation through the use of cogeneration, gas turbines and steam turbines. Natural gas is also well suited for a combined use in association with renewable energy sources such as wind or solar and for alimenting peak-load power stations functioning in tandem with hydroelectric plants. Most grid peaking power plants and some off-grid engine-generators use natural gas. Particularly high efficiencies can be achieved through combining gas turbines with a steam turbine in combined cycle mode. Natural gas burns more cleanly than other hydrocarbon fuels, such as oil and coal, and produces less carbon dioxide per unit of energy released. For transportation, burning natural gas produces about 30 per cent less carbon dioxide than burning petroleum. For an equivalent amount of heat, burning natural gas produces about 45 per cent less than burning coal for power. The US Energy Information Administration reports the following emissions in million metric tons of carbon dioxide in the world for 2012:

- Natural gas: 6,799
- Petroleum: 11,695
- Coal: 13,787

Coal-fired electric power generation emits around 2,000 pounds of carbon dioxide for every megawatt hour generated, which is almost double the carbon dioxide released by a natural gas-fired electric plant per megawatt hour generated. Because of this higher carbon efficiency of natural gas generation, as the fuel mix in the United States has changed to reduce coal and increase natural gas generation, carbon dioxide emissions have unexpectedly fallen. Those measured in the first quarter of 2012 were the lowest of any recorded for the first quarter of any year since 1992.

Combined cycle power generation using natural gas is currently the cleanest available source of power using hydrocarbon fuels, and this technology is widely and increasingly used as natural gas can be obtained at increasingly reasonable costs. Fuel cell technology may eventually provide cleaner options for converting natural gas into electricity, but as yet it is not price-competitive. Locally produced electricity and heat using natural gas powered Combined Heat and Power plant (CHP or Cogeneration plant) is considered energy efficient and a rapid way to cut carbon emissions. Natural gas power plants are increasing in popularity and generate 22% of the worlds total electricity. Approximately half as much as generated with coal.

Domestic Use

Natural gas dispensed from a simple stovetop can generate temperatures in excess of 1100 °C (2000 °F) making it a powerful domestic cooking and heating fuel. In much of the developed world it is supplied through pipes to homes, where it is used for

many purposes including ranges and ovens, gas-heated clothes dryers, heating/cooling, and central heating. Heaters in homes and other buildings may include boilers, furnaces, and water heaters.

Compressed natural gas (CNG) is used in rural homes without connections to piped-in public utility services, or with portable grills. Natural gas is also supplied by independent natural gas suppliers through Natural Gas Choice programs throughout the United States. However, as CNG costs more than LPG, LPG (propane) is the dominant source of rural gas.

Transportation

CNG is a cleaner and also cheaper alternative to other automobile fuels such as gasoline (petrol) and diesel. By the end of 2012 there were 17.25 millionnatural gas vehicles worldwide, led by Iran (3.3 million), Pakistan (3.1 million), Argentina (2.18 million), Brazil (1.73 million), India (1.5 million), and China(1.5 million). The energy efficiency is generally equal to that of gasoline engines, but lower compared with modern diesel engines. Gasoline/petrol vehicles converted to run on natural gas suffer because of the low compression ratio of their engines, resulting in a cropping of delivered power while running on natural gas (10%–15%). CNG-specific engines, however, use a higher compression ratio due to this fuel's higher octane number of 120–130.



Figure 4. A Washington, D.C. Metrobus, which runs on natural gas.

Fertilizers

Natural gas is a major feedstock for the production of ammonia, via the Haber process, for use in fertilizer production.

Aviation

Russian aircraft manufacturer Tupolev is currently running a development program to produce LNG- and hydrogen-powered aircraft. The program has been running since the mid-1970s, and seeks to develop LNG and hydrogen variants of the Tu-204 and Tu-334 passenger aircraft, and also the Tu-330 cargo aircraft. It claims that at current market prices, an LNG-powered aircraft would cost 5,000 roubles (~ US$218/ £112) less to operate per ton, roughly equivalent to 60 per cent, with considerable reductions to carbon monoxide, hydrocarbon and nitrogen oxide emissions.

The advantages of liquid methane as a jet engine fuel are that it has more specific energy than the standard kerosene mixes do and that its low temperature can help cool the air which the engine compresses for greater volumetric efficiency, in effect replacing an intercooler. Alternatively, it can be used to lower the temperature of the exhaust.

Hydrogen

Natural gas can be used to produce hydrogen, with one common method being the hydrogen reformer. Hydrogen has many

applications: it is a primary feedstock for the chemical industry, a hydrogenating agent, an important commodity for oil refineries, and the fuel source in hydrogen vehicles.

Other

Natural gas is also used in the manufacture of fabrics, glass, steel, plastics, paint, and other products.

STORAGE AND TRANSPORT

Because of its low density, it is not easy to store natural gas or to transport it by vehicle. Natural gas pipelines are impractical across oceans. Many existing pipelines in America are close to reaching their capacity, prompting some politicians representing northern states to speak of potential shortages. In Western Europe, the gas pipeline network is already dense. New pipelines are planned or under construction in Eastern Europe and between gas fields in Russia, Near East and Northern Africa and Western Europe. See also List of natural gas pipelines.

LNG carriers transport liquefied natural gas (LNG) across oceans, while tank trucks can carry liquefied or compressed natural gas (CNG) over shorter distances. Sea transport using CNG carrier ships that are now under development may be competitive with LNG transport in specific conditions.

Gas is turned into liquid at a liquefaction plant, and is returned to gas form at regasification plant at the terminal. Shipborne regasification equipment is also used. LNG is the preferred form for long distance, high volume transportation of natural gas, whereas pipeline is preferred for transport for distances up to 4,000 km (2,485 mi) over land and approximately half that distance offshore.

CNG is transported at high pressure, typically above 200 bars. Compressors and decompression equipment are less capital intensive and may be economical in smaller unit sizes than liquefaction/regasification plants. Natural gas trucks and carriers may transport natural gas directly to end-users, or to distribution points such as pipelines.

In the past, the natural gas which was recovered in the course of recovering petroleum could not be profitably sold, and was simply burned at the oil field in a process known as flaring. Flaring is now illegal in many countries. Additionally, higher demand in the last 20–30 years has made production of gas associated with oil economically viable. As a further option, the gas is now sometimes re-injected into the formation for enhanced oil recovery by pressure maintenance as well as miscible or immiscible flooding. Conservation, re-injection, or flaring of natural gas associated with oil is primarily dependent on proximity to markets (pipelines), and regulatory restrictions.

A “master gas system” was invented in Saudi Arabia in the late 1970s, ending any necessity for flaring. Satellite observation, however, shows that flaring and venting are still practiced in some gas-extracting countries.

Natural gas is used to generate electricity and heat for desalination. Similarly, some landfills that also discharge methane gases have been set up to capture the methane and generate electricity.

Natural gas is often stored underground inside depleted gas reservoirs from previous gas wells, salt domes, or in tanks as liquefied natural gas. The gas is injected in a time of low demand and extracted when demand picks up. Storage nearby end users helps to meet volatile demands, but such storage may not always be practicable.

With 15 countries accounting for 84 per cent of the worldwide extraction, access to natural gas has become an important issue in international politics, and countries vie for control of pipelines. In the first decade of the 21st century, Gazprom, the state-owned energy company in Russia, engaged in disputes with Ukraine and Belarus over the price of natural gas, which have created concerns that gas deliveries to parts of Europe could be cut off for political reasons. The United States is preparing to export natural gas.

Floating Liquefied Natural Gas (FLNG) is an innovative technology designed to enable the development of offshore gas resources that would otherwise remain untapped because due to environmental or economic factors it is nonviable to develop them via a land-based LNG operation. FLNG technology also provides a number of environmental and economic advantages:

- Environmental—Because all processing is done at the gas field, there is no requirement for long pipelines to shore, compression units to pump the gas to shore, dredging and jetty construction, and onshore construction of an LNG processing plant, which significantly reduces the environmental footprint. Avoiding construction also helps preserve marine and coastal

environments. In addition, environmental disturbance will be minimised during decommissioning because the facility can easily be disconnected and removed before being refurbished and re-deployed elsewhere.
- Economic—Where pumping gas to shore can be prohibitively expensive, FLNG makes development economically viable. As a result, it will open up new business opportunities for countries to develop offshore gas fields that would otherwise remain stranded, such as those offshore East Africa.

Many gas and oil companies are considering the economic and environmental benefits of Floating Liquefied Natural Gas (FLNG). However, for the time being, the only FLNG facility now in development is being built by Shell, due for completion around 2017.

ENVIRONMENTAL EFFECTS

Effect of Natural Gas Release

Natural gas is mainly composed of methane. After release to the atmosphere it is removed by gradual oxidation to carbon dioxide and water by hydroxyl radicals (·OH) formed in the troposphere or stratosphere, giving the overall chemical reaction $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$. While the lifetime of atmospheric methane is relatively short when compared to carbon dioxide, with a half-life of about 7 years, it is more efficient at trapping heat in the atmosphere, so that a given quantity of methane has 84 times the global-warming potential of carbon dioxide over a 20-year period and 28 times over a 100-year period. Natural gas is thus a more potent greenhouse gas than carbon dioxide due to the greater global-warming potential of methane. Current estimates by the EPA place global emissions of methane at 85 billion cubic metres (3.0×10^{12} cu ft) annually, or 3.2 per cent of global production. Direct emissions of methane represented 14.3 per cent by volume of all global anthropogenic greenhouse gas emissions in 2004.

During extraction, storage, transportation, and distribution, natural gas is known to leak into the atmosphere, particularly during the extraction process. A Cornell University study in 2011 demonstrated that the leak rate of methane may be high enough to jeopardize its global warming advantage over coal. This study was criticized later for its over-estimation of methane leakage values. Preliminary results of some air sampling from airplanes done by the National Oceanic and Atmospheric Administration indicated higher-than-estimated methane releases by gas wells in some areas, but the overall results showed methane emissions in line with previous EPA estimates.

Natural gas extraction also releases an isotope of radon, ranging in activity from 5 to 200,000 becquerels per cubic meter of gas.

CO_2 Emissions

Natural gas is often described as the cleanest fossil fuel. It produces about 29% and 44% less carbon dioxide per joule delivered than oil and coal respectively, and potentially fewer pollutants than other hydrocarbon fuels. However, in absolute terms, it comprises a substantial percentage of human carbon emissions, and this contribution is projected to grow. According to the IPCC Fourth Assessment Report, in 2004, natural gas produced about 5.3 billion tons a year of CO_2 emissions, while coal and oil produced 10.6 and 10.2 billion tons respectively. According to an updated version of the Special Report on Emissions Scenario by 2030, natural gas would be the source of 11 billion tons a year, with coal and oil now 8.4 and 17.2 billion respectively because demand is increasing 1.9 percent a year.

Other Pollutants

Natural gas produces far lower amounts of sulfur dioxide and nitrous oxides than any other hydrocarbon fuels. The other pollutants due to natural gas combustion are listed below in pounds per billion BTU:

- Carbon monoxide–40
- Sulfur dioxide–1
- Nitrogen oxide–92
- Particulates–7

SAFETY CONCERNS

Production

In mines, where methane seeping from rock formations has no odor, sensors are used, and mining apparatus such as the Davy lamp has been specifically developed to avoid ignition sources.



Figure 5. A pipeline odorant injection station

Some gas fields yield sour gas containing hydrogen sulfide (H_2S). This untreated gas is toxic. Amine gas treating, an industrial scale process which removes acidic gaseous components, is often used to remove hydrogen sulfide from natural gas.

Extraction of natural gas (or oil) leads to decrease in pressure in the reservoir. Such decrease in pressure in turn may result in subsidence, sinking of the ground above. Subsidence may affect ecosystems, waterways, sewer and water supply systems, foundations, and so on.

Another ecosystem effect results from the noise of the process. This can change the composition of animal life in the area, and have consequences for plants as well in that animals disperse seeds and pollen.

Fracking

Releasing natural gas from low-permeability rock such as sandstone or shale is accomplished by a process called hydraulic fracturing or “hydrofracking.” It’s estimated that hydraulic fracturing will eventually account for nearly 70% of natural gas development in North America. Worldwide hydraulic fracturing has been used to stimulate approximately one million oil and gas wells

To allow the natural gas to flow out of the rock, well operators force 1 to 9 million US gallons (34,000 m^3) of water mixed with a variety of chemicals through the wellbore casing into the rock. The high pressure water breaks up or “fracks” the rock, which releases the trapped gas. Sand is added to the water as a proppant to keep the fractures in the rock open, thus enabling the gas to flow into the casing and then to the surface. The chemicals are added to the frack fluid to reduce friction and combat corrosion. Dealing with fracking fluid can be a challenge. Along with the gas, 30 percent to 70 percent of the chemically laced frack fluid, or flow back, returns to the surface. Additionally, a significant amount of brine, containing salts and other minerals, may be produced with the gas.

Use

In order to assist in detecting leaks, a minute amount of odorant is added to the otherwise colorless and almost odorless gas

used by consumers. The odor has been compared to the smell of rotten eggs, due to the added tert-Butylthiol (t-butyl mercaptan). Sometimes a related compound, thiophane, may be used in the mixture. Situations in which an odorant that is added to natural gas can be detected by analytical instrumentation, but cannot be properly detected by an observer with a normal sense of smell, have occurred in the natural gas industry. This is caused by odor masking, when one odorant overpowers the sensation of another. As of 2011, the industry is conducting research on the causes of odor masking.

Explosions caused by natural gas leaks occur a few times each year. Individual homes, small businesses and other structures are most frequently affected when an internal leak builds up gas inside the structure. Frequently, the blast is powerful enough to significantly damage a building but leave it standing. In these cases, the people inside tend to have minor to moderate injuries. Occasionally, the gas can collect in high enough quantities to cause a deadly explosion, disintegrating one or more buildings in the process. The gas usually dissipates readily outdoors, but can sometimes collect in dangerous quantities if flow rates are high enough. However, considering the tens of millions of structures that use the fuel, the individual risk of using natural gas is very low.



Figure 6. Gas network emergency vehicle responding to a major fire in Kiev, Ukraine

Natural gas heating systems are a minor source of carbon monoxide deaths in the United States. According to the US Consumer Product Safety Commission (2008), 56 per cent of unintentional deaths from non-fire CO poisoning were associated with engine-driven tools like gas-powered generators and lawnmowers. Natural gas heating systems accounted for 4 per cent of these deaths. Improvements in natural gas furnace designs have greatly reduced CO poisoning concerns. Detectors are also available that warn of carbon monoxide and/or explosive gas (methane, propane, etc.).

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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12.6: Coal

Coal (from the Old English term *col*, which has meant “mineral of fossilized carbon” since the 13th century)is a combustible black or brownish-black sedimentary rock usually occurring in rock strata in layers or veins called **coal beds** or **coal seams**. The harder forms, such as anthracite coal, can be regarded as metamorphic rock because of later exposure to elevated temperature and pressure. Coal is composed primarily of carbon along with variable quantities of other elements, chiefly hydrogen, sulfur, oxygen, and nitrogen.



Figure 1. Bituminous coal

Throughout history, coal has been used as an energy resource, primarily burned for the production of electricity and/or heat, and is also used for industrial purposes, such as refining metals. A fossil fuel, coal forms when dead plant matter is converted into peat, which in turn is converted into lignite, then sub-bituminous coal, after that bituminous coal, and lastly anthracite. This involves biological and geological processes that take place over a long period. The United States Energy Information Administration estimates coal reserves at 948×10^9 short tons (860 Gt). One estimate for resources is 18 000 Gt.

Coal is the largest source of energy for the generation of electricity worldwide, as well as one of the largest worldwide anthropogenic sources ofcarbon dioxide releases. In 1999, world gross carbon dioxide emissions from coal usage were 8,666 million tonnes of carbon dioxide. In 2011, world gross emissions from coal usage were 14,416 million tonnes. Coal-fired electric power generation emits around 2,000 pounds of carbon dioxide for every megawatt-hour generated, which is almost double the approximately 1100 pounds of carbon dioxide released by a natural gas-fired electric plant per megawatt-hour generated. Because of this higher carbon efficiency of natural gas generation, as the market in the United States has changed to reduce coal and increase natural gas generation, carbon dioxide emissions have fallen. Those measured in the first quarter of 2012 were the lowest of any recorded for the first quarter of any year since 1992 In 2013, the head of the UN climate agency advised that most of the world’s coal reserves should be left in the ground to avoid catastrophic global warming.

Coal is extracted from the ground by coal mining, either underground by shaft mining, or at ground level by open pit mining extraction. Since 1983 the world top coal producer has been China. In 2011 China produced 3,520 million tonnes of coal – 49.5% of 7,695 million tonnes world coal production. In 2011 other large producers were United States (993 million tonnes), India (589), European Union (576) and Australia (416). In 2010 the largest exporters were Australia with 328 million tonnes (27.1% of world coal export) and Indonesia with 316 million tonnes (26.1%), while the largest importers were Japan with 207 million tonnes (17.5% of world coal import), China with 195 million tonnes (16.6%) and South Korea with 126 million tonnes (10.7%).

FORMATION

At various times in the geologic past, the Earth had dense forests in low-lying wetland areas. Due to natural processes such

as flooding, these forests were buried underneath soil. As more and more soil deposited over them, they were compressed. The temperature also rose as they sank deeper and deeper. As the process continued the plant matter was protected from biodegradation and oxidation, usually by mud or acidic water. This trapped the carbon in immense peat bogs that were eventually covered and deeply buried by sediments. Under high pressure and high temperature, dead vegetation was slowly converted to coal. As coal contains mainly carbon, the conversion of dead vegetation into coal is called carbonization.



Figure 2. Coastal exposure of the Point Aconi Seam (Nova Scotia)

The wide, shallow seas of the Carboniferous Period provided ideal conditions for coal formation, although coal is known from most geological periods. The exception is the coal gap in the Permian–Triassic extinction event, where coal is rare. Coal is known from Precambrian strata, which predate land plants—this coal is presumed to have originated from residues of algae.

RANKS

As geological processes apply pressure to dead biotic material over time, under suitable conditions, its metamorphic grade increases successively into:

- Peat, considered to be a precursor of coal, has industrial importance as a fuel in some regions, for example, Ireland and Finland. In its dehydrated form, peat is a highly effective absorbent for fuel and oil spills on land and water. It is also used as a conditioner for soil to make it more able to retain and slowly release water.
- Lignite, or brown coal, is the lowest rank of coal and used almost exclusively as fuel for electric power generation. Jet, a compact form of lignite, is sometimes polished and has been used as an ornamental stone since the Upper Palaeolithic.
- **Sub-bituminous coal**, whose properties range from those of lignite to those of bituminous coal, is used primarily as fuel for steam-electric power generation and is an important source of light aromatic hydrocarbons for the chemical synthesis industry.
- **Bituminous coal** is a dense sedimentary rock, usually black, but sometimes dark brown, often with well-defined bands of bright and dull material; it is used primarily as fuel in steam-electric power generation, with substantial quantities used for heat and power applications in manufacturing and to make coke.
- "**Steam coal**" is a grade between bituminous coal and anthracite, once widely used as a fuel for steam locomotives. In this specialized use, it is sometimes known as "sea-coal" in the United States. Small steam coal (dry small steam nuts or DSSN) was used as a fuel for domestic water heating.
- **Anthracite**, the highest rank of coal, is a harder, glossy black coal used primarily for residential and commercial space heating. It may be divided further into metamorphically altered bituminous coal and "petrified oil," as from the deposits in Pennsylvania.
- **Graphite**, technically the highest rank, is difficult to ignite and is not commonly used as fuel—it is mostly used in pencils and, when powdered, as a lubricant.

The classification of coal is generally based on the content of volatiles. However, the exact classification varies between countries. According to the German classification, coal is classified as follows:

German Classification	English Designation	Volatiles %	C Carbon %	H Hydrogen %	O Oxygen %	S Sulfur %	Heat content kJ/kg
Braunkohle	Lignite (brown coal)	45–65	60–75	6.0–5.8	34-17	0.5-3	<28,470
Flammkohle	Flame coal	40-45	75-82	6.0-5.8	>9.8	~1	<32,870
Gasflammkohle	Gas flame coal	35-40	82-85	5.8-5.6	9.8-7.3	~1	<33,910
Gaskohle	Gas coal	28-35	85-87.5	5.6-5.0	7.3-4.5	~1	<34,960
Fettkohle	Fat coal	19-28	87.5-89.5	5.0-4.5	4.5-3.2	~1	<35,380
Esskohle	Forge coal	14-19	89.5-90.5	4.5-4.0	3.2-2.8	~1	<35,380
Magerkohle	Nonbaking coal	10-14	90.5-91.5	4.0-3.75	2.8-3.5	~1	35,380
Anthrazit	Anthracite	7-12	>91.5	<3.75	<2.5	~1	<35,300
Note, the percentages are percent by mass of the indicated elements							

The middle six grades in the table represent a progressive transition from the English-language sub-bituminous to bituminous coal, while the last class is an approximate equivalent to anthracite, but more inclusive (US anthracite has < 6% volatiles).

Cannel coal (sometimes called “candle coal”) is a variety of fine-grained, high-rank coal with significant hydrogen content. It consists primarily of “exinite” macerals, now termed “liptinite.”

Hilt's Law

Hilt’s law is a geological term that states that, in a small area, the deeper the coal, the higher its rank (grade). The law holds true if the thermal gradient is entirely vertical, but metamorphism may cause lateral changes of rank, irrespective of depth.

CONTENT

Average content

Substance	Content
Mercury (Hg)	0.10±0.01 ppm
Arsenic (As)	1.4 – 71 ppm
Selenium (Se)	3 ppm

USES TODAY

Coal as Fuel

Coal is primarily used as a solid fuel to produce electricity and heat through combustion. World coal consumption was about 7.25 billion tonnes in 2010 (7.99 billion short tons) and is expected to increase 48% to 9.05 billion tonnes (9.98 billion short tons) by 2030. China produced 3.47 billion tonnes (3.83 billion short tons) in 2011. India produced about 578 million tonnes (637.1 million short tons) in 2011. 68.7% of China’s electricity comes from coal. The USA consumed about 13% of the world total in 2010, i.e. 951 million tonnes (1.05 billion short tons), using 93% of it for generation of electricity. 46% of total power generated in the USA was done using coal.



Figure 3. Castle Gate Power Plant near Helper, Utah, USA

When coal is used for electricity generation, it is usually pulverized and then combusted (burned) in a furnace with a boiler. The furnace heat converts boiler water to steam, which is then used to spin turbines which turn generators and create electricity. The thermodynamic efficiency of this process has been improved over time; some older coal-fired power stations have thermal efficiencies in the vicinity of 25% whereas the newest supercritical and "ultra-supercritical" steam cycle turbines, operating at temperatures over 600 °C and pressures over 27 MPa (over 3900 psi), can practically achieve thermal efficiencies in excess of 45% (LHV basis) using anthracite fuel, or around 43% (LHV basis) even when using lower-grade lignite fuel. Further thermal efficiency improvements are also achievable by improved pre-drying (especially relevant with high-moisture fuel such as lignite or biomass) and cooling technologies.



Figure 4. Coal rail cars

An alternative approach of using coal for electricity generation with improved efficiency is the integrated gasification combined cycle (IGCC) power plant. Instead of pulverizing the coal and burning it directly as fuel in the steam-generating boiler, the coal can be first gasified (see coal gasification) to create syngas, which is burned in a gas turbine to produce electricity (just like natural gas is burned in a turbine). Hot exhaust gases from the turbine are used to raise steam in a heat recovery steam generator which powers a supplemental steam turbine. Thermal efficiencies of current IGCC power plants range from 39-42% (HHV basis) or ~42-45% (LHV basis) for bituminous coal and assuming utilization of mainstream gasification technologies (Shell, GE Gasifier, CB&I). IGCC power plants outperform conventional pulverized coal-fueled plants in terms of pollutant emissions, and allow for relatively easy carbon capture.

At least 40% of the world's electricity comes from coal, and in 2012, about one-third of the United States' electricity came from coal, down from approximately 49% in 2008. As of 2012 in the United States, use of coal to generate electricity was declining, as plentiful supplies of natural gas obtained by hydraulic fracturing of tight shale formations became available at low prices.

In Denmark, a net electric efficiency of > 47% has been obtained at the coal-fired Nordjyllandsværket CHP Plant and an overall plant efficiency of up to 91% with cogeneration of electricity and district heating. The multifuel-fired Avedøreværket CHP Plant just outside Copenhagen can achieve a net electric efficiency as high as 49%. The overall plant efficiency with cogeneration of electricity and district heating can reach as much as 94%.

An alternative form of coal combustion is as coal-water slurry fuel (CWS), which was developed in the Soviet Union. CWS significantly reduces emissions, improving the heating value of coal. Other ways to use coal are combined heat and power cogeneration and an MHD topping cycle.

The total known deposits recoverable by current technologies, including highly polluting, low-energy content types of coal (i.e., lignite, bituminous), is sufficient for many years. However, consumption is increasing and maximal production could be reached within decades (see world coal reserves, below). On the other hand much may have to be left in the ground to avoid climate change.

Coking Coal and Use of Coke



Figure 5. Coke oven at a smokeless fuel plant in Wales, United Kingdom

Coke is a solid carbonaceous residue derived from low-ash, low-sulfur bituminous coal from which the volatile constituents are driven off by baking in an oven without oxygen at temperatures as high as 1,000 °C (1,832 °F), so the fixed carbon and residual ash are fused together. Metallurgical coke is used as a fuel and as a reducing agent in smelting iron ore in a blast furnace. The result is pig iron, and is too rich in dissolved carbon, so it must be treated further to make steel. The coking coal should be low in sulfur and phosphorus, so they do not migrate to the metal. Based on the ash percentage, the coking coal can be divided into various grades. These grades are:

- Steel Grad—I (Not exceeding 15%)
- Steel Grade—II (Exceeding 15% but not exceeding 18%)
- Washery Grade—I (Exceeding 18% but not exceeding 21%)
- Washery Grade—II (Exceeding 21% but not exceeding 24%)
- Washery Grade—III (Exceeding 24% but not exceeding 28%)
- Washery Grade—IV (Exceeding 28% but not exceeding 35%)

The coke must be strong enough to resist the weight of overburden in the blast furnace, which is why coking coal is so important in making steel using the conventional route. However, the alternative route is direct reduced iron, where any carbonaceous fuel can be used to make sponge or pelletised iron. Coke from coal is grey, hard, and porous and has a heating value of 24.8 million Btu/ton (29.6 MJ/kg). Some cokemaking processes produce valuable byproducts, including coal tar, ammonia, light oils, and coal

gas.

Petroleum coke is the solid residue obtained in oil refining, which resembles coke, but contains too many impurities to be useful in metallurgical applications.

Gasification

Coal gasification can be used to produce syngas, a mixture of carbon monoxide (CO) and hydrogen (H_2) gas. Often syngas is used to fire gas turbines to produce electricity, but the versatility of syngas also allows it to be converted into transportation fuels, such as gasoline and diesel, through the Fischer-Tropsch process; alternatively, syngas can be converted into methanol, which can be blended into fuel directly or converted to gasoline via the methanol to gasoline process.[59]Gasification combined with Fischer-Tropsch technology is currently used by the Sasol chemical company of South Africa to make motor vehicle fuels from coal and natural gas. Alternatively, the hydrogen obtained from gasification can be used for various purposes, such as powering ahydrogen economy, making ammonia, or upgrading fossil fuels.

During gasification, the coal is mixed with oxygen and steam while also being heated and pressurized. During the reaction, oxygen and water molecules oxidize the coal into carbon monoxide (CO), while also releasing hydrogen gas (H_2). This process has been conducted in both underground coal mines and in the production of town gas.

C (*as Coal*) + O_2 + H_2O → H_2 + CO

If the refiner wants to produce gasoline, the syngas is collected at this state and routed into a Fischer-Tropsch reaction. If hydrogen is the desired end-product, however, the syngas is fed into thewater gas shift reaction, where more hydrogen is liberated.

CO + H_2O → CO_2 + H_2

In the past, coal was converted to make coal gas (town gas), which was piped to customers to burn for illumination, heating, and cooking.

Liquefaction

Coal can also be converted into synthetic fuels equivalent to gasoline or diesel by several different direct processes (which do not intrinsically require gasification or indirect conversion). In the direct liquefaction processes, the coal is either hydrogenated or carbonized. Hydrogenation processes are the Bergius process, the SRC-I and SRC-II (Solvent Refined Coal) processes, the NUS Corporation hydrogenation process and several other single-stage and two-stage processes. In the process of low-temperature carbonization, coal is coked at temperatures between 360 and 750 °C (680 and 1,380 °F). These temperatures optimize the production of coal tars richer in lighter hydrocarbons than normal coal tar. The coal tar is then further processed into fuels. An overview of coal liquefaction and its future potential is available.

Coal liquefaction methods involve carbon dioxide (CO_2) emissions in the conversion process. If coal liquefaction is done without employing either carbon capture and storage (CCS) technologies or biomass blending, the result is lifecycle greenhouse gas footprints that are generally greater than those released in the extraction and refinement of liquid fuel production from crude oil. If CCS technologies are employed, reductions of 5–12% can be achieved in Coal to Liquid (CTL) plants and up to a 75% reduction is achievable when co-gasifying coal with commercially demonstrated levels of biomass (30% biomass by weight) in coal/biomass-to-liquids plants. For future synthetic fuel projects, carbon dioxide sequestration is proposed to avoid releasing CO_2 into the atmosphere. Sequestration adds to the cost of production.

Refined Coal

Refined coal is the product of a coal-upgrading technology that removes moisture and certain pollutants from lower-rank coals such as sub-bituminous and lignite (brown) coals. It is one form of several precombustion treatments and processes for coal that alter coal's characteristics before it is burned. The goals of precombustion coal technologies are to increase efficiency and reduce emissions when the coal is burned. Depending on the situation, precombustion technology can be used in place of or as a supplement to postcombustion technologies to control emissions from coal-fueled boilers.

Industrial Processes

Finely ground bituminous coal, known in this application as sea coal, is a constituent of foundry sand. While the molten metal is in the mould, the coal burns slowly, releasing reducing gases at pressure, and so preventing the metal from penetrating the pores of the sand. It is also contained in "mould wash," a paste or liquid with the same function applied to the mould before casting. Sea coal can be mixed with the clay lining (the "bod") used for the bottom of a cupola furnace. When heated, the coal decomposes and the bod becomes slightly friable, easing the process of breaking open holes for tapping the molten metal.

Production of Chemicals

Coal is an important feedstock in production of a wide range of chemical fertilizers and other chemical products. The main route to these products is coal gasification to produce syngas. Primary chemicals that are produced directly from the syngas include methanol, hydrogen and carbon monoxide, which are the chemical building blocks from which a whole spectrum of derivative chemicals are manufactured, including olefins, acetic acid, formaldehyde, ammonia,urea and others. The versatility of syngas as a precursor to primary chemicals and high-value derivative products provides the option of using relatively inexpensive coal to produce a wide range of valuable commodities.

Historically, production of chemicals from coal has been used since the 1950s and has become established in the market. According to the 2010 Worldwide Gasification Database, a survey of current and planned gasifiers, from 2004 to 2007 chemical production increased its gasification product share from 37% to 45%. From 2008 to 2010, 22% of new gasifier additions were to be for chemical production.

Because the slate of chemical products that can be made via coal gasification can in general also use feedstocks derived from natural gas and petroleum, the chemical industry tends to use whatever feedstocks are most cost-effective. Therefore, interest in using coal tends to increase for higher oil and natural gas prices and during periods of high global economic growth that may strain oil and gas production. Also, production of chemicals from coal is of much higher interest in countries like South Africa, China, India and the United States where there are abundant coal resources. The abundance of coal combined with lack of natural gas resources in China is strong inducement for the coal to chemicals industry pursued there. In the United States, the best example of the industry is Eastman Chemical Company which has been successfully operating a coal-to-chemicals plant at its Kingsport, Tennessee, site since 1983. Similarly, Sasol has built and operated coal-to-chemicals facilities in South Africa.

Coal to chemical processes do require substantial quantities of water. As of 2013 much of the coal to chemical production was in the People's Republic of China where environmental regulation and water management was weak.

COAL AS A TRADED COMMODITY

In North America, Central Appalachian coal futures contracts are currently traded on the New York Mercantile Exchange (trading symbol *QL*). The trading unit is 1,550 short tons (1,410 t) per contract, and is quoted in U.S. dollars and cents per ton. Since coal is the principal fuel for generating electricity in the United States, coal futures contracts provide coal producers and the electric power industry an important tool for hedging and risk management.

In addition to the NYMEX contract, the IntercontinentalExchange (ICE) has European (Rotterdam) and South African (Richards Bay) coal futures available for trading. The trading unit for these contracts is 5,000 tonnes (5,500 short tons), and are also quoted in U.S. dollars and cents per ton.

The price of coal increased from around $30.00 per short ton in 2000 to around $150.00 per short ton as of September 2008. As of October 2008, the price per short ton had declined to $111.50. Prices further declined to $71.25 as of October 2010. In early 2015, it was trading near $56/ton.

ENVIRONMENTAL EFFECTS

A number of adverse health, and environmental effects of coal burning exist, especially in power stations, and of coal mining, including:

- Coal-fired power plants cause nearly 24,000 premature deaths annually in the United States, including 2,800 from lung cancer. Annual health costs in Europe from use of coal to generate electricity are €42.8 billion, or $55 billion.

- Generation of hundreds of millions of tons of waste products, including fly ash, bottom ash, and flue-gas desulfurization sludge, that contain mercury,uranium, thorium, arsenic, and other heavy metals
- Acid rain from high sulfur coal
- Interference with groundwater and water table levels due to mining
- Contamination of land and waterways and destruction of homes from fly ash spills, such as the Kingston Fossil Plant coal fly ash slurry spill
- Impact of water use on flows of rivers and consequential impact on other land uses
- Dust nuisance
- Subsidence above tunnels, sometimes damaging infrastructure
- Uncontrollable coal seam fire which may burn for decades or centuries
- Coal-fired power plants without effective fly ash capture systems are one of the largest sources of human-caused background radiation exposure.
- Coal-fired power plants emit mercury, selenium, and arsenic, which are harmful to human health and the environment.
- Release of carbon dioxide, a greenhouse gas, causes climate change and global warming, according to the IPCC and the EPA. Coal is the largest contributor to the human-made increase of CO_2 in the atmosphere.
- Approximately 75 Tg/S per year of sulfur dioxide (SO_2) is released from burning coal. After release, the sulfur dioxide is oxidized to gaseous H_2SO_2 which scatters solar radiation, hence its increase in the atmosphere exerts a cooling effect on climate that masks some of the warming caused by increased greenhouse gases. Release of SO_2 also contributes to the widespread acidification of ecosystems.

BIOREMEDIATION

The white rot fungus Trametes versicolor can grow on and metabolize naturally occurring coal. The bacteria Diplococcus has been found to degrade coal, raising its temperature.

ENERGY DENSITY AND CARBON IMPACT

The energy density of coal, i.e. its heating value, is roughly 24 megajoules per kilogram (approximately 6.7 kilowatt-hours per kg). For a coal power plant with a 40% efficiency, it takes an estimated 325 kg (717 lb) of coal to power a 100 W lightbulb for one year.

As of 2006, the average efficiency of electricity-generating power stations was 31%; in 2002, coal represented about 23% of total global energy supply, an equivalent of 3.4 billion tonnes of coal, of which 2.8 billion tonnes were used for electricity generation.

The US Energy Information Agency's 1999 report on CO_2 emissions for energy generation quotes an emission factor of 0.963 kg CO_2/kWh for coal power, compared to 0.881 kg CO_2/kWh (oil), or 0.569 kg CO_2/kWh (natural gas).

UNDERGROUND FIRES

Thousands of coal fires are burning around the world. Those burning underground can be difficult to locate and many cannot be extinguished. Fires can cause the ground above to subside, their combustion gases are dangerous to life, and breaking out to the surface can initiate surface wildfires. Coal seams can be set on fire by spontaneous combustion or contact with a mine fire or surface fire. Lightning strikes are an important source of ignition. The coal continues to burn slowly back into the seam until oxygen (air) can no longer reach the flame front. A grass fire in a coal area can set dozens of coal seams on fire. Coal fires in China burn an estimated 120 million tons of coal a year, emitting 360 million metric tons of CO_2, amounting to 2–3% of the annual worldwide production of CO_2 from fossil fuels. In Centralia, Pennsylvania (a borough located in the Coal Region of the United States), an exposed vein of anthracite ignited in 1962 due to a trash fire in the borough landfill, located in an abandoned anthracite strip mine pit. Attempts to extinguish the fire were unsuccessful, and it continues to burn underground to this day. TheAustralian Burning Mountain was originally believed to be a volcano, but the smoke and ash comes from a coal fire that has been burning for some 6,000 years.

At Kuh i Malik in Yagnob Valley, Tajikistan, coal deposits have been burning for thousands of years, creating vast underground labyrinths full of unique minerals, some of them very beautiful. Local people once used this method to mine ammoniac. This place has been well-known since the time of Herodotus, but European geographers misinterpreted the Ancient Greek descriptions as the evidence of active volcanism in Turkestan (up to the 19th century, when the Russian army invaded the area).

The reddish siltstone rock that caps many ridges and buttes in the Powder River Basin in Wyoming and in western North Dakota is called *porcelanite*, which resembles the coal burning waste “clinker” or volcanic “scoria.” Clinker is rock that has been fused by the natural burning of coal. In the Powder River Basin approximately 27 to 54 billion tons of coal burned within the past three million years. Wild coal fires in the area were reported by the Lewis and Clark Expedition as well as explorers and settlers in the area.

PRODUCTION TRENDS

In 2006, China was the top producer of coal with 38% share followed by the United States and India, according to the British Geological Survey. As of 2012 coal production in the United States was falling at the rate of 7% annually with many power plants using coal shut down or converted to natural gas; however, some of the reduced domestic demand was taken up by increased exports with five coal export terminals being proposed in the Pacific Northwest to export coal from the Powder River Basin to China and other Asian markets; however, as of 2013, environmental opposition was increasing. High-sulfur coal mined in Illinois which was unsaleable in the United States found a ready market in Asia as exports reached 13 million tons in 2012.

World Coal Reserves

The 948 billion short tons of recoverable coal reserves estimated by the Energy Information Administration are equal to about 4,196 BBOE (billion barrels of oil equivalent). The amount of coal burned during 2007 was estimated at 7.075 billion short tons, or 133.179 quadrillion BTU’s. This is an average of 18.8 million BTU per short ton. In terms of heat content, this is about 57,000,000 barrels (9,100,000 m^3) of oil equivalent per day. By comparison in 2007, natural gas provided 51,000,000 barrels (8,100,000 m^3) of oil equivalent per day, while oil provided 85,800,000 barrels (13,640,000 m^3) per day.

British Petroleum, in its 2007 report, estimated at 2006 end that there were 147 years reserves-to-production ratio based on *proven* coal reserves worldwide. This figure only includes reserves classified as “proven”; exploration drilling programs by mining companies, particularly in under-explored areas, are continually providing new reserves. In many cases, companies are aware of coal deposits that have not been sufficiently drilled to qualify as “proven.” However, some nations haven’t updated their information and assume reserves remain at the same levels even with withdrawals.



Figure 6. A coal mine in Wyoming, United States. The United States has the world’s largest coal reserves.

Of the three fossil fuels, coal has the most widely distributed reserves; coal is mined in over 100 countries, and on all continents except Antarctica. The largest reserves are found in the United States, Russia, China, Australia and India.

REFLECTION QUESTIONS

- What skill does this content help you develop?

- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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12.7: Extraction Methods

DESCRIBE SOME OF THE EXTRACTION METHODS AND HOW EXTRACTION IMPACTS SOCIETY AND OUR ENVIRONMENT

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Mining and Mineral Use
- Reading: Mining
- Reading: Open-Pit Mining

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12.8: Mining and Mineral Use

INTRODUCTION

Some minerals are very useful. An **ore** is a rock that contains minerals with useful elements. Aluminum in bauxite ore (figure 1) is extracted from the ground and refined to be used in aluminum foil and many other products. The cost of creating a product from a mineral depends on how abundant the mineral is and how much the extraction and refining processes cost. Environmental damage from these processes is often not figured into a product's cost. It is important to use mineral resources wisely.



Figure 1. Aluminum is made from the aluminum-bearing minerals in bauxite.

FINDING AND MINING MINERALS

Geologic processes create and concentrate minerals that are valuable natural resources. Geologists study geological formations and then test the physical and chemical properties of soil and rocks to locate possible ores and determine their size and concentration.

A mineral deposit will only be mined if it is profitable. A concentration of minerals is only called an **ore deposit** if it is profitable to mine. There are many ways to mine ores.

Surface Mining

Surface mining allows extraction of ores that are close to Earth's surface. Overlying rock is blasted and the rock that contains the valuable minerals is placed in a truck and taken to a refinery. As pictured in figure 2, surface mining includes open-pit mining and mountaintop removal. Other methods of surface mining include strip mining, placer mining, and dredging. Strip mining is like open pit mining but with material removed along a strip.

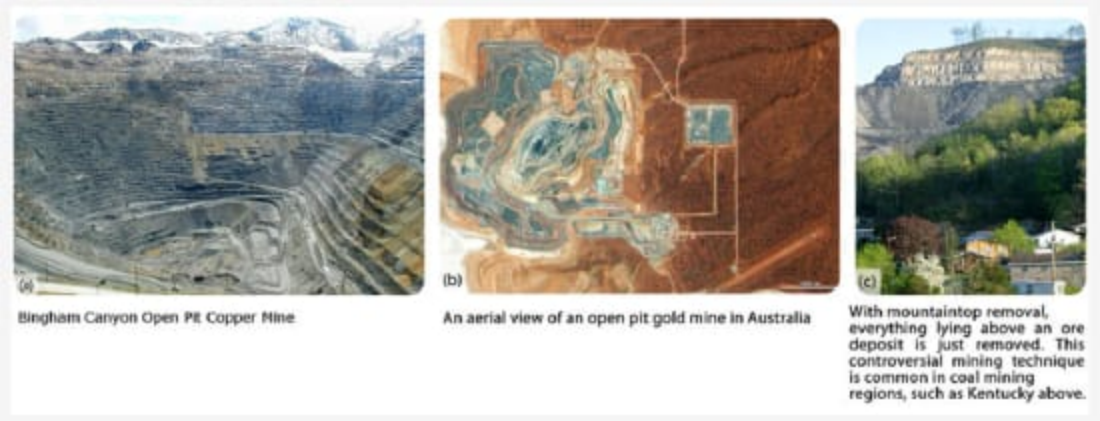


Figure 2. These different forms of surface mining are methods of extracting ores close to Earth's surface.

Placers are valuable minerals found in stream gravels. California's nickname, the Golden State, can be traced back to the discovery of placer deposits of gold in 1848. The gold weathered out of hard metamorphic rock in the western Sierra Nevada, which also contains deposits of copper, lead, zinc, silver, chromite, and other valuable minerals. The gold traveled down rivers and then settled in gravel deposits. Currently, California has active mines for gold and silver and for non-metal minerals such as sand and gravel, which are used for construction.

Underground Mining

Underground mining is used to recover ores that are deeper into Earth's surface. Miners blast and tunnel into rock to gain access to the ores. How underground mining is approached – from above, below, or sideways – depends on the placement of the ore body, its depth, concentration of ore, and the strength of the surrounding rock.

Underground mining is very expensive and dangerous. Fresh air and lights must also be brought into the tunnels for the miners, and accidents are far too common.

ORE EXTRACTION

The ore's journey to becoming a useable material is only just beginning when the ore leaves the mine (figure 3). Rocks are crushed so that the valuable minerals can be separated from the waste rock. Then the minerals are separated out of the ore. A few methods for extracting ore are:

- heap leaching: the addition of chemicals, such as cyanide or acid, to remove ore.
- flotation: the addition of a compound that attaches to the valuable mineral and floats.
- smelting: roasting rock, causing it to segregate into layers so the mineral can be extracted.

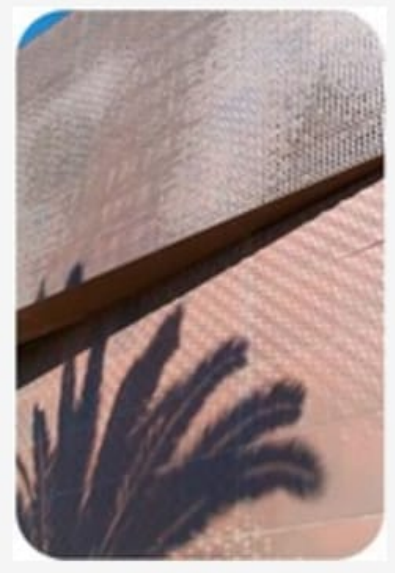


Figure 3. The de Young Museum in San Francisco is covered in copper panels. Copper is mined and extracted from copper ores.

To extract the metal from the ore, the rock is melted at a temperature greater than 900°C, which requires a lot of energy. Extracting metal from rock is so energy intensive that if you recycle just 40 aluminum cans, you will save the energy equivalent of one gallon of gasoline.

MINING AND THE ENVIRONMENT

Although mining provides people with many needed resources, the environmental costs can be high. Surface mining clears the landscape of trees and soil, and nearby streams and lakes are inundated with sediment. Pollutants from the mined rock, such as heavy metals, enter the sediment and water system. Acids flow from some mine sites, changing the composition of nearby waterways (figure 4).



Figure 4. Acid drainage from a surface coal mine in Missouri.

U.S. law has changed so that in recent decades a mine region must be restored to its natural state, a process called **reclamation**. This is not true of older mines. Pits may be refilled or reshaped and vegetation planted. Pits may be allowed to fill with water and become lakes or may be turned into landfills. Underground mines may be sealed off or left open as homes for bats.

VALUABLE MINERALS

Some minerals are valuable because they are beautiful. Jade has been used for thousands of years in China. Diamonds sparkle on many engagement rings. Minerals like jade, turquoise, diamonds, and emeralds are gemstones. A **gemstone**, or gem, is a material that is cut and polished for jewelry. Many gemstones, including many in figure 5, are minerals.



Figure 5. Gemstones come in many colors.

Gemstones are usually rare and do not break or scratch easily. Most are cut along cleavage faces and then polished so that light bounces back off the cleavage planes (figure 6). Light does not pass through gemstones that are opaque, such as turquoise.



Figure 6. Uncut (left) and cut (right) ruby. The cut and polished ruby sparkles.

Gemstones are not just used in jewelry. 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 such as sandpaper.

Minerals are used in much less obvious places. The mineral gypsum is used for the sheetrock in homes. Window glass is made from sand, which is mostly quartz. Halite is mined for rock salt. Copper is used in electrical wiring, and bauxite is the source for the aluminum used in soda cans.

LESSON SUMMARY

- Geologists use many methods to find mineral deposits that will be profitable to mine.
- Ore deposits can be mined by surface or underground mining methods.
- Mining provides important resources but has environmental costs.
- By U.S. law, currently mined land must undergo reclamation. This is not true for old mines.
- Metal 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.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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12.9: Mining

Mining is the extraction of valuable minerals or other geological materials from the earth from an orebody, lode, vein, seam, or reef, which forms the mineralized package of economic interest to the miner.



Figure 1. Surface coal mining

Ores recovered by mining include metals, coal, oil shale, gemstones, limestone, dimension stone, rock salt, potash, gravel, and clay. Mining is required to obtain any material that cannot be grown through agricultural processes, or created artificially in a laboratory or factory. Mining in a wider sense includes extraction of any non-renewable resource such as petroleum, natural gas, or even water.

Mining of stone and metal has been done since pre-historic times. Modern mining processes involve prospecting for ore bodies, analysis of the profit potential of a proposed mine, extraction of the desired materials, and final reclamation of the land after the mine is closed.

The nature of mining processes creates a potential negative impact on the environment both during the mining operations and for years after the mine is closed. This impact has led most of the world's nations to adopt regulations designed to moderate the negative effects of mining operations. Safety has long been a concern as well, and modern practices have improved safety in mines significantly.

HISTORY

Prehistoric Mining

Since the beginning of civilization, people have used stone, ceramics and, later, metals found close to the Earth's surface. These were used to make early tools and weapons; for example, high quality flint found in northern France and southern England was used to create flint tools. Flint mines have been found in chalk areas where seams of the stone were followed underground by shafts and galleries. The mines at Grimes Graves are especially famous, and like most other flint mines, are Neolithic in origin (ca 4000 BC-ca 3000 BC). Other hard rocks mined or collected for axes included the greenstone of the Langdale axe industry based in the English Lake District.



Figure 2. Chalcolithic copper mine in Timna Valley, Negev Desert

The oldest known mine on archaeological record is the “Lion Cave” in Swaziland, which radiocarbon dating shows to be about 43,000 years old. At this sitePaleolithic humans mined hematite to make the red pigment ochre. Mines of a similar age in Hungary are believed to be sites where Neanderthals may have mined flint for weapons and tools.

Ancient Egypt

Ancient Egyptians mined malachite at Maadi. At first, Egyptians used the bright green malachite stones for ornamentations and pottery. Later, between 2613 and 2494 BC, large building projects required expeditions abroad to the area of Wadi Maghara in order “to secure minerals and other resources not available in Egypt itself.” Quarries forturquoise and copper were also found at “Wadi Hamamat, Tura, Aswan and various other Nubian sites” on the Sinai Peninsula and at Timna.

Mining in Egypt occurred in the earliest dynasties. The gold mines of Nubia were among the largest and most extensive of any in Ancient Egypt, and are described by the Greek author Diodorus Siculus. He mentions that fire-setting was one method used to break down the hard rock holding the gold. One of the complexes is shown in one of the earliest known maps. The miners crushed the ore and ground it to a fine powder before washing the powder for the gold dust.

Ancient Greek and Roman Mining

Mining in Europe has a very long history. Examples include the silver mines of Laurium, which helped support the Greek city state of Athens. However, it is the Romans who developed large scale mining methods, especially the use of large volumes of water brought to the minehead by numerous aqueducts. The water was used for a variety of purposes, including removing overburden and rock debris, called hydraulic mining, as well as washing comminuted, or crushed, ores and driving simple machinery.

The Romans used hydraulic mining methods on a large scale to prospect for the veins of ore, especially a now obsolete form of mining known as hushing. It involved building numerous aqueducts to supply water to the minehead where it was stored in large reservoirs and tanks. When a full tank was opened, the wave of water sluiced away the overburden to expose the bedrock underneath and any gold veins. The rock was then attacked by fire-setting to heat the rock, which would be quenched with a stream of water. The thermal shock cracked the rock, enabling it to be removed, aided by further streams of water from the overhead tanks. The Roman miners used similar methods to work cassiterite deposits in Cornwall and lead ore in the Pennines.

The methods had been developed by the Romans in Spain in 25 AD to exploit large alluvial gold deposits, the largest site being at Las Medulas, where seven long aqueducts were built to tap local rivers and to sluice the deposits. Spain was one of the most important mining regions, but all regions of the Roman Empire were exploited. In Great Britain the natives had mined minerals for millennia, but when theRomans came, the scale of the operations changed dramatically.

The Romans needed what Britain possessed, especially gold, silver, tin, and lead. Roman techniques were not limited to surface mining. They followed the ore veins underground once opencast mining was no longer feasible. At Dolaucothi they stoped out the

veins, and drove aditsthrough barren rock to drain the stopes. The same adits were also used to ventilate the workings, especially important when fire-setting was used. At other parts of the site, they penetrated the water table and dewatered the mines using several kinds of machine, especially reverse overshot water-wheels. These were used extensively in the copper mines at Rio Tinto in Spain, where one sequence comprised 16 such wheels arranged in pairs, and lifting water about 80 feet (24 m). They were worked as treadmills with miners standing on the top slats. Many examples of such devices have been found in old Roman mines and some examples are now preserved in the British Museum and the National Museum of Wales.

Medieval Europe

Mining as an industry underwent dramatic changes in medieval Europe. The mining industry in the early Middle Ages was mainly focused on the extraction of copper and iron. Other precious metals were also used mainly for gilding or coinage. Initially, many metals were obtained through open-pit mining, and ore was primarily extracted from shallow depths, rather than though the digging of deep mine shafts. Around the 14th century, the demand for weapons, armour, stirrups, and horseshoes greatly increased the demand for iron. Medieval knights, for example, were often laden with up to 100 pounds of plate or chain link armour in addition to swords, lances and other weapons. The overwhelming dependency on iron for military purposes helped to spur increased iron production and extraction processes.

The silver crisis of 1465 occurred when the mines had all reached depths at which the shafts could no longer be pumped dry with the available technology. Although an increased use of bank notes and credit during this period did decrease the value of, and dependence on, precious metals, these forms of currency still remained vital to the story of medieval mining.

In the mid-sixteenth century the great attack on mineral deposits spread from central Europe to England. England had iron, zinc, copper, lead, and tin ores. On the continent all mineral deposits belonged to the crown, and this regalian right was stoutly maintained; but in England it was pared down to gold and silver (of which there was virtually none) by a judicial decision of 1568 and a law of 1688. Landlords therefore owned the base metals and coal under their estates and had a strong inducement to extract them or to lease the deposits and collect royalties from mine operators. English, German, and Dutch capital combined to finance extraction and refining. Hundreds of German technicians and skilled workers were brought over; in 1642 a colony of 4,000 foreigners was mining and smelting copper at Keswick in the northwestern mountains.

Use of water power in the form of water mills was extensive. The water mills were employed in crushing ore, raising ore from shafts, and ventilating galleries by powering giant bellows. Black powder was first used in mining in Selmecbánya, Kingdom of Hungary in 1627. Black powder allowed blasting of rock and earth to loosen and reveal ore veins. Blasting was much faster than fire-setting and allowed the mining of previously impenetrable metals and ores. In 1762, the world's first mining academy was established in the same town.

The widespread adoption of agricultural innovations such as the iron plowshare, as well as the growing use of metal as a building material, was also a driving force in the tremendous growth of the iron industry during this period. Inventions like the arrastra were often used by the Spanish to pulverize ore after being mined. This device was powered by animals and used the same principles used for grain threshing.

Much of the knowledge of medieval mining techniques comes from books such as Biringuccio's *De la pirotechnia* and probably most importantly from Georg Agricola's *De re metallica* (1556). These books detail many different mining methods used in German and Saxon mines. One of the prime issues confronting medieval miners (and one which Agricola explains in detail) was the removal of water from mining shafts. As miners dug deeper to access new veins, flooding became a very real obstacle. The mining industry became dramatically more efficient and prosperous with the invention of mechanical and animal driven pumps.

Classical Philippine Civilization

Mining in the Philippines began around 1000 BC. The early Filipinos worked various mines of gold, silver, copper and iron. Jewels, gold ingots, chains, calombigas and earrings were handed down from antiquity and inherited from their ancestors. Gold dagger handles, gold dishes, tooth plating, and huge gold ornamets were also used. In Laszlo Legeza's "Tantric elements in pre-Hispanic Philippines Gold Art", he mentioned that gold jewelry of Philippine origin was found in Ancient Egypt. According toAntonio Pigafetta, the people of Mindoro possessed great skill in mixing gold with other metals and gave it a natural and perfect appearance that could deceive even the best of silversmiths. The natives were also known for the jewelries made of other precious stones such as carnelian, agate and pearl. Some outstanding examples of Philippine jewelry included necklaces, belts, armlets and rings placed around the waist.

The Americas

There are ancient, prehistoric copper mines along Lake Superior, and metallic copper was still found there, near the surface, in colonial times. Indians availed themselves of this copper starting at least 5,000 years ago," and copper tools, arrowheads, and other artifacts that were part of an extensive native trade network have been discovered. In addition, obsidian, flint, and other minerals were mined, worked, and traded. Early French explorers who encountered the sites made no use of the metals due to the difficulties of transporting them, but the copper was eventually traded throughout the continent along major river routes. In Saskatchewan, Canada, there also are ancient quartz mines near Waddy Lake and surrounding regions.

In the early colonial history of the Americas, "native gold and silver was quickly expropriated and sent back to Spain in fleets of gold- and silver-laden galleons," the gold and silver mostly from mines in Central and South America. Turquoise dated at 700 A.D. was mined in pre-Columbian America; in the Cerillos Mining District in New Mexico, estimates are that "about 15,000 tons of rock had been removed from Mt. Chalchihuitl using stone tools before 1700."



Figure 3. Lead mining in the upper Mississippi River region of the U.S., 1865.

Mining in the United States became prevalent in the 19th century, and the General Mining Act of 1872 was passed to encourage mining of federal lands. As with the California Gold Rush in the mid-19th century, mining for minerals and precious metals, along with ranching, was a driving factor in the Westward Expansion to the Pacific coast. With the exploration of the West, mining camps were established and "expressed a distinctive spirit, an enduring legacy to the new nation;" Gold Rushers would experience the same problems as the Land Rushers of the transient West that preceded them. Aided by railroads, many traveled West for work opportunities in mining. Western cities such as Denver and Sacramento originated as mining towns.

As new areas were explored, it was usually the gold (placer and then load) and then silver that were taken first, with other metals often waiting for railroads or canals. Coarse gold dust and nuggets do not require smelting and are easy to identify and transport.

Modern Period

In the early 20th century, the gold and silver rush to the western United States also stimulated mining for base metals such as copper, lead, and iron as well as coal. Areas in modern Montana, Utah, Arizona, and later Alaska became predominate suppliers of copper to the world, which was increasingly demanding copper for electrical and households goods. Canada's mining industry grew more slowly than did the United States' due to limitations in transportation, capital, and U.S. competition; Ontario was the major producer of the early 20th century with nickel, copper, and gold.

Meanwhile, Australia experienced the Australian gold rushes and by the 1850s was producing 40% of the world's gold, followed by the establishment of large mines such as the Mount Morgan Mine, which ran for nearly a hundred years, Broken Hill ore deposit (one of the largest zinc-lead ore deposits), and the iron ore mines at Iron Knob. After declines in production, another boom in mining occurred in the 1960s. Now, in the early 21st century, Australia remains a major world mineral producer.

As the 21st century begins, a globalized mining industry of large multinational corporations has arisen. Peak minerals and environmental impacts have also become a concern. Different elements, particularly rare earth minerals, have begun to increase in demand as a result of new technologies.

MINE DEVELOPMENT AND LIFECYCLE

The process of mining from discovery of an ore body through extraction of minerals and finally to returning the land to its natural state consists of several distinct steps. The first is discovery of the ore body, which is carried out through prospecting or exploration to find and then define the extent, location and value of the ore body. This leads to a mathematical resource estimation to estimate the size and grade of the deposit.

This estimation is used to conduct a pre-feasibility study to determine the theoretical economics of the ore deposit. This identifies, early on, whether further investment in estimation and engineering studies is warranted and identifies key risks and areas for further work. The next step is to conduct a feasibility study to evaluate the financial viability, the technical and financial risks, and the robustness of the project.

This is when the mining company makes the decision whether to develop the mine or to walk away from the project. This includes mine planning to evaluate the economically recoverable portion of the deposit, the metallurgy and ore recoverability, marketability and payability of the ore concentrates, engineering concerns, milling and infrastructure costs, finance and equity requirements, and an analysis of the proposed mine from the initial excavation all the way through to reclamation. The proportion of a deposit that is economically recoverable is dependent on the enrichment factor of the ore in the area.

To gain access to the mineral deposit within an area it is often necessary to mine through or remove waste material which is not of immediate interest to the miner. The total movement of ore and waste constitutes the mining process. Often more waste than ore is mined during the life of a mine, depending on the nature and location of the ore body. Waste removal and placement is a major cost to the mining operator, so a detailed characterization of the waste material forms an essential part of the geological exploration program for a mining operation.

Once the analysis determines a given ore body is worth recovering, development begins to create access to the ore body. The mine buildings and processing plants are built, and any necessary equipment is obtained. The operation of the mine to recover the ore begins and continues as long as the company operating the mine finds it economical to do so. Once all the ore that the mine can produce profitably is recovered, reclamation begins to make the land used by the mine suitable for future use.

MINING TECHNIQUES

Mining techniques can be divided into two common excavation types: surface mining and sub-surface (underground) mining. Today, surface mining is much more common, and produces, for example, 85% of minerals (excluding petroleum and natural gas) in the United States, including 98% of metallic ores.

Targets are divided into two general categories of materials: *placer deposits*, consisting of valuable minerals contained within river gravels, beach sands, and other unconsolidated materials; and *lode deposits*, where valuable minerals are found in veins, in layers, or in mineral grains generally distributed throughout a mass of actual rock. Both types of ore deposit, placer or lode, are mined by both surface and underground methods.

Some mining, including much of the rare earth elements and uranium mining, is done by less-common methods, such as in-situ leaching: this technique involves digging neither at the surface nor underground. The extraction of target minerals by this technique requires that they be soluble, e.g., potash, potassium chloride, sodium chloride, sodium sulfate, which dissolve in water. Some minerals, such as copper minerals and uranium oxide, require acid or carbonate solutions to dissolve.

Surface Mining

Surface mining is done by removing (stripping) surface vegetation, dirt, and, if necessary, layers of bedrock in order to reach buried ore deposits. Techniques of surface mining include: open-pit mining, which is the recovery of materials from an open pit in the ground, quarrying or gathering building materials from an open-pit mine; strip mining, which consists of stripping surface layers off to reveal ore/seams underneath; and mountaintop removal, commonly associated with coal mining, which involves taking the top of a mountain off to reach ore deposits at depth. Most (but not all) placer deposits, because of their shallowly buried nature, are mined by surface methods. Finally, landfill mining involves sites where landfills are excavated and processed.



Figure 4. Garzweiler surface mine, Germany

Underground Mining

Sub-surface mining consists of digging tunnels or shafts into the earth to reach buried ore deposits. Ore, for processing, and waste rock, for disposal, are brought to the surface through the tunnels and shafts. Sub-surface mining can be classified by the type of access shafts used, the extraction method or the technique used to reach the mineral deposit. Drift mining utilizes horizontal access tunnels, slope mining uses diagonally sloping access shafts, and shaft mining utilizes vertical access shafts. Mining in hard and soft rock formations require different techniques.



Figure 5. Mantrip used for transporting miners within an underground mine

Other methods include shrinkage stope mining, which is mining upward, creating a sloping underground room, long wall mining, which is grinding a long ore surface underground, and room and pillar mining, which is removing ore from rooms while leaving pillars in place to support the roof of the room. Room and pillar mining often leads to retreat mining, in which supporting pillars are removed as miners retreat, allowing the room to cave in, thereby loosening more ore. Additional sub-surface mining methods include hard rock mining, which is mining of hard rock (igneous, metamorphic or sedimentary) materials, bore hole mining, drift and fill mining, long hole slope mining, sub level caving, and block caving.

MACHINES

Heavy machinery is used in mining to explore and develop sites, to remove and stockpile overburden, to break and remove rocks of various hardness and toughness, to process the ore, and to carry out reclamation projects after the mine is closed. Bulldozers, drills, explosives and trucks are all necessary for excavating the land. In the case of placer mining, unconsolidated gravel, or alluvium, is fed into machinery consisting of a hopper and a shaking screen or trommel which frees the desired minerals from the waste gravel. The minerals are then concentrated using sluices or jigs.

Large drills are used to sink shafts, excavate stopes, and obtain samples for analysis. Trams are used to transport miners, minerals and waste. Lifts carry miners into and out of mines, and move rock and ore out, and machinery in and out, of underground mines. Huge trucks, shovels and cranes are employed in surface mining to move large quantities of overburden and ore. Processing plants utilize large crushers, mills, reactors, roasters and other equipment to consolidate the mineral-rich material and extract the desired compounds and metals from the ore.



Figure 6. The Bagger 288 is a bucket-wheel excavator used in strip mining. It is also the largest land vehicle of all time.

PROCESSING

Once the mineral is extracted, it is often then processed. The science of extractive metallurgy is a specialized area in the science of metallurgy that studies the extraction of valuable metals from their ores, especially through chemical or mechanical means.

Mineral processing (or mineral dressing) is a specialized area in the science of metallurgy that studies the mechanical means of crushing, grinding, and washing that enable the separation (extractive metallurgy) of valuable metals or minerals from their gangue (waste material). Processing of placer ore material consists of gravity-dependent methods of separation, such as sluice boxes. Only minor shaking or washing may be necessary to disaggregate (unclump) the sands or gravels before processing. Processing of ore from a lode mine, whether it is a surface or subsurface mine, requires that the rock ore be crushed and pulverized before extraction of the valuable minerals begins. After lode ore is crushed, recovery of the valuable minerals is done by one, or a combination of several, mechanical and chemical techniques.

Since most metals are present in ores as oxides or sulfides, the metal needs to be reduced to its metallic form. This can be accomplished through chemical means such as smelting or through electrolytic reduction, as in the case of aluminium. Geometallurgy combines the geologic sciences with extractive metallurgy and mining.

ENVIRONMENTAL EFFECTS

Environmental issues can include erosion, formation of sinkholes, loss of biodiversity, and contamination of soil, groundwater and surface water by chemicals from mining processes. In some cases, additional forest logging is done in the vicinity of mines to create space for the storage of the created debris and soil. Contamination resulting from leakage of chemicals can also affect the health of the local population if not properly controlled. Extreme examples of pollution from mining activities include coal fires, which can last for years or even decades, producing massive amounts of environmental damage.

Mining companies in most countries are required to follow stringent environmental and rehabilitation codes in order to minimize environmental impact and avoid impacting human health. These codes and regulations all require the common steps of environmental impact assessment, development of environmental management plans, mine closure planning (which must be done before the start of mining operations), and environmental monitoring during operation and after closure. However, in some areas, particularly in the developing world, government regulations may not be well enforced.

For major mining companies and any company seeking international financing, there are a number of other mechanisms to enforce good environmental standards. These generally relate to financing standards such as the Equator Principles, IFC environmental standards, and criteria for Socially responsible investing. Mining companies have used this oversight from the financial sector to argue for some level of self-policing. In 1992, a Draft Code of Conduct for Transnational Corporations was proposed at the Rio Earth Summit by the UN Centre for Transnational Corporations (UNCTC), but the Business Council for Sustainable Development (BCSD) together with the International Chamber of Commerce (ICC) argued successfully for self-regulation instead.

This was followed by the Global Mining Initiative which was begun by nine of the largest metals and mining companies and which led to the formation of theInternational Council on Mining and Metals, whose purpose was to “act as a catalyst” in an effort to improve social and environmental performance in the mining and metals industry internationally. The mining industry has provided funding to various conservation groups, some of which have been working with conservation agendas that are at odds with an emerging acceptance of the rights of indigenous people—particularly the right to make land-use decisions.

Certification of mines with good practices occurs through the International Organization for Standardization (ISO). For example, ISO 9000 and ISO 14001, which certify an "auditable environmental management system," involve short inspections, although they have been accused of lacking rigor. Certification is also available through Ceres' Global Reporting Initiative, but these reports are voluntary and unverified. Miscellaneous other certification programs exist for various projects, typically through nonprofit groups.

The purpose of a 2012 EPS PEAKS paper was to provide evidence on policies managing ecological costs and maximize socio-economic benefits of mining using host country regulatory initiatives. It found existing literature suggesting donors encourage developing countries to:

- Make the environment-poverty link and introduce cutting-edge wealth measures and natural capital accounts.
- Reform old taxes in line with more recent financial innovation, engage directly with the companies, enacting land use and impact assessments, and incorporate specialized support and standards agencies.
- Set in play transparency and community participation initiatives using the wealth accrued.

Waste

Ore mills generate large amounts of waste, called tailings. For example, 99 tons of waste are generated per ton of copper, with even higher ratios in gold mining. These tailings can be toxic. Tailings, which are usually produced as a slurry, are most commonly dumped into ponds made from naturally existing valleys. These ponds are secured by impoundments (dams or embankment dams). In 2000 it was estimated that 3,500 tailings impoundments existed, and that every year, 2 to 5 major failures and 35 minor failures occurred; for example, in the Marcopper mining disaster at least 2 million tons of tailings were released into a local river. Subaqueous tailings disposal is another option. The mining industry has argued that submarine tailings disposal (STD), which disposes of tailings in the sea, is ideal because it avoids the risks of tailings ponds; although the practice is illegal in the United States and Canada, it is used in the developing world.

The waste is classified as either sterile or mineralised, with acid generating potential, and the movement and storage of this material forms a major part of the mine planning process. When the mineralised package is determined by an economic cut-off, the near-grade mineralised waste is usually dumped separately with view to later treatment should market conditions change and it becomes economically viable. Civil engineering design parameters are used in the design of the waste dumps, and special conditions apply to high-rainfall areas and to seismically active areas. Waste dump designs must meet all regulatory requirements of the country in whose jurisdiction the mine is located. It is also common practice to rehabilitate dumps to an internationally acceptable standard, which in some cases means that higher standards than the local regulatory standard are applied.

MINING INDUSTRY

Mining exists in many countries. London is known as the capital of global "mining houses" such as Rio Tinto Group, BHP Billiton, and Anglo American PLC. The US mining industry is also large, but it is dominated by the coal and other nonmetal minerals (e.g., rock and sand), and various regulations have worked to reduce the significance of mining in the United States. In 2007 the totalmarket capitalization of mining companies was reported at US$962 billion, which compares to a total global market cap of publicly traded companies of about US$50 trillion in 2007. In 2002, Chile and Peru were reportedly the major mining countries of South America. The mineral industry of Africa includes the mining of various minerals; it produces relatively little of the industrial metals copper, lead, and zinc, but according to one estimate has as a percent of world reserves 40% of gold, 60% of cobalt, and 90% of the world's platinum group metals. Mining in India is a significant part of that country's economy. In the developed world, mining in Australia, with BHP Billiton founded and headquartered in the country, and mining in Canada are particularly significant. For rare earth minerals mining, China reportedly controlled 95% of production in 2013.

While exploration and mining can be conducted by individual entrepreneurs or small businesses, most modern-day mines are large enterprises requiring large amounts of capital to establish. Consequently, the mining sector of the industry is dominated by large, often multinational, companies, most of them publicly listed. It can be argued that what is referred to as the 'mining industry' is actually two sectors, one specializing in exploration for new resources and the other in mining those resources. The exploration sector is typically made up of individuals and small mineral resource companies, called "juniors", which are dependent on venture capital. The mining sector is made up of large multinational companies that are sustained by production from their mining operations. Various other industries such as equipment manufacture, environmental testing, and metallurgy analysis rely on, and support, the mining industry throughout the world. Canadian stock exchanges have a particular focus on mining companies, particularly junior exploration companies through Toronto's TSX Venture Exchange; Canadian companies raise capital on these exchanges and then invest the money in exploration globally. Some have argued that below juniors there exists

a substantial sector of illegitimate companies primarily focused on manipulating stock prices.

Mining operations can be grouped into five major categories in terms of their respective resources. These are oil and gas extraction, coal mining, metal ore mining, nonmetallic mineral mining and quarrying, and mining support activities. Of all of these categories, oil and gas extraction remains one of the largest in terms of its global economic importance. Prospecting potential mining sites, a vital area of concern for the mining industry, is now done using sophisticated new technologies such as seismic prospecting and remote-sensing satellites. Mining is heavily affected by the prices of the commodity minerals, which are often volatile. The 2000s commodities boom ("commodities supercycle") increased the prices of commodities, driving aggressive mining. In addition, the price of gold increased dramatically in the 2000s, which increased gold mining; for example, one study found that conversion of forest in the Amazon increased six-fold from the period 2003–2006 (292 ha/yr) to the period 2006–2009 (1,915 ha/yr), largely due to artisanal mining.

Corporate Classifications

Mining companies can be classified based on their size and financial capabilities:

- Major companies are considered to have an adjusted annual mining-related revenue of more than US$500 million, with the financial capability to develop a major mine on its own.
- Intermediate companies have at least $50 million in annual revenue but less than $500 million.
- **Junior** companies rely on equity financing as their principal means of funding exploration. Juniors are mainly pure exploration companies, but may also produce minimally, and do not have a revenue exceeding US$50 million.

Regulation and Governance

New regulation and process of legislative reforms aims to enrich the harmonization and stability of the mining sector in mineral-rich countries. The new legislation for mining industry in the African countries still appears as an emerging issue with a potential to be solved, until a consensus is reached on the best approach. By the beginning of 20th century the booming and more complex mining sector in mineral-rich countries provided only slight benefits to local communities in terms of sustainability. Increasing debates and influence by NGOs and communities appealed for a new program which would have had also included a disadvantaged communities, and would have had worked towards sustainable development even after mine closure (included transparency and revenue management). By the early 2000s, community development issues and resettlements became mainstreamed in Bank mining projects. Mining-industry expansion after an increase of mineral prices in 2003 and also potential fiscal revenues in those countries created an omission in the other economic sectors in terms of finances and development. Furthermore, it had highlighted regional and local demand of mining-revenues and lack of ability of sub-national governments to use the revenues. The Fraser Institute (a Canadian think tank) has highlighted the environmental protection laws in developing countries, as well as the voluntary efforts by mining companies to improve their environmental impact.

In 2007 the Extractive Industries Transparency Initiative (EITI) was mainstreamed in all countries cooperating with the World Bank in mining industry reform. The EITI is operating and implementing with a support of EITI Multi-Donor Trust Fund, managed by The World Bank. The Extractive Industries Transparency Initiative (EITI) aims to increase transparency in transactions between governments and companies within extractive industries by monitoring the revenues and benefits between industries and recipient governments. The entrance process is voluntary for each country and is being monitored by multi-stakeholders involving government, private companies and civil society representatives, responsible for disclosure and dissemination of the reconciliation report; however, the competitive disadvantage of company-by company public report is for some of the businesses in Ghana, the main constraint. Therefore, the outcome assessment in terms of failure or success of the new EITI regulation does not only "rest on the government's shoulders" but also on civil society and companies.

On the other hand, criticism points out two main implementation issues; inclusion or exclusion of artisanal mining and small-scale mining (ASM) from the EITI and how to deal with "non-cash" payments made by companies to subnational governments. Furthermore, disproportion of the revenues mining industry creates to the comparatively small number of people that it employs, causes another controversy. The issue of artisanal mining is clearly an issue in EITI Countries such as the Central African Republic, D.R. Congo, Guinea, Liberia and Sierra Leone – i.e. almost half of the mining countries implementing the EITI. Among other things, limited scope of the EITI involving disparity in terms of knowledge of the industry and negotiation skills, thus far flexibility of the policy (e.g. liberty of the countries to expand beyond the minimum requirements and adapt it to their needs), creates another risk of unsuccessful implementation. Public awareness increase, where government should act as a bridge between public and initiative for a successful outcome of the policy is an important element to be considered.

World Bank

The World Bank has been involved in mining since 1955, mainly through grants from its International Bank for Reconstruction and Development, with the Bank's Multilateral Investment Guarantee Agency offering political risk insurance. Between 1955 and 1990 it provided about $2 billion to fifty mining projects, broadly categorized as reform and rehabilitation, greenfield mine construction, mineral processing, technical assistance, and engineering. These projects have been criticized, particularly the Ferro Carajas project of Brazil, begun in 1981. The World Bank established mining codes intended to increase foreign investment; in 1988 it solicited feedback from 45 mining companies on how to increase their involvement.

In 1992 the World Bank began to push for privatization of government-owned mining companies with a new set of codes, beginning with its report *The Strategy for African Mining*. In 1997, Latin America's largest miner Companhia Vale do Rio Doce (CVRD) was privatized. These and other developments such as the Philippines 1995 Mining Act led the bank to publish a third report (*Assistance for Minerals Sector Development and Reform in Member Countries*) which endorsed mandatory environment impact assessments and attention to the concerns of the local population. The codes based on this report are influential in the legislation of developing nations. The new codes are intended to encourage development through tax holidays, zero custom duties, reduced income taxes, and related measures. The results of these codes were analyzed by a group from the University of Quebec, which concluded that the codes promote foreign investment but "fall very short of permitting sustainable development." The observed negative correlation between natural resources and economic development is known as the resource curse.

SAFETY

Safety has long been a concern in the mining business especially in sub-surface mining. The Courrières mine disaster, Europe's worst mining accident, involved the death of 1,099 miners in Northern France on March 10, 1906. This disaster was surpassed only by the Benxihu Colliery accident in China on April 26, 1942, which killed 1,549 miners. While mining today is substantially safer than it was in previous decades, mining accidents still occur. Government figures indicate that 5,000 Chinese miners die in accidents each year, while other reports have suggested a figure as high as 20,000. Mining accidents continue worldwide, including accidents causing dozens of fatalities at a time such as the 2007 Ulyanovskaya Mine disaster in Russia, the 2009 Heilongjiang mine explosion in China, and the 2010 Upper Big Branch Mine disaster in the United States.

Mining ventilation is a significant safety concern for many miners. Poor ventilation inside sub-surface mines causes exposure to harmful gases, heat, and dust, which can cause illness, injury, and death. The concentration of methane and other airborne contaminants underground can generally be controlled by dilution (ventilation), capture before entering the host air stream (methane drainage), or isolation (seals and stoppings). Rock dusts, including coal dust and silicon dust, can cause long-term lung problems including silicosis, asbestosis, and pneumoconiosis (also known as miners lung or black lungdisease). A ventilation system is set up to force a stream of air through the working areas of the mine. The air circulation necessary for effective ventilation of a mine is generated by one or more large mine fans, usually located above ground. Air flows in one direction only, making circuits through the mine such that each main work area constantly receives a supply of fresh air. Watering down in coal mines also helps to keep dust levels down: by spraying the machine with water and filtering the dust-laden water with a scrubber fan, miners can successfully trap the dust.

Gases in mines can poison the workers or displace the oxygen in the mine, causing asphyxiation. For this reason, the U.S. Mine Safety and Health Administration requires that groups of miners in the United States carry gas detection equipment that can detect common gases, such as CO, O_2, H_2S, CH_4, as well as calculate % Lower Explosive Limit. Regulation requires that all production stop if there is a concentration of 1.4% of flammable gas present. Additionally, further regulation is being requested for more gas detection as newer technology such as nanotechnology is introduced.

Ignited methane gas is a common source of explosions in coal mines, which in turn can initiate more extensive coal dust explosions. For this reason, rock dusts such as limestone dust are spread throughout coal mines to diminish the chances of coal dust explosions as well as to limit the extent of potential explosions, in a process known as rock dusting. Coal dust explosions can also begin independently of methane gas explosions. Frictional heat and sparks generated by mining equipment can ignite both methane gas and coal dust. For this reason, water is often used to cool rock-cutting sites.

Miners utilize equipment strong enough to break through extremely hard layers of the Earth's crust. This equipment, combined with the closed work space in which underground miners work, can cause hearing loss. For example, a roof bolter (commonly used by mine roof bolter operators) can reach sound power levels of up to 115 dB. Combined with the reverberant effects of underground mines, a miner without proper hearing protection is at a high risk forhearing loss. By age 50, nearly 90% of U.S. coal miners have some hearing loss, compared to only 10% among workers not exposed to loud noises. Roof bolters are among

the loudest machines, but auger miners, bulldozers, continuous mining machines, front end loaders, and shuttle cars and trucks are also among those machines most responsible for excessive noise in mine work.

Since mining entails removing dirt and rock from its natural location, thereby creating large empty pits, rooms, and tunnels, cave-ins as well as ground and rock falls are a major concern within mines. Modern techniques for timbering and bracing walls and ceilings within sub-surface mines have reduced the number of fatalities due to cave-ins, but ground falls continue to represent up to 50% of mining fatalities. Even in cases where mine collapses are not instantly fatal, they can trap mine workers deep underground. Cases such as these often lead to high-profile rescue efforts, such as when 33 Chilean miners were trapped deep underground for 69 days in 2010.

High temperatures and humidity may result in heat-related illnesses, including heat stroke, which can be fatal. The presence of heavy equipment in confined spaces also poses a risk to miners. To improve the safety of mine workers, modern mines use automation and remote operation including, for example, such equipment as automated loaders and remotely operated rockbreakers. However, despite modern improvements to safety practices, mining remains a dangerous occupation throughout the world.

Abandoned Mines

There are upwards of 560,000 abandoned mines on public and privately owned lands in the United States alone. Abandoned mines may be dangerous to anyone who attempts to explore them without proper knowledge and safety training.



Figure 7. Warning sign near a dangerous area filled with open mineshafts, Calico Ghost Town, California.

RECORDS

As of 2008, the deepest mine in the world is TauTona in Carletonville, South Africa at 3.9 kilometers (2.4 mi), replacing the neighboring Savuka Mine in the North West Province of South Africa at 3,774 meters (12,382 ft). East Rand Mine in Boksburg, South Africa briefly held the record at 3,585 meters (11,762 ft), and the first mine declared the deepest in the world was also TauTona when it was at 3,581 meters (11,749 ft).

The Moab Khutsong gold mine in North West Province (South Africa) has the world's longest winding steel wire rope, able to lower workers to 3,054 meters (10,020 ft) in one uninterrupted four-minute journey.

The deepest mine in Europe is the 16th shaft of the uranium mines in Příbram, Czech Republic at 1,838 meters (6,030 ft), second is Bergwerk Saar in Saarland, Germany at 1,750 meters (5,740 ft).

The deepest open-pit mine in the world is Bingham Canyon Mine in Bingham Canyon, Utah, United States at over 1,200 meters (3,900 ft). The largest and second deepest open-pit copper mine in the world is Chuquicamata in Chuquicamata, Chile at 900

meters (3,000 ft), 940,600 tons of copper and 17,700 tons of molybdenum produced annually.



Figure 8. Chuquicamata, Chile, site of the largest circumference and second deepest open pit copper mine in the world.

The deepest open-pit mine with respect to sea level is Tagebau Hambach in Germany, where the base of the pit is 293 meters (961 ft) below sea level.

The largest underground mine is Kiirunavaara Mine in Kiruna, Sweden. With 450 kilometers (280 mi) of roads, 40 million tonnes of ore produced yearly, and a depth of 1,270 meters (4,170 ft), it is also one of the most modern underground mines. The deepest borehole in the world is Kola Superdeep Borehole at 12,262 meters (40,230 ft). This, however, is not a matter of mining but rather related to scientific drilling.

METAL RESERVES AND RECYCLING

During the twentieth century, the variety of metals used in society grew rapidly. Today, the development of major nations such as China and India and advances in technologies are fueling an ever greater demand. The result is that metal mining activities are expanding and more and more of the world's metal stocks are above ground in use rather than below ground as unused reserves. An example is the in-use stock of copper. Between 1932 and 1999, copper in use in the USA rose from 73 kilograms (161 lb) to 238 kilograms (525 lb) per person.

95% of the energy used to make aluminum from bauxite ore is saved by using recycled material. However, levels of metals recycling are generally low. In 2010, the International Resource Panel, hosted by the United Nations Environment Programme (UNEP), published reports on metal stocks that exist within society and their recycling rates.

The report's authors observed that the metal stocks in society can serve as huge mines above ground. However, they warned that the recycling rates of some rare metals used in applications such as mobile phones, battery packs for hybrid cars, and fuel cells are so low that unless future end-of-life recycling rates are dramatically stepped up these critical metals will become unavailable for use in modern technology.

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
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12.10: Open-Pit Mining

Open-pit mining, or **open-cast mining** is a surface mining technique of extracting rock or minerals from the earth by their removal from an open pit or borrow.

This form of mining differs from extractive methods that require tunneling into the earth, such as long wall mining. Open-pit mines are used when deposits of commercially useful minerals or rocks are found near the surface; that is, where the overburden (surface material covering the valuable deposit) is relatively thin or the material of interest is structurally unsuitable for tunneling (as would be the case for sand, cinder, and gravel). For minerals that occur deep below the surface—where the overburden is thick or the mineral occurs as veins in hard rock—underground mining methods extract the valued material.

Open-pit mines that produce building materials and dimension stone are commonly referred to as “quarries.”

Open-pit mines are typically enlarged until either the mineral resource is exhausted, or an increasing ratio of overburden to ore makes further mining uneconomic. When this occurs, the exhausted mines are sometimes converted to landfills for disposal of solid wastes. However, some form of water control is usually required to keep the mine pit from becoming a lake, if the mine is situated in a climate of considerableprecipitation or if any layers of the pit forming the mine border productive aquifers.

EXTRACTION

Open-cast mines are dug on benches, which describe vertical levels of the hole. These benches are usually on four to sixty meter intervals, depending on the size of the machinery that is being used. Many quarries do not use benches, as they are usually shallow.



Figure 1. Note the angled and stepped sides of the Sunrise Dam Gold Mine, Australia.

Most walls of the pit are generally dug on an angle less than vertical, to prevent and minimize damage and danger from rock falls. This depends on how weathered the rocks are, and the type of rock, and also how many structural weaknesses occur within the rocks, such as a faults, shears, joints orfoliations.

The walls are stepped. The inclined section of the wall is known as the batter, and the flat part of the step is known as the bench or berm. The steps in the walls help prevent rock falls continuing down the entire face of the wall. In some instances additional ground support is required and rock bolts, cable bolts and shotcrete are used. De-watering bores may be used to relieve water pressure by drilling horizontally into the wall, which is often enough to cause failures in the wall by itself.

A haul road is usually situated at the side of the pit, forming a ramp up which trucks can drive, carrying ore and waste rock.

Waste rock is piled up at the surface, near the edge of the open pit. This is known as the waste dump. The waste dump is also tiered and stepped, to minimize degradation.

Ore which has been processed is known as tailings, and is generally a slurry. This is pumped to a tailings dam or settling pond, where the water evaporates. Tailings dams can often be toxic due to the presence of unextracted sulfide minerals, some forms of toxic minerals in the gangue, and often cyanide which is used to treat gold ore via the cyanide leach process. This toxicity can harm the surrounding environment.

REHABILITATION

After mining finishes, the mine area must undergo rehabilitation. Waste dumps are contoured to flatten them out, to further stabilise them. If the ore contains sulfides it is usually covered with a layer of clay to prevent access of rain and oxygen from the air, which can oxidise the sulfides to produce sulfuric acid, a phenomenon known as acid mine drainage. This is then generally covered with soil, and vegetation is planted to help consolidate the material. Eventually this layer will erode, but it is generally hoped that the rate of leaching or acid will be slowed by the cover such that the environment can handle the load of acid and associated heavy metals. There are no long term studies on the success of these covers due to the relatively short time in which large scale open pit mining has existed. It may take hundreds to thousands of years for some waste dumps to become “acid neutral” and stop leaching to the environment. The dumps are usually fenced off to prevent livestock denuding them of vegetation. The open pit is then surrounded with afence, to prevent access, and it generally eventually fills up with ground water. In arid areas it may not fill due to deep groundwater levels.



Figure 2. Opencut coal mine loadout station and reclaimed land at the North Antelope Rochelle coal mine in Wyoming, United States.



Figure 3. An open-pit sulfur mine at Tarnobrzeg, Poland undergoing land rehabilitation

TYPICAL OPEN CUT GRADES

Gold is generally extracted in open-pit mines at 1 to 2 ppm (parts per million) but in certain cases, 0.75 ppm gold is economical. This was achieved by bulk heap leaching at the Peak Hill mine in western New South Wales, near Dubbo, Australia.

Nickel, generally as laterite, is extracted via open-pit down to 0.2%. Copper is extracted at grades as low as 0.15% to 0.2%, generally in massive open-pit mines in Chile, where the size of the resources and favorable metallurgy allows economies of scale.

Materials typically extracted from open-pit mines include:

- Bitumen
- Clay
- Coal
- Copper
- Coquina
- Diamonds
- Gravel and stone (stone refers to bedrock, while gravel is unconsolidated material)
- Granite
- Gritstone
- Gypsum
- Limestone
- Marble
- Metal ores, such as Copper, Iron, Gold, Silver and Molybdenum
- Uranium
- Phosphate

REFLECTION QUESTIONS

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12.11: Geologic Materials as Energy Sources

DESCRIBE GEOLOGIC MATERIALS AS CURRENT OR POTENTIAL ENERGY RESOURCES AND CATEGORIZE SOURCES AS RENEWABLE OR NONRENEWABLE

[Insert brief introductory statement here.]

Open Educational Resources

The outcome for this section will be covered by several Open Educational Resources. Review and reflect on each one as you prepare to complete the assessment for this module.

- Reading: Earth's Energy
- Reading: Use and Conservation of Resources

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12.12: Earth's Energy

Much of Earth's energy comes from the Sun. Nearly all life on Earth depends on solar energy since plants use sunlight to make food through the process of photosynthesis. Photosynthesis was the process that fed plants and animals, which in turn, over the course of millions of years, became fossil fuels. The Sun heats some areas of Earth more than other areas, which causes wind. The Sun's energy also drives the water cycle, which moves water over the surface of the Earth. Some of these types of energy can be harnessed for use by people.

The other main source of energy is Earth's internal heat. This heat has two origins: the breakdown of chemical elements by radioactivity, and the heat that is left over from when the planet came together. These two sources will be described in more detail in later chapters.

ENERGY RESOURCES

Everything requires energy. Even when you are sitting as still as you possibly can, your body is using energy to breathe, circulate blood, digest food, and perform many other functions. Producing light or heat requires energy. Making something requires energy. Plants and animals all require energy to function. To repeat, everything requires energy!

The Need for Energy

Energy is the ability to do work or produce change. Every living thing needs energy to perform its daily functions and even more energy to grow. Plants get energy from the "food" they make by photosynthesis, and animals get energy directly or indirectly from that food. People also use energy for many things, such as cooking food, keeping ice cream cold in the freezer, heating a house, constructing a skyscraper, or lighting their homes. Because billions of people all around the world use energy, there is a huge need for energy resources (figure 1). Energy conservation is something everyone can do now to help reduce the strain on energy resources.



Figure 1. Electrical transmission towers like the one shown in this picture help deliver the electricity people use for energy every day.

The **law of conservation of energy** says that energy cannot be created or destroyed. This means that even though energy changes form, the total amount of energy always stays the same. How does energy get converted from one type to another when you kick a soccer ball? When your body breaks down the food you eat, it stores the energy from the food as **chemical energy**. Chemical energy is stored within chemical bonds. But some of this stored energy has to be released to make your leg muscles move. The chemical energy is converted to another form of energy 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 from the kick. So you can think

of the action of kicking the ball as a story of energy changing forms.

To learn the quadratic equations related to getting a rapidly moving car to overcome its kinetic energy and come to a stop, watch this video:

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

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. If a ball is sitting on the very edge at the top of the hill, it is not moving, but it has a lot of potential energy.

Animations showing the conversion of potential energy to kinetic energy can be seen at the following sites:

- Energy Transformation for Downhill Skiing
- Energy Transformation on a Roller Coaster
- Energy Transformation for a Dart

Energy, Fuel, and Heat

If you read a book beneath a lit lamp, that lamp has energy from electricity. The energy to make the electricity comes from **fuel.** Fuel has energy that it releases. A fuel is any material that can release energy in a chemical change.

What are some examples of fuel, and what are they used for?

1. Food is fuel for your body.
2. Sunlight is the energy plants need to make food by photosynthesis.
3. Gasoline is fuel for cars.
4. Hydrogen is fuel for the Sun.

For a fuel to be useful, its energy must be released in a way that can be controlled. Controlling the release of energy makes it possible for the energy to be used to do work. When fuel is used for its energy, it is usually burned, and most of the energy is released as **heat** (figure 2). The heat may then be used to do work. Think of a person striking a match to set some small twigs on fire. After the twigs burn 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. Pretty soon the fire is roaring, and a pot of water placed on the fire starts to boil. Some of the liquid water evaporates.



Figure 2. A controlled fire.

What is the source of energy for boiling and evaporating the water? Although some chemical energy from the match was put into starting the fire, the heat to boil and evaporate the water comes from the energy that was stored in the wood. The wood is the fuel for the fire.

Types of Energy Resources

Energy resources are either renewable or non-renewable. **Non-renewable resources** are used faster than they can be replaced,so the supply available to society is limited (see example in figure 3). **Renewable resources** will not run out because they are replaced as quickly as they are used. Can you think of some renewable and non-renewable energy sources?



Figure 3. Anthracite coal is a non-renewable energy resource.

Non-Renewable Resources

Fossil fuels—coal, oil, and natural gas—are the most common example of non-renewable energy resources. Fossil fuels are formed from fossils, the partially decomposed remains of once living plants and animals. These fossils took millions of years to form. When fossil fuels are burned for energy, they release pollutants into the atmosphere. Fossil fuels also release carbon dioxide and

other greenhouse gases, which are causing global temperatures to rise. The environmental effects of fossil fuel use are discussed in the “Climate” and “Human Actions and the Atmosphere” chapters.

Renewable Resources

Renewable energy resources include solar, water, wind, biomass, and geothermal. These resources are either virtually limitless like the Sun, which will continue to shine for billions of years, or will be replaced faster than we can use them. Amounts of falling water or wind will change over the course of time, but they are quite abundant. Biomass energy, like wood for fire, can be replaced quickly.

The use of renewable resources may also cause problems. Some are expensive, while some, such as trees, have other uses. Some cause environmental problems. As the technology improves and more people use renewable energy, the prices may come down. At the same time, as we use up fossil fuels, coal, oil, and natural gas, these non-renewable resources will become more expensive. At some point, even if renewable energy costs are high, non-renewable energy will be even more expensive. Ultimately, we will have to use renewable sources.

Important Things to Consider about Energy Resources

With both renewable and non-renewable 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 creates large amounts of pollution, that fuel also may not be the best choice for an energy resource.

Today we rely on electricity more than ever, but the resources that currently supply our power are finite. The race is on to harness more renewable resources, but getting all that clean energy from production sites to homes and businesses is proving to be a major challenge.

YouTube Video

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NON-RENEWABLE ENERGY 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. Although fossil fuels provide very high quality energy, they are non-renewable.

In large part, non-renewable energy sources are responsible for the world’s lights seen in this animation.

Formation of Fossil Fuels

Can you name some fossils? How about dinosaur bones or dinosaur footprints? Animal skeletons, teeth, shells, coprolites (otherwise known as feces), or any other remains or trace from a living creature that becomes a rock is a **fossil**.



Figure 4. This wetland may look something like an ancient coal-forming swamp.

The same processes that formed these fossils also created some of our most important energy resources, **fossil fuels**. Coal, oil, and natural gas are fossil fuels. Fossil fuels come from living matter starting about 500 million years ago. As plants and animals died, their remains settled on the ground on land and in swamps, lakes, and seas (figure 4).

Over time, layer upon layer of these remains accumulated. Eventually, the layers were buried so deeply that they were crushed by an enormous mass of earth. The weight of this earth pressing down on these plant and animal remains created intense heat and pressure. After millions of years of heat and pressure, the material in these layers turned into chemicals called **hydrocarbons** (figure 5). Here is an animated view of a hydrocarbon.

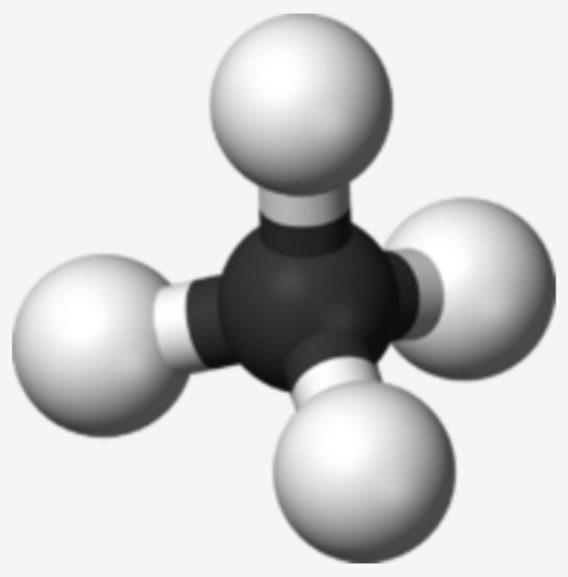


Figure 5. Hydrocarbons are made of carbon and hydrogen atoms. This molecule with one carbon and four hydrogen atoms is methane.

Hydrocarbons can be solid, liquid, or gaseous. The solid form is what we know as coal. The liquid form is petroleum, or crude oil. Natural gas is the gaseous form.

Coal

Coal, a solid fossil fuel formed from the partially decomposed remains of ancient forests, is burned primarily to produce electricity. Coal use is undergoing enormous growth as the availability of oil and natural gas decreases and cost increases. This increase in

coal use is happening particularly in developing nations, such as China, where coal is cheap and plentiful.

Coal Formation

Coal forms from dead plants that settled at the bottom of ancient swamps. Lush coal swamps were common in the tropics during the Carboniferous period, which took place more than 300 million years ago (figure 6). The climate was warmer then.



Figure 6. The location of the continents during the Carboniferous period. Notice that quite a lot of land area is in the region of the tropics.

Mud and other dead plants buried the organic material in the swamp, and burial kept oxygen away. When plants are buried without oxygen, the organic material can be preserved or fossilized. Sand and clay settling on top of the decaying plants squeezed out the water and other substances. Millions of years later, what remains is a carbon-containing rock that we know as coal.



Figure 7. Bituminous coal is a sedimentary rock.

Coal is black or brownish-black. The most common form of coal is bituminous, a sedimentary rock that contains impurities such as sulfur (figure 7). Anthracite coal, seen in figure 3, has been metamorphosed and is nearly all carbon. For this reason, anthracite coal burns more cleanly than bituminous coal.

Coal Use

Around the world, coal is the largest source of energy for electricity. The United States is rich in coal (figure 8). California once had a number of small coal mines, but the state no longer produces coal. To turn coal into electricity, the rock is crushed into powder, which is then burned in a furnace that has a boiler. Like other fuels, coal releases its energy as heat when it burns. Heat from the burning coal boils the water in the boiler to make steam. The steam spins turbines, which turn generators to create electricity. In this way, the energy stored in the coal is converted to useful energy like electricity.

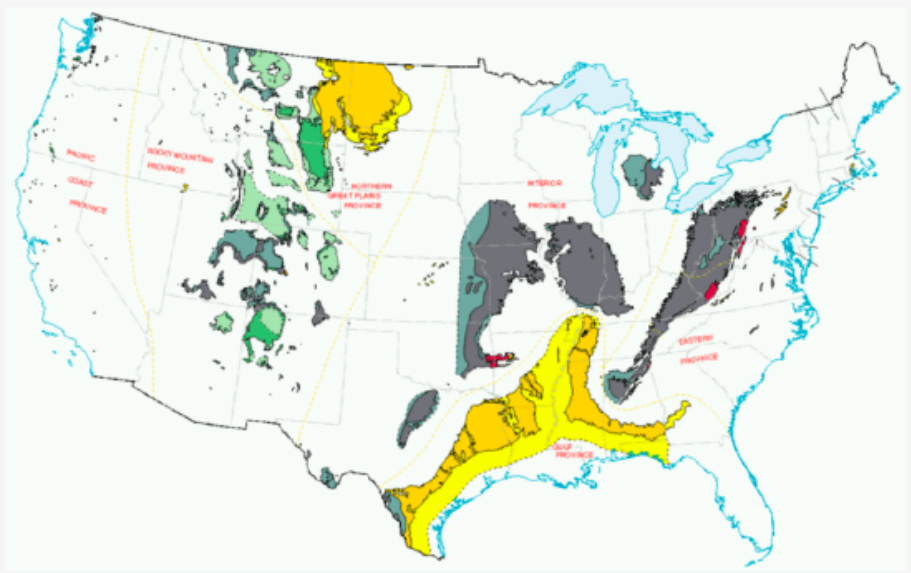


Figure 8. United States coal-producing regions in 1996. Orange is highest grade anthracite; red is low volatile bituminous; gray and gray-green is medium to high-volatile bituminous; green is subbituminous; and yellow is the lowest grade lignite

Coal that has been located but is not being used is part of our reserves. Reserves are important because if the price of the resource goes up or the cost of extracting it goes down, they may be useful.

Consequences of Coal Use

For coal to be used as an energy source, it must first be mined. Coal mining occurs at the surface or underground by methods that are described in the “Earth’s Minerals” chapter (figure 9). Mining, especially underground mining, can be dangerous. In April 2010, twenty-nine miners were killed at a West Virginia coal mine when gas that had accumulated in the mine tunnels exploded and started a fire.

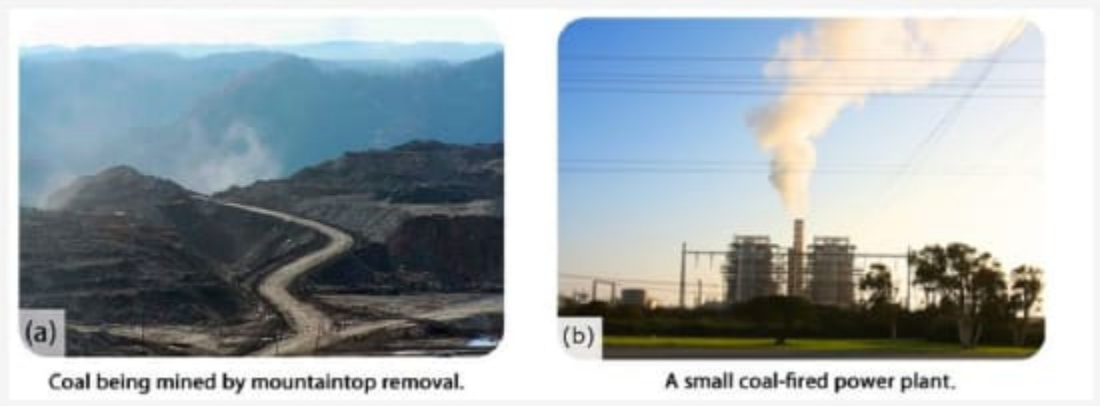


Figure 9. The coal used in power plants must be mined. One method to mine coal is by mountaintop removal.

Some possible types of environmental damage from mining are discussed in the “Earth’s Minerals” chapter. Coal mining exposes minerals and rocks from underground to air and water at the surface. Many of these minerals contain the element sulfur, which

mixes with air and water to make sulfuric acid, a highly corrosive chemical. If the sulfuric acid gets into streams, it can kill fish, plants, and animals that live in or near the water.

Oil

Oil is a liquid fossil fuel that is extremely useful because it can be transported easily and can be used in cars and other vehicles. Oil is currently the single largest source of energy in the world.

Oil Formation

Oil from the ground is called **crude oil**, which is a mixture of many different hydrocarbons. Crude oil is a thick dark brown or black liquid hydrocarbon. Oil also forms from buried dead organisms, but these are tiny organisms that live on the sea surface and then sink to the seafloor when they die. The dead organisms are kept away from oxygen by layers of other dead creatures and sediments. As the layers pile up, heat and pressure increase. Over millions of years, the dead organisms turn into liquid oil.

Oil Production

In order to be collected, the oil must be located between a porous rock layer and an impermeable layer (figure 10). Trapped above the porous rock layer and beneath the impermeable layer, the oil will remain between these layers until it is extracted from the rock.

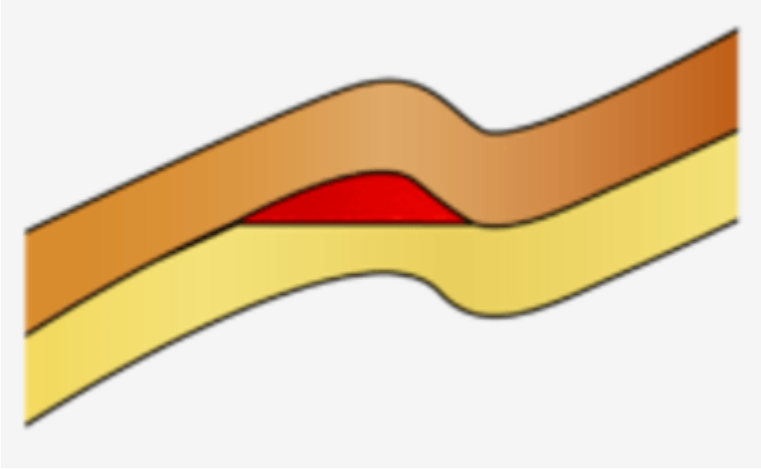


Figure 10. Oil (red) is found in the porous rock layer (yellow) and trapped by the impermeable layer (brown). The folded structure has allowed the oil to pool so a well can be drilled into the reservoir.

- Here is an animation of an oil deposit forming.
- The oil pocket is then drilled into from the surface. Here is an animation of an oil deposit being drilled.
- Sideways drilling allows a deposit that lies beneath land that cannot be drilled to be mined for oil.

To separate the different types of hydrocarbons in crude oil for different uses, the crude oil must be refined in refineries like the one shown in figure 11. Refining is possible because each hydrocarbon in crude oil boils at a different temperature. When the oil is boiled in the refinery, separate equipment collects the different compounds.



Figure 11. Refineries like this one separate crude oil into many useful fuels and other chemicals.

Oil Use

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

Gasoline is in a convenient form for use in cars and other transportation vehicles. In a car engine, the burned gasoline mostly turns into carbon dioxide and water vapor. The fuel releases most of its energy as heat, which causes the gases to expand. This creates enough force to move the pistons inside the engine and to power the car.

Consequences of Oil Use

The United States does produce oil, but the amount produced is only about one-quarter as much as the nation uses. The United States has only about 1.5% of the world's proven oil reserves, and so most of the oil used by Americans must be imported from other nations.

The main oil-producing regions in the United States are the Gulf of Mexico, Texas, Alaska, and California. Most offshore drilling occurs in the Gulf of Mexico, but there are offshore platforms in California as well (Figure 12). Here is an animation of the location of petroleum basins in the contiguous United States.

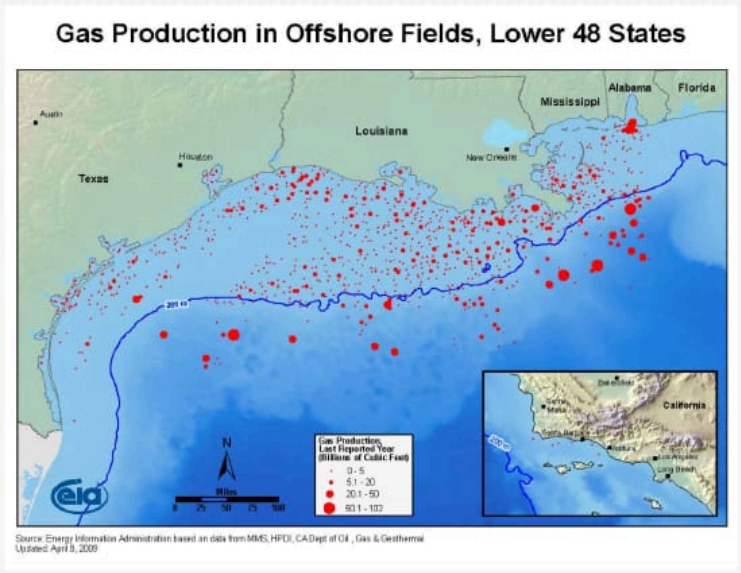


Figure 12. Offshore well locations in the Gulf of Mexico. Note that some wells are located in very deep water.

As in every type of mining, mining for oil has environmental consequences. Oil rigs are unsightly (figure 13), and spills are too common (figure 14).



Figure 13. Drill rigs at the San Ardo Oil Field in Monterey, California.



Figure 14. A deadly explosion on an oil rig in the Gulf of Mexico in April 2010 led to a massive oil spill. When this picture was taken in July 2010, oil was still spewing into the Gulf. The long-term consequences of the spill are being studied and are as yet unknown.

Natural Gas

Natural gas, often known simply as gas, is composed mostly of the hydrocarbon methane (refer to figure 5 for the structure).

Natural Gas Formation

Natural gas forms under the same conditions that create oil. Organic material buried in the sediments harden to become a shale formation that is the source of the gas. Although natural gas forms at higher temperatures than crude oil, the two are often found together. The formation of a minable oil and gas deposit is seen in this animation.

The largest natural gas reserves in the United States are in the Appalachian Basin, Texas, and the Gulf of Mexico region (Figure 15). California also has natural gas, found mostly in the Central Valley. In the northern Sacramento Valley and the Sacramento Delta, a sediment-filled trough formed along a location where crust was pushed together (an ancient convergent margin). Here is an animation of global natural gas reserves.

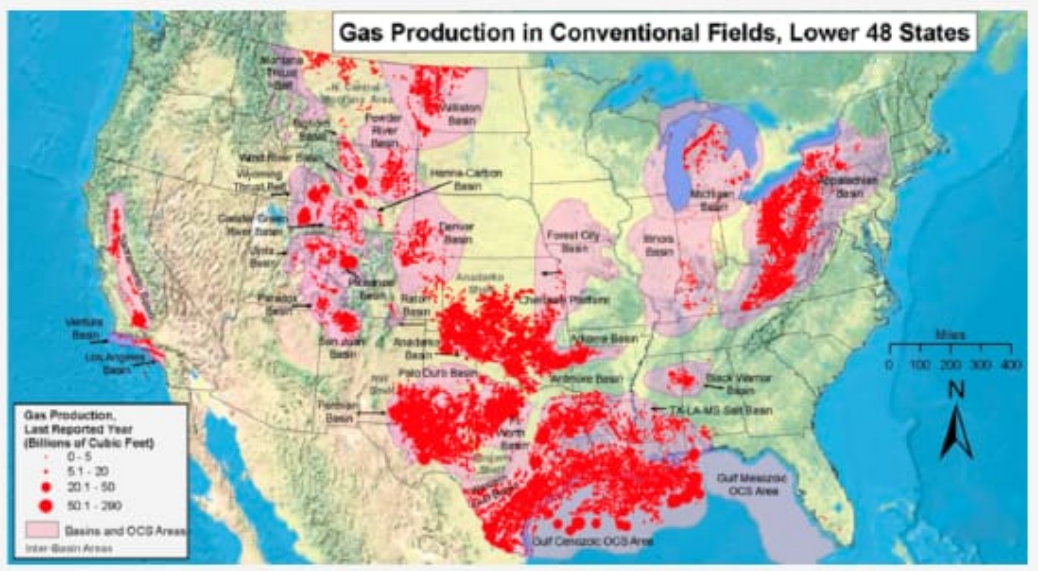


Figure 15. Gas production in the Lower 48 United States.

Natural Gas Use

Like crude oil, 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 chemicals, such as water, make the gas less useful as a fuel. Processing natural gas removes almost everything except the methane. Once the gas is processed, it is ready to be delivered and used. Natural gas is delivered to homes for uses such as cooking and heating. Like coal and oil, natural gas is also burned to generate heat for powering turbines. The spinning turbines turn generators, and the generators create electricity.

Consequences of Natural Gas Use

Natural gas burns much cleaner than other fossil fuels, meaning that it causes less air pollution. Natural gas also produces less carbon dioxide than other fossil fuels do for the same amount of energy, so its global warming effects are less (figure 16). See the pollution created by a car burning gasoline and a car burning natural gas in this animation.



Figure 16. A natural gas drill rig.

Unfortunately, drilling for natural gas can be environmentally destructive. One technique used is hydraulic fracturing, also called fracking, which increases the rate of recovery of natural gas. Fluids are pumped through a borehole to create fractures in the reservoir rock that contains the natural gas. Material is added to the fluid to prevent the fractures from closing. The damage comes primarily from chemicals in the fracturing fluids. Chemicals that have been found in the fluids may be carcinogens (cancer-causing), radioactive materials, or endocrine disruptors, which interrupt hormones in the bodies of humans and animals. The fluids may get into groundwater or may runoff into streams and other surface waters.

Fossil Fuel Reserves

Fossil fuels provide about 85% of the world's energy at this time. Worldwide fossil fuel usage has increased many times over in the past half century (coal: 2.6x, oil: 8x, natural gas: 14x) because of population increases, because of increases in the number of cars, televisions, and other fuel-consuming uses in the developed world, and because of lifestyle improvements in the developing world. Past and predicted use of different types of energy in the United States can be seen in this animation.

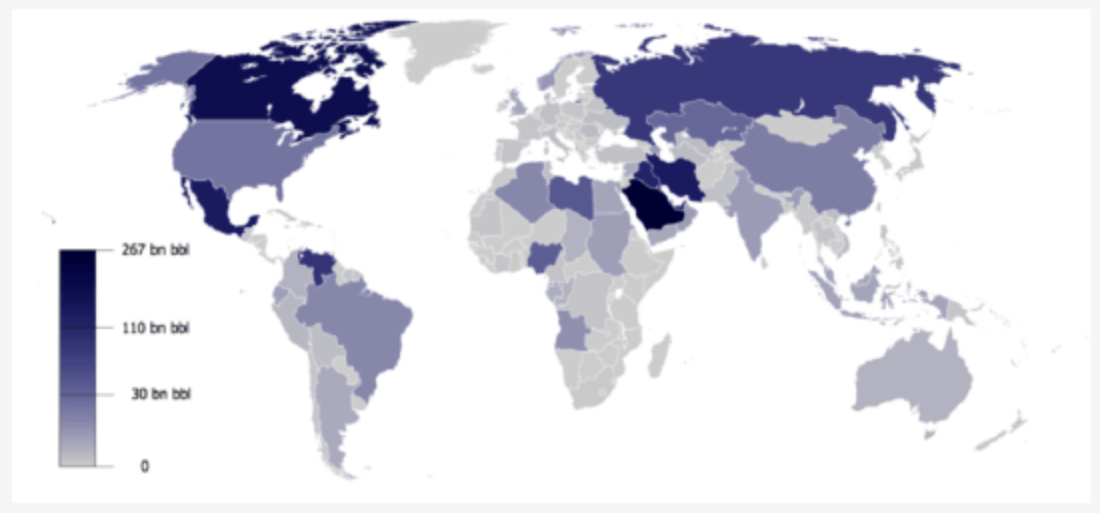


Figure 17. Worldwide oil reserves.

The amount of fossil fuels that remain untapped is unknown but can likely be measured in decades for oil and natural gas and in a few centuries for coal (figure 17). Alternative sources of fossil fuels, such as oil shales and tar sands, are increasingly being exploited (figure 18).



Figure 18. A satellite image of an oil-sands mine in Canada.

The environmental consequences of mining these fuels, and of fossil fuel use in general, along with the fact that these fuels do not have a limitless supply, are prompting the development of alternative energy sources.

Nuclear Energy

When the nucleus of an atom is split, it releases a huge amount of energy called **nuclear energy.** For nuclear energy to be used as a power source, scientists and engineers have learned to split nuclei and to control the release of energy (Figure 19).

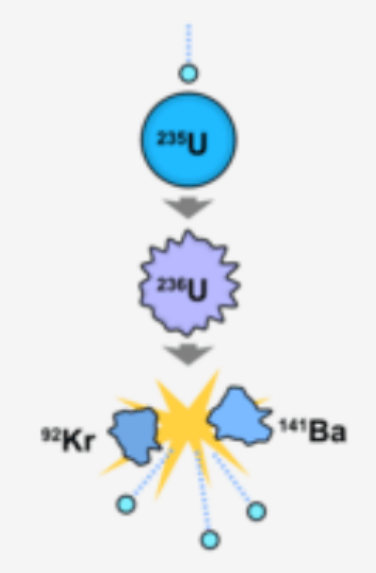


Figure 19. When struck by a tiny particle, Uranium-235 breaks apart and releases energy.

Nuclear Energy Use

Nuclear power plants, such as the one seen in figure 20, use uranium, which is mined, processed, and then concentrated into fuel rods. When the uranium atoms in the fuel rods are hit by other extremely tiny particles, they split apart. The number of tiny particles allowed to hit the fuel rods needs to be controlled or they would cause a dangerous explosion. The energy from a nuclear power plant heats water, which creates steam and causes a turbine to spin. The spinning turbine turns a generator, which in turn produces electricity.



Figure 20. Nuclear power plants like this one provide France with almost 80% of its electricity.

Many countries around the world use nuclear energy as a source of electricity. In the United States, a little less than 20% of electricity comes from nuclear energy.

Consequences of Nuclear Power

Nuclear power is clean. It does not pollute the air or release carbon dioxide. However, the use of nuclear energy does create other environmental problems. Uranium must be mined (figure 21). The process of splitting atoms creates radioactive waste, which

remains dangerous for thousands or hundreds of thousands of years. As yet, there is no long-term solution for storing this waste.



Figure 21. Uranium mine in Kakadu National Park, Australia.

The development of nuclear power plants has been on hold for three decades. Accidents at Three Mile Island and Chernobyl, Ukraine verified people's worst fears about the dangers of harnessing nuclear power (figure 22).



Figure 22. Damaged building near the site of the Chernobyl disaster.

Recently, nuclear power appeared to be making a comeback as society looked for alternatives to fossil fuels. But the 2011 disaster at the Fukushima Daiichi Nuclear Power Plant in Japan may have resulted in a new fear of nuclear power. The cause of the disaster was a 9.0 magnitude earthquake and subsequent tsunami, which compromised the plant. Although a total meltdown was averted, the plant experienced multiple partial meltdowns, core breaches, radiation releases, and cooling failures. The plant is scheduled for a complete cold shutdown before the end of 2011.

KQED: Nuclear Energy Use. Nuclear power is a controversial subject in California and most other places. Nuclear power has no pollutants including carbon emissions, but power plants are not always safe and the long-term disposal of wastes is a problem that has not yet been solved. The future of nuclear power is murky.

RENEWABLE ENERGY RESOURCES

Fossil fuels have the advantage of being cheap and transportable, but they cause environmental damage and will eventually run out. Renewable energy sources, by definition, will not run out, and most do not cause much pollution. But renewable energy sources do have a downside, too. Both the advantages and disadvantages of solar, water, wind, biomass, and geothermal energy will be described in this lesson.

Solar Power

The Sun is Earth's main source of energy, making the development of solar power a natural choice for an alternative energy source.

Solar Energy

Energy from the Sun comes from the lightest element, hydrogen, fusing together to create the second lightest element, helium. Nuclear fusion releases tremendous amounts of solar 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 as **radiation**.

Solar Power Use

Solar energy has been used for power on a small scale for hundreds of years, and plants have used it for billions of year. Unlike energy from fossil fuels, which almost always come from a central power plant or refinery, solar power can be harnessed locally (figure 23). A set of solar panels on a home's rooftop can be used to heat water for a swimming pool or can provide electricity to the house.

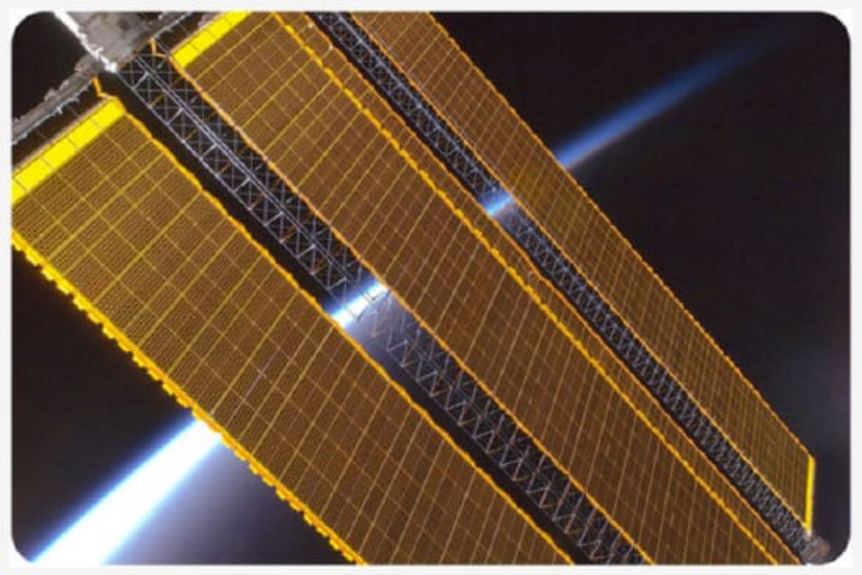


Figure 23. Solar panels supply power to the International Space Station.

Society's use of solar power on a larger scale is just starting to increase. Scientists and engineers have very active, ongoing research into new ways to harness energy from the Sun more efficiently. Because of the tremendous amount of incoming sunlight, solar power is being developed in the United States in southeastern California, Nevada, and Arizona.

Solar power plants turn sunlight into electricity using a large group of mirrors to focus sunlight on one place, called a receiver (figure 24). A liquid, such as oil or water, flows through this receiver and is heated to a high temperature by the focused sunlight. The heated liquid transfers its heat to a nearby object that is at a lower temperature through a process called **conduction**. The energy conducted by the heated liquid is used to make electricity.



Figure 24. 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.

Here's a video of how solar energy can be concentrated so that it can be used for power.

Consequences of Solar Power Use

Solar energy has many benefits. It is extremely abundant, widespread, and will never run out. But there are problems with the widespread use of solar power.



Figure 25. This experimental car is one example of the many uses that engineers have found for solar energy.

- Sunlight must be present. Solar power is not useful in locations that are often cloudy or at night. However, storage technology is being developed.
- The technology needed for solar power is still expensive. An increase in interested customers will provide incentive for companies to research and develop new technologies and to figure out how to mass-produce existing technologies (figure 25).
- Solar panels require a lot of space. Fortunately, solar panels can be placed on any rooftop to supply at least some of the power required for a home or business.

Water Power

Water covers 70% of the planet's surface, and water power (hydroelectric power) is the most widely used form of renewable energy in the world. Hydroelectric power from streams provides almost one fifth of the world's electricity.

Hydroelectric Power

Remember that potential energy is the energy of an object waiting to fall. Water held behind a dam has a lot of potential energy. In a hydroelectric plant, a dam across a riverbed holds a stream to create a reservoir. Instead of flowing down its normal channel, the water is allowed to flow into a large turbine. As the water moves, it has kinetic energy, which makes the turbine spin. The turbine is connected to a generator, which makes electricity (figure 26).

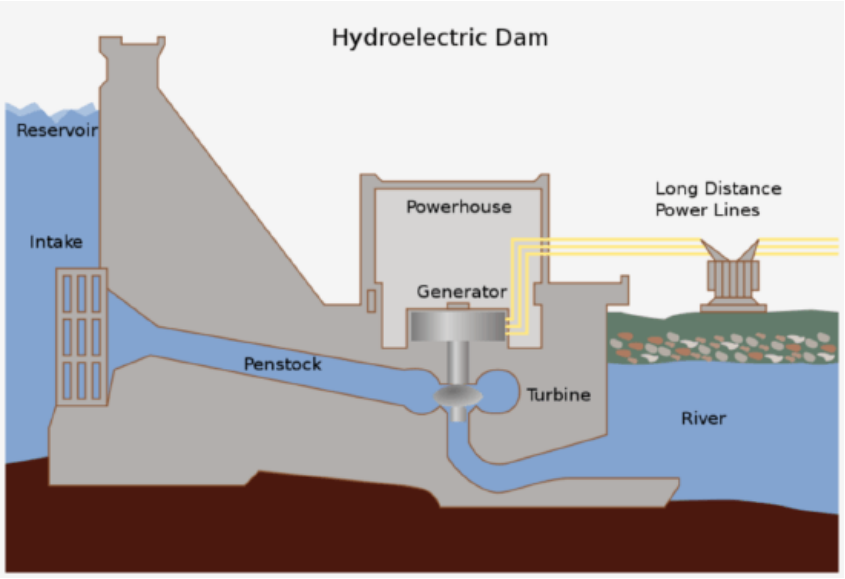


Figure 26. A cross-section of a hydroelectric plant.

Most of the streams in the United States and elsewhere in the developed world that are suitable for hydroelectric power have already been dammed (figure 27). In California, about 14.5% of the total electricity comes from hydropower. The state's nearly 400 hydropower plants are mostly located in the eastern mountain ranges where large streams descend down a steep grade.



Figure 27. Hydroelectric dams like this one use the power of moving water to create electricity.

Consequences of Water Power Use

The major benefit of hydropower is that it generates power without releasing any pollution. Hydropower is also a renewable resource since the stream will keep on flowing. However, there are a limited number of suitable dam sites. Hydropower also has environmental problems. When a large dam disrupts a river's flow, it changes the ecosystem upstream. As the land is flooded by

rising water, plants and animals are displaced or killed. Many beautiful landscapes, villages, and archeological sites have been drowned by the water in a reservoir (figure 28).



Figure 28. Glen Canyon Dam in Arizona created Lake Powell. The dam was controversial because it flooded Glen Canyon, a beautiful desert canyon.

The dam and turbines also change the downstream environment for fish and other living things. Dams slow the release of silt so that downstream deltas retreat and seaside cities become dangerously exposed to storms and rising sea levels.

Ocean Water Power

The energy of waves and tides can be used to produce water power. 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. Because of the many problems with them, tide and wave power plants are not very common.

KQED: Harnessing Power from the Sea. Although not yet widely used, many believe tidal power has more potential than wind or solar power for meeting alternative energy needs. Quest radio looks at plans for harnessing power from the sea by San Francisco and along the northern California coast.

Wind Power

Wind power is the fastest growing renewable energy source in the world. Windmills are now seen in many locations, either individually or, more commonly, in large fields. Wind Powering America follows the development of wind power in the United States over the past several years.

Wind Energy

Energy from the sun also creates wind, which can be used as wind power. The sun heats different locations on Earth by different amounts. Air that becomes warm rises and then sucks cooler air into that spot. The movement of air from one spot to another along the ground creates wind. Since wind is moving, it has kinetic energy.

Wind Power Use

Wind is the source of energy for wind power. Wind has been used for power for centuries. For example, windmills were used to grind grain and pump water. Sailing ships traveled by wind power long before ships were powered by fossil fuels. Wind can be used to generate electricity, as the moving air spins a turbine to create electricity (figure 29). This animation shows how wind power works.



Figure 29. Wind turbines like the ones shown here turn wind into electricity without creating pollution.

Consequences of Wind Power

Wind power has many advantages. It does not burn, so it does not release pollution or carbon dioxide. Also, wind is plentiful in many places. Wind, however, does not blow all of the time, even though power is needed all of the time. Just as with solar power, engineers are working on technologies that can store wind power for later use.

Windmills are expensive and wear out quickly. A lot of windmills are needed to power a region, so nearby residents may complain about the loss of a nice view if a wind farm is built. Coastlines typically receive a lot of wind, but wind farms built near beaches may cause unhappiness for local residents and tourists.

The Cape Wind Project off of Cape Cod has been approved but is generating much controversy. Opponents are in favor of green power but not at that location. Proponents say that clean energy is needed and the project would supply 75% of the electricity needed for Cape Cod and nearby islands (figure 30).

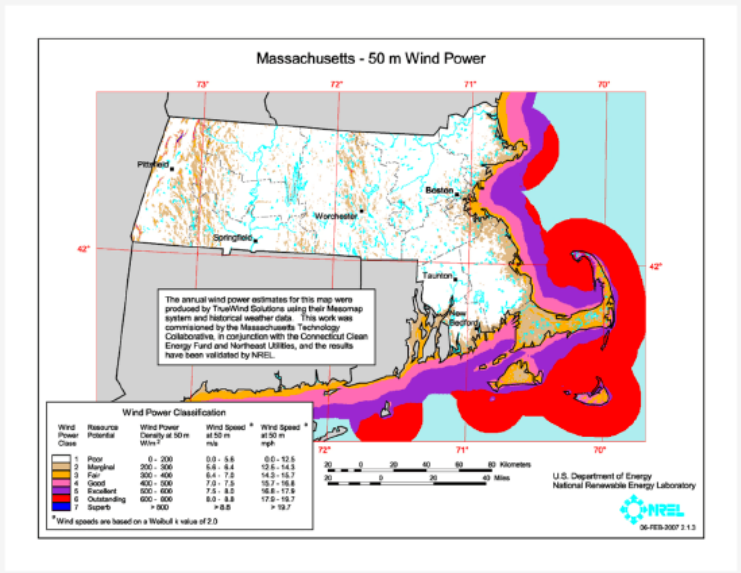


Figure 30. Cape Wind off of Cape Cod in Massachusetts receives a great deal of wind (red color) but is also popular with tourists for its beauty.

California was an early adopter of wind power. Windmills are found in mountain passes where the cooler Pacific Ocean air is sucked through on its way to 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.

Geothermal Power

Geothermal energy comes from heat deep below the surface of the Earth. Nothing must be done to the geothermal energy. It is a resource that can be used without processing.

Geothermal Energy

The heat that is used for geothermal power may come to the surface naturally as hot springs or geysers, like The Geysers in northern California. Where water does not naturally come to the surface, engineers may pump cool water into the ground. The water is heated by the hot rock and then pumped back to the surface for use. The hot water or steam from a geothermal well spins a turbine to make electricity.

Geothermal energy is clean and safe. The energy source is renewable since hot rock is found everywhere in the Earth, although in many parts of the world the hot rock is not close enough to the surface for building geothermal power plants. In some areas, geothermal power is common (figure 31).



Figure 31. A geothermal energy plant in Iceland. Iceland gets about one fourth of its electricity from geothermal sources.

In the United States, California is a leader in producing geothermal energy. The largest geothermal power plant in the state is in the Geysers Geothermal Resource Area in Napa and Sonoma Counties, north of San Francisco. The source of heat is thought to be a large magma chamber lying beneath the area.

KQED: Geothermal Heats Up. Where Earth's internal heat gets close to the surface, geothermal power is a clean source of energy. In California, The Geysers supplies energy for many nearby homes and businesses.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Biomass

Biomass is the material that comes from plants and animals that were recently living. Biomass can be burned directly, such as setting fire to wood. For as long as humans have had fire, people have used biomass for heating and cooking. People can also process biomass to make fuel, called **biofuel.** Biofuel can be created from crops, such as corn or algae, and processed for use in a car (figure 32). The advantage to biofuels is that they burn more cleanly than fossil fuels. As a result, they create less pollution and less carbon dioxide. Critics say, however, that the amount of energy, fertilizer, and land needed to produce the crops used make biofuels only a slightly better alternative than fossil fuels.



Figure 32. Biofuels, such as ethanol, are added to gasoline to cut down the amount of fossil fuels that are used.

- KQED: How Green is Biomass Energy? Organic material, like almond shells, can be made into electricity. Biomass power is a great use of wastes and is more reliable than other renewable energy sources, but harvesting biomass energy uses energy and biomass plants produce pollutants including greenhouse gases.
- KQED: From Waste to Watts: Biofuel Bonanza. Cow manure can have a second life as a source of methane gas, which can be converted to electricity. Not only that food scraps can also be converted into green energy.
- KQED: Biofuels: Beyond Ethanol. To generate biomass energy, break down the cell walls of plants to release the sugars and then ferment those sugars to create fuel. Corn is a very inefficient source; scientists are looking for much better sources of biomass energy.
- Algae Power. Many people think that the best source of biomass energy for the future is algae. Compared to corn, algae is not a food crop, it can grow in many places, its much easier to convert to a usable fuel and its carbon neutral.
- Power Up with Leftovers. Food that is tossed out produces methane, a potent greenhouse gas. But that methane from leftovers can be harnessed and used as fuel. Sounds like a win-win situation.

LESSON SUMMARY

- According to the law of conservation of energy, energy is neither created nor destroyed.
- Renewable resources can be replaced at the rate they are being used.
- Non-renewable resources are available in limited amounts or are being used faster than they can be replaced.
- Fossil fuels are non-renewable sources of energy that produce environmental damage.
- Coal, oil, and natural gas are fossil fuels formed from the remains of living organisms.
- Coal is the largest source of energy for producing electricity.
- Oil and natural gas are important energy sources for vehicles and electricity generation.
- Nuclear energy is produced by splitting atoms. It also produces radioactive wastes that are very dangerous for many years.
- Solar energy, water power, wind power, geothermal energy, and biomass 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 and tidal and wave plants.

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

REFLECTION QUESTIONS

- What skill does this content help you develop?
- What are the key topics covered in this content?
- How can the content in this section help you demonstrate mastery of a specific skill?
- What questions do you have about this content?

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12.13: Use and Conservation of Resources

INTRODUCTION

Natural resources may be living or non-living. Their value may be tangible, such as the price of an ounce of gold, or intangible, like the psychological value of being able to visit pristine natural areas. Some natural resources must be used and used wisely, but some must be preserved to maintain their value.

MYSTERY IN THE FOREST

Like all forests, the Monongahela National Forest of West Virginia is an important natural resource. A forest is a resource in ways that are obvious and ways that are not so obvious. This forest is used for many things including:

- Recreation, such as hiking, camping, and picnicking.
- Habitat for many organisms, including nine endangered species and 50 species of rare plants.
- Streams [207 kilometers (129 miles)] for fishing, particularly trout fishing.
- Wildlife management areas for hunting deer, squirrels, turkeys, rabbits, mink, and foxes.
- Mineral and energy resources such as coal, gas, limestone, and gravel.
- Hardwood trees used for **timber**, which brings in over $7 million a year.

But Monongahela National Forest has a problem; for several years, trees in the forest have not grown well. What are some reasons that trees might not grow well (figure 1)?

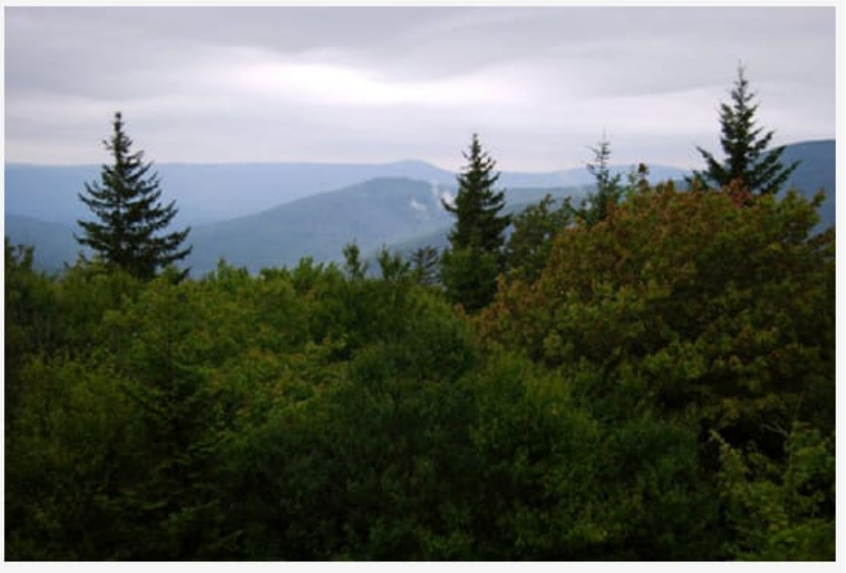


Figure 1. The Monongahela National Forest in West Virginia contains many natural resources. Notice the air pollution that obscures the view.

Scientists have been working for several years to solve the mystery. The scientists suspected that the soil is missing nutrients that the trees and other plants need to grow. Can you design an experiment that scientists could do to test this hypothesis? (There is a clue in the caption for figure 1.)

The scientists sampled the soil and tested it for important nutrients. They discovered that the soil has very low levels of plant nutrients, such as magnesium and calcium. Can you develop a hypothesis for why these nutrients might be missing from the soil? The scientists thought that air pollution from nearby factories had released chemicals into the environment that removed the nutrients from the soil and carried them away. How would the scientists test that hypothesis?

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.

Like the Monongahela National Forest, people use parts of the Earth for many reasons, such as food, water, building materials, timber, recreation, and energy (figure 2). As you've already learned, human activities can degrade natural resources, just like air pollution from factories is speeding up the loss of soil nutrients in West Virginia.



Figure 2. We use Earth's resources for many purposes, including recreation and natural beauty.

For natural resources to continue to be available, they need to be protected. We also need to **conserve** natural resources so they will last longer. When we practice conservation, we make sure resources will be available in the future, both for ourselves and for other organisms.

RENEWABLE VERSUS NON-RENEWABLE RESOURCES

In the Earth's Energy chapter, energy resources were classified as renewable or non-renewable. How do you think other natural resources, such as minerals and forests, are classified? Like energy resources, all natural resources are divided into renewable and non-renewable. Can you define these terms?

Renewable resources can be regenerated or grown so rapidly that they reappear at the same rate or even faster as they are being used (figure 3). Are forests a renewable resource? Why are they a renewable resource? Why aren't they a renewable resource? Although new trees can grow to replace logged trees, their growth is often too slow for the trees to be of use for a long time. Loggers just move to a new area rather than wait for the forest to regenerate.



Figure 3. An old growth forest, like this tropical rainforest in Malaysia, is a complex ecosystem with many types of plants and animals. When a forest is destroyed by logging, it takes hundreds or thousands of years for the forest to regenerate.

Other examples of resources that are renewable but not entirely renewable include soil, wildlife, and water. How do these resources fit in both categories? Soil has a very slow renewal rate, so they are often non-renewable. Fish and other wildlife can reproduce and so are a renewable resource, yet it is possible to take so many of these creatures that the populations are not able to rebound, making them a non-renewable resource (figure 4). Organisms can be over-hunted, over-fished or have populations decline because of habitat loss so that their numbers go so low they are no longer a renewable resource.



Figure 4. Chimpanzees are eaten and taken as pets so their numbers in the wild are declining.

Non-renewable resources are resources that cannot be regenerated on a useful timescale. Fossil fuels and most minerals are non-renewable resources. We can (and eventually will) run out of these resources.

COMMON MATERIALS WE USE FROM THE EARTH

People depend on natural resources for just about everything that keeps us fed and sheltered, as well as for the things that keep us entertained. Every person in the United States uses about 20,000 kilograms (40,000 pounds) of minerals every year for a wide range of products, such as cell phones, TVs, jewelry, and cars. Table 1 shows some common objects, the materials they are made from and whether they are renewable or non-renewable.

Table 1. Common Objects We Use From the Earth

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
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

RESOURCE AVAILABILITY

From the table above you can see that many of the resources we depend on are non-renewable. Non-renewable resources vary in their availability; some are very abundant and others are rare. Materials, such as gravel or sand are technically non-renewable but are so abundant that running out is no issue. Some resources are truly limited in quantity: When they are gone, they are gone and something must be found that will replace them. There are even resources, such as diamonds and rubies, that are valuable in part because they are so rare.

Besides abundance, resource value is determined by how easy it is to locate and extract. If a resource is difficult to use, it will not be used until the price for that resource becomes so great that it is worth paying for. For example, the oceans are filled with an abundant supply of water, but desalination is costly, so it is used only where water is really limited (figure 5). As the cost of desalination plants comes down, more will likely be built.



Figure 5. Tampa Bay, Florida, has one of the few desalination plants in the United States.

Politics is also part of determining resource availability and cost. Nations that have a desired resource in abundance will often **export** that resource to other countries, while countries that need that resource must **import** it from one of the countries that produces it. This situation is a potential source of economic and political trouble.

Of course the greatest example of this is oil. Only 12 countries have approximately 80% of all of the world's oil (Figure 6). However, the biggest users of oil, the United States, China, and Japan, are all located outside this oil-rich region. This leads to a situation in which the availability and price of the oil is determined largely by one set of countries that have their own interests to look out for. The result has sometimes been war, which may have been attributed to all sorts of reasons, but at the bottom, the reason is oil.



Figure 6. The nations in blue are the 12 biggest producers of oil; they are Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates, and Venezuela.

The topic of overconsumption was touched on in the Ecosystems and Human Populations chapter. Many people in developed countries, such as the United States and most of Europe, use many more natural resources than people in many other countries. We have many luxury and recreational items, and it is often cheaper for us to throw something away than to fix it or just hang on to it for a while longer. This consumerism leads to greater resource use, but it also leads to more waste. Pollution from discarded materials degrades the land, air, and water (figure 7).



Figure 7. Pollution from discarded materials degrades the environment and reduces the availability of natural resources.

Natural resource use is generally lower in developing countries because people cannot afford many products. Some of these nations export natural resources to the developed world since their deposits may be richer and the cost of labor lower. Environmental regulations are often more lax, further lowering the cost of resource extraction.

Besides obtaining resources, we also dump waste on these nations. Many of our electronic wastes, which we think are being recycled, end up in developing countries where they pose a problem for human health and the environment. Electronic wastes are sent to developing nations where people pick through them for valuable materials. These wastes contain many toxic compounds and are hazardous.

CONSERVING NATURAL RESOURCES



Figure 8. Recycling can help conserve natural resources.

So that people in developed nations maintain a good lifestyle and people in developing nations have the ability to improve their lifestyles, natural resources must be conserved and protected (figure 8). People are researching ways to find renewable alternatives to non-renewable resources. Here is a checklist of ways to conserve resources:

- Buy less stuff (use items as long as you can, and ask yourself if you really need something new).
- Reduce excess packaging (drink tap water instead of water from plastic bottles).

- Recycle materials such as metal cans, old cell phones, and plastic bottles.
- Purchase products made from recycled materials.
- Reduce pollution so that resources are maintained.
- Prevent soil erosion.
- Plant new trees to replace those that are cut down.
- Drive cars less, take public transportation, bicycle, or walk.
- Conserve energy at home (turn out lights when they are not needed).

National Geographic videos found on this site in Environment Videos, Environmental Threats, Deforestation.

- “Sustainable Logging”

Or Environment Videos, Habitats, Rainforest.

- “Mamirarua” is a sustainable development reserve that is protecting the Amazon
- “Vancouver Rain Forest” explores an alliance between conservationists and logging companies

Or find ways to go green from National Geographic videos, Environment Videos, Going Green.

- The problem with plastic bags is discussed in this Conservation in action, “Edward Norton: Bag the Bag”
- Trying to mitigate problems caused by intensive logging in Ecuador while helping the people who live there improve their standards of living is in “Ecuador Conservation”

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.
- Natural resources must be preserved and protected from pollution and overuse.
- Buying fewer new products and recycling will help to conserve resources.

REFLECTION QUESTIONS

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12.14: Putting It Together

SUMMARY

In this section, we used almost all of the concepts we have learned so far. While plate tectonics may not have been mentioned directly, we know the role it plays in the formation of rock, minerals and mineral resources. In this section, we focused on these items:

1. How mineral resources and fossil fuels are formed
2. How these resources are mined
3. Nonrenewable and renewable resources
4. What type and amount of resources we use in our everyday life

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GLOSSARY

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