An Introduction to Geology

Delicate Arch, Arches National Park, Utah
An Introduction to Geology

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This text is provided to you as an Open Educational Resource which you access online. It is designed to give you a comprehensive introduction to Geology at no or very nominal cost. It contains both written and graphic text material, intra-text links to other internal material which may aid in understanding topics and concepts, intra-text links to the appendices and glossary for tables and definitions of words, and extra-text links to videos and web material that clarifies and augments topics and concepts. Like any new or scientific subject, Geology has its own vocabulary for geological concepts. For you to converse effectively with this text and colleagues in this earth science course, you will use the language of geology, so comprehending these terms is important. Use the intra-text links to the Glossary and other related material freely to gain familiarity with this language.

Tips for study

Each chapter begins with a list of KEY CONCEPTS you should be able to grasp through effective study of the chapter material. These are stated as Student Learning Objectives (SLOs) in behavioral terms. In other words, when you have completed study of that chapter, you should be able to do stated things with your understanding. Within chapters, each section concludes with a set of questions, called “Did I Get it?” questions. After completing the section, you should get these key points and answer questions related to the student learning objectives. At the end of each chapter are summaries of the sections and chapter review questions so you can review each section in the context of the chapter.
1 Understanding Science

STUDENT LEARNING OUTCOMES

At the end of this chapter, students should be able to:

- Contrast objective versus subjective observations, and quantitative versus qualitative observations
- Identify a pseudoscience based on its lack of falsifiability
- Contrast the methods used by Aristotle and Galileo to describe the natural environment
- Explain the scientific method and apply it to a problem or question
- Describe the foundations of modern geology, such as the principle of uniformitarianism
- Contrast uniformitarianism with catastrophism
- Explain why studying geology is important
- Identify how Earth materials are transformed by rock cycle processes
- Describe the steps involved in a reputable scientific study
- Explain rhetorical arguments used by science deniers
1.1 What is Science?

Scientists seek to understand the fundamental principles that explain natural patterns and processes. Science is more than just a body of knowledge, science provides a means to evaluate and create new knowledge without bias [1]. Scientists use objective evidence over subjective evidence, to reach sound and logical conclusions.

An objective observation is without personal bias and the same by all individuals. Humans are biased by nature, so they cannot be completely objective; the goal is to be as unbiased as possible. A subjective observation is based on a person’s feelings and beliefs and is unique to that individual.

Another way scientists avoid bias is by using quantitative over qualitative measurements whenever possible. A quantitative measurement is expressed with a specific numerical value. Qualitative observations are general or relative descriptions. For example, describing a rock as red or heavy is a qualitative observation. Determining a rock’s color by measuring wavelengths of reflected light or its density by measuring the proportions of minerals it contains is quantitative. Numerical values are more precise than general descriptions, and they can be analyzed using statistical calculations. This is why quantitative measurements are much more useful to scientists than qualitative observations.

Establishing truth in science is difficult because all scientific claims are falsifiable, which means any initial hypothesis may be tested and proven false. Only after exhaustively eliminating false results, competing ideas, and possible variations does a hypothesis become regarded as a reliable scientific theory. This meticulous scrutiny reveals weaknesses or flaws in a hypothesis and is the strength that supports all scientific ideas.

Canyons like this, carved in the deposit left by the May 18th, 1980 eruption of Mt. St. Helens, are sometimes used by purveyors of pseudoscience as evidence for the Earth being very young. In reality, the non-lithified volcanic deposit is carved much more easily than other canyons like the Grand Canyon.
and procedures. In fact, proving current ideas are wrong has been the driving force behind many scientific careers.

Falsifiability separates science from pseudoscience. Scientists are wary of explanations of natural phenomena that discourage or avoid falsifiability. An explanation that cannot be tested or does not meet scientific standards is not considered science, but pseudoscience. Pseudoscience is a collection of ideas that may appear scientific but does not use the scientific method. Astrology is an example of pseudoscience. It is a belief system that attributes the movement of celestial bodies to influencing human behavior. Astrologers rely on celestial observations, but their conclusions are not based on experimental evidence and their statements are not falsifiable. This is not to be confused with astronomy which is the scientific study of celestial bodies and the cosmos [2; 3].

Science is also a social process. Scientists share their ideas with peers at conferences, seeking guidance and feedback. Research papers and data submitted for publication are rigorously reviewed by qualified peers, scientists who are experts in the same field. The scientific review process aims to weed out misinformation, invalid research results, and wild speculation. Thus, it is slow, cautious, and conservative. Scientists tend to wait until a hypothesis is supported by overwhelming amount of evidence from many independent researchers before accepting it as scientific theory.
1.1 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. Which of the following are objective statements? SELECT THREE

- ☐ The Earth is 4 1/2 billion years old
- ☐ Geology is an important science
- ☐ The blue cupcakes taste better
- ☐ Geology is my major
- ☐ I observed that it rained yesterday

2. What distinguishes science from pseudoscience?

- ☐ Science deals with the mainstream ideas, pseudoscience does not.
- ☐ In science, we just know that things are the way they are.
- ☐ Measurements can prove a concept to be correct and scientific.
- ☐ Pseudoscience uses experimentation to objectively reach conclusions.
- ☐ Concepts must be falsifiable to be considered science.
1.2 The Scientific Method

Modern science is based on the scientific method, a procedure that follows these steps:

- Formulate a question or observe a problem
- Apply objective experimentation and observation
- Analyze collected data and Interpret results
- Devise an evidence-based theory
- Submit findings to peer review and/or publication

This has a long history in human thought but was first fully formed by Ibn al-Haytham over 1,000 years ago. At the forefront of the scientific method are conclusions based on objective evidence, not opinion or hearsay [4].

**STEP ONE: OBSERVATION, PROBLEM, OR RESEARCH QUESTION**

The procedure begins with identifying a problem or research question, such as a geological phenomenon that is not well explained in the scientific community’s collective knowledge. This step usually involves reviewing the scientific literature to understand previous studies that may be related to the question.

**STEP TWO: HYPOTHESIS**

Once the problem or question is well defined, the scientist proposes a possible answer, a hypothesis, before conducting an experiment or field work. This hypothesis must be specific, falsifiable, and should be based on other scientific work. Geologists often develop multiple working hypotheses because they usually cannot impose strict experimental controls or have limited opportunities to visit a field location.[5; 6; 7].

A famous hypothesis: Leland Stanford wanted to know if a horse lifted all 4 legs off the ground during a gallop, since the legs are too fast for the human eye to perceive it. These series of photographs by Eadweard Muybridge proved the horse, in fact, does have all four legs off the ground during the gallop.
STEP THREE: EXPERIMENT AND HYPOTHESIS REVISION

The next step is developing an experiment that either supports or refutes the hypothesis. Many people mistakenly think experiments are only done in a lab; however, an experiment can consist of observing natural processes in the field. Regardless of what form an experiment takes, it always includes the systematic gathering of objective data. This data is interpreted to determine whether it contradicts or supports the hypothesis, which may be revised and tested again. When a hypothesis holds up under experimentation, it is ready to be shared with other experts in the field.

STEP FOUR: PEER REVIEW, PUBLICATION, AND REPLICATION

Scientists share the results of their research by publishing articles in scientific journals, such as Science and Nature. Reputable journals and publishing houses will not publish an experimental study until they have determined its methods are scientifically rigorous and the conclusions are supported by evidence. Before an article is published, it undergoes a rigorous peer review by scientific experts who scrutinize the methods, results, and discussion. Once an article is published, other scientists may attempt to replicate the results. This replication is necessary to confirm the reliability of the study’s reported results. A hypothesis that seemed compelling in one study might be proven false in studies conducted by other scientists. New technology can be applied to published studies, which can aid in confirming or rejecting once-accepted ideas and/or hypotheses.
**STEP FIVE: THEORY DEVELOPMENT**

In casual conversation, the word *theory* implies guesswork or speculation. In the language of science, an explanation or conclusion made in a *theory* carries much more weight because it is supported by experimental verification and widely accepted by the scientific community. After a hypothesis has been repeatedly tested for falsifiability through documented and independent studies, it eventually becomes accepted as a scientific theory.

While a hypothesis provides a tentative explanation *before* an experiment, a theory is the best explanation *after* being confirmed by multiple independent experiments. Confirmation of a theory may take years, or even longer. For example, the continental drift hypothesis first proposed by Alfred Wegener in 1912 was initially dismissed. After decades of additional evidence collection by other scientists using more advanced technology, Wegener’s hypothesis was accepted and revised as the theory of plate tectonics.

The theory of evolution by natural selection is another example. Originating from the work of Charles Darwin in the mid-19th century, the theory of evolution has withstood generations of scientific testing for falsifiability. While it has been updated and revised to accommodate knowledge gained by using modern technologies, the theory of evolution continues to be supported by the latest evidence.
Quiz: 1.2 Did I Get It?
This quiz is for you to check your comprehension of this section.

1. In the scientific method, which of these steps would normally follow experimentation and sharing of results?

- ○ Hypothesis creation
- ○ Hypothesis development
- ○ Peer review
- ○ Theory development
- ○ Observation

2. Which of the following best matches the word theory?

- ○ An untested idea
- ○ An idea that can be tested
- ○ An infallible truth
- ○ An educated guess
- ○ A well-tested idea
Western scientific thought began in the ancient city of Athens, Greece. Athens was governed as a democracy, which encouraged individuals to think independently, at a time when most civilizations were ruled by monarchies or military conquerors. Foremost among the early philosopher/scientists to use empirical thinking was Aristotle, born in 384 BCE. Empiricism emphasizes the value of evidence gained from experimentation and observation. Aristotle studied under Plato and tutored Alexander the Great. Alexander would later conquer the Persian Empire, and in the process spread Greek culture as far east as India.

Aristotle applied an empirical method of analysis called deductive reasoning, which applies known principles of thought to establish new ideas or predict new outcomes. Deductive reasoning starts with generalized principles and logically extends them to new ideas or specific conclusions. If the initial principle is valid, then it is highly likely the conclusion is also valid. An example of deductive reasoning is if $A=B$, and $B=C$, then $A=C$. Another example is if all birds have feathers, and a sparrow is a bird, then a sparrow must also have feathers. The problem with deductive reasoning is if the initial principle is flawed, the conclusion will inherit that flaw. Here is an example of a flawed initial principle leading to the wrong conclusion; if all animals that fly are birds, and bats also fly, then bats must also be birds.

This type of empirical thinking contrasts with inductive reasoning, which begins from new observations and attempts to discern underlying generalized principles. A conclusion made through inductive reasoning comes from analyzing measurable evidence, rather making a logical connection. For example, to determine whether bats are birds a scientist might list various characteristics observed in birds—the presence of feathers, a toothless beak, hollow bones, lack of forelegs, and externally laid eggs. Next, the scientist would check whether bats share the same characteristics, and if they do not, draw the conclusion that bats are not birds.

Both types of reasoning are important in science because they emphasize the two most important aspects of science: observation and inference. Scientists test existing principles to see if they accurately infer or predict their observations. They also analyze new observations to determine if the inferred underlying principles still support them.

Fresco by Raphael of Plato (left) and Aristotle (right).
Greek culture was spread by Alexander and then absorbed by the Romans, who help further extend Greek knowledge into Europe through their vast infrastructure of roads, bridges, and aqueducts [11]. After the fall of the Roman Empire in 476 CE, scientific progress in Europe stalled [8]. Scientific thinkers of medieval time had such high regard for Aristotle’s wisdom and knowledge they faithfully followed his logical approach to understanding nature for centuries. By contrast, science in the Middle East flourished and grew between 800 and 1450 CE, along with culture and the arts.

Near the end of the medieval period, empirical experimentation became more common in Europe. During the Renaissance, which lasted from the 14th through 17th centuries, artistic and scientific thought experienced a great awakening [12; 13; 14]. European scholars began to criticize the traditional Aristotelian approach and by the end of the Renaissance period, empiricism was poised to become a key component of the scientific revolution that would arise in the 17th century [15].

An early example of how Renaissance scientists began to apply a modern empirical approach is their study of the solar system. In the second century, the Greek astronomer Claudius Ptolemy observed the Sun, Moon, and stars moving across the sky. Applying Aristotelian logic to his astronomical calculations, he deductively reasoned all celestial bodies orbited around the Earth, which was located at the center of the universe. Ptolemy was a highly regarded mathematician, and his mathematical calculations were widely accepted by the scientific community. The view of the cosmos with Earth at its center is called the geocentric model. This geocentric model persisted until the Renaissance period, when some revolutionary thinkers challenged the centuries-old hypothesis.

By contrast, early Renaissance scholars such as astronomer Nicolaus Copernicus (1473-1543) proposed an alternative explanation for the perceived movement of the Sun,
Moon, and stars. Sometime between 1507 and 1515, he provided credible mathematical proof for a radically new model of the cosmos, one in which the Earth and other planets orbited around a centrally located Sun. After the invention of the telescope in 1608, scientists used their enhanced astronomical observations to support this heliocentric, Sun-centered, model [16; 17].

Two scientists, Johannes Kepler and Galileo Galilei, are credited with jump-starting the scientific revolution [15]. They accomplished this by building on Copernicus work and challenging long-established ideas about nature and science.

Johannes Kepler (1571-1630) was a German mathematician and astronomer who expanded on the heliocentric model—improving Copernicus’ original calculations and describing planetary motion as elliptical paths. Galileo Galilei (1564 – 1642) was an Italian astronomer who used the newly developed telescope to observe the four largest moons of Jupiter [18]. This was the first piece of direct evidence to contradict the geocentric model, since moons orbiting Jupiter could not also be orbiting Earth.

Galileo strongly supported the heliocentric model and attacked the geocentric model, arguing for a more scientific approach to determine the credibility of an idea [19]. Because of this he found himself at odds with prevailing scientific views and the Catholic Church. In 1633 he was found guilty of heresy and placed under house arrest, where he would remain until his death in 1642 [18; 19].

Galileo is regarded as the first modern scientist because he conducted experiments that would prove or disprove falsifiable ideas and based his conclusions on mathematical analysis of quantifiable evidence—a radical departure from the deductive thinking of Greek philosophers such as Aristotle [15; 18]. His methods marked the beginning of a major shift in how scientists studied the natural world, with an increasing number of them relying on evidence and experimentation to form their hypotheses. It was during
this revolutionary time that geologists such as James Hutton and Nicolas Steno also made great advances in their scientific fields of study [15].

**Quiz: 1.3 Did I Get It?**

This quiz is for you to check your comprehension of this section.

1. Which of the following is the advantage of inductive reasoning, in contrast with deductive (Aristotelian) reasoning?

   - ☐ Reasoning is more sound
   - ☐ Focus on observation
   - ☐ Focus on conclusions
   - ☐ Use of replication

2. What evidence was found by Galileo that proved the Earth could not be the center of the universe?

   - ☐ Craters on the moon
   - ☐ Moons orbiting around Jupiter
   - ☐ Orbit of Saturn
   - ☐ Asteroid belt
   - ☐ Comet return time

3. The idea that the Sun was the center of the Solar System was first proposed by Nicolaus Copernicus in 1543 and is known as the ________.

   - ☐ Suncentric model
   - ☐ Solar Orbital model
   - ☐ Geocentric model
   - ☐ Heliocentric model
   - ☐ Divinitycentric model
1.4 Foundations of Modern Geology

As part of the scientific revolution in Europe, modern geologic principles developed in the 17th and 18th centuries. One major contributor was Nicolaus Steno (1638-1686), a Danish priest who studied anatomy and geology. Steno was the first to propose the Earth’s surface could change over time. He suggested sedimentary rocks, such as sandstone and shale, originally formed in horizontal layers with the oldest on the bottom and progressively younger layers on top [20].

In the 18th century, Scottish naturalist James Hutton (1726–1797) studied rivers and coastlines and compared the sediments they left behind to exposed sedimentary rock strata. He hypothesized the ancient rocks must have been formed by processes like those producing the features in the oceans and streams. Hutton also proposed the Earth was much older than previously thought. Modern geologic processes operate slowly. Hutton realized if these processes formed rocks, then the Earth must be very old, possibly hundreds of millions of years old [21; 22].

Hutton’s idea is called the principle of uniformitarianism and states that natural processes operate the same now as in the past, i.e. the laws of nature are uniform across space and time. Geologist often state “the present is the key to the past,” meaning they can understand ancient rocks by studying modern geologic processes.

Prior to the acceptance of uniformitarianism, scientists such as German geologist Abraham Gottlob Werner (1750-1817) and French anatomist Georges Cuvier (1769-1832) thought rocks and landforms were formed by great catastrophic events. Cuvier championed this view, known as catastrophism, and stated, “The thread of operation is broken; nature has changed course, and none of the agents she employs today would have been sufficient to produce her former works.” He meant processes that operate today did not operate in the past [23; 21]. Known as the father of vertebrate paleontology, Cuvier made significant contributions to the study of ancient life and taught at Paris’s Museum of Natural
History. Based on his study of large vertebrate fossils, he was the first to suggest species could go extinct. However, he thought new species were introduced by special creation after catastrophic floods [21; 24].

Hutton’s ideas about uniformitarianism and Earth’s age were not well received by the scientific community of his time. His ideas were falling into obscurity when Charles Lyell, a British lawyer and geologist (1797-1875), wrote the Principles of Geology in the early 1830s and later, Elements of Geology [25; 21]. Lyell’s books promoted Hutton’s principle of uniformitarianism, his studies of rocks and the processes that formed them, and the idea that Earth was possibly over 300 million years old. Lyell and his three-volume Principles of Geology had a lasting influence on the geologic community and public at large, who eventually accepted uniformitarianism and millionfold age for the Earth [26; 21]. The principle of uniformitarianism became so widely accepted, that geologists regarded catastrophic change as heresy. This made it harder for ideas like the sudden demise of the dinosaurs by asteroid impact to gain traction.

A contemporary of Lyell, Charles Darwin (1809-1882) took Principles of Geology on his five-year trip on the HMS Beagle [27]. Darwin used uniformitarianism and deep geologic time to develop his initial ideas about evolution. Lyell was one of the first to publish a reference to Darwin’s idea of evolution [28].

The next big advancement, and perhaps the largest in the history of geology, is the theory of plate tectonics and continental drift. Dogmatic acceptance of uniformitarianism inhibited the progress of this idea, mainly because of the permanency placed on the continents and their positions. Ironically, slow and steady movement of plates would fit well into a uniformitarianism model. However, much time passed and a great deal of scientific resistance had to be overcome before the idea took hold. This happened for several reasons. Firstly, the movement was so slow it was overlooked. Secondly, the best evidence was hidden under the ocean. Finally, the accepted theories were anchored by a large amount of inertia. Instead of being bias free, scientists resisted and ridiculed the emerging idea of plate tectonics. This example of dogmatic thinking is still to this day a tarnish on the geoscience community.
Plate tectonics is most commonly attributed to Alfred Wegener, the first scientist to compile a large data set supporting the idea of continents shifting places over time. He was mostly ignored and ridiculed for his ideas, but later workers like Marie Tharp, Bruce Heezen, Harry Hess, Laurence Morley, Frederick Vine, Drummond Matthews, Kiyoo Wadati, Hugo Benioff, Robert Coats, and J. Tuzo Wilson benefited from advances in sub-sea technologies. They discovered, described, and analyzed new features like the mid-ocean ridge, alignment of earthquakes, and magnetic striping. Gradually these scientists introduced a paradigm shift that revolutionized geology into the science we know today.

*J. Tuzo Wilson*
Quiz: 1.4 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. Which of these assumptions is required for uniformitarianism to hold true?

- Circle Volcanoes and floods and similar landscape-shaping forces must have had the same intensity in the past as they do now.
- Circle Geologic time is vast and all processes must have occurred slowly.
- Circle Processes have been following the same set of rules of nature since the beginning of time.
- Circle Every geologic process that operated on Earth in the past has to still operate today.
- Circle The geologic features and layers that we see today were formed by a series of brief catastrophic events.

2. Which of these is consistent with uniformitarianism? SELECT FOUR

- Circle Each year, a layer of sediment is laid down. Eventually, a large thickness is made.
- Circle An earthquake moved the ground upward 6 inches. In the previous million years, these earthquakes have made the mountain grow taller.
- Circle A large asteroid hit the Earth and caused devastation which killed many species, like the dinosaurs.
- Circle Erosion occurs in the valley every spring when the rains come. By this logic, the valley will be getting deeper every year.
- Circle A single enormous eruption created the island, caused by an unprecedented type of lava.
- Circle Today certain clams and corals only live in shallow tropical marine environments. Ancient rocks with coral fossils also must have formed in tropical marine environments.

3. What simple scientific technique did geologists like Hutton, Steno, and Lyell use to draw fundamental geologic conclusions?

- Circle Digging underground to observe three-dimensional structures
- Circle Performing experiments to replicate the rock record
- Circle Using gems and metal deposits to understand geology
- Circle Comparing ancient rocks/fossils to modern counterparts
- Circle Analyzing the chemistry of the rock record
1.5 The Study of Geology

Geologists apply the scientific method to learn about Earth’s materials and processes. Geology plays an important role in society; its principles are essential to locating, extracting, and managing natural resources; evaluating environmental impacts of using or extracting these resources; as well as understanding and mitigating the effects of natural hazards.

Geology often applies information from physics and chemistry to the natural world, like understanding the physical forces in a landslide or the chemical interaction between water and rocks. The term comes from the Greek word geo, meaning Earth, and logos, meaning to think or reckon with.

1.5.1 Why Study Geology?

Geology plays a key role in how we use natural resources—any naturally occurring material that can be extracted from the Earth for economic gain. Our developed modern society, like all societies before it, is dependent on geologic resources. Geologists are involved in extracting fossil fuels, such as coal and petroleum; metals such as copper, aluminum, and iron; and water resources in streams and underground reservoirs inside soil and rocks. They can help conserve our planet’s finite supply of nonrenewable resources, like petroleum, which are fixed in quantity and depleted by consumption. Geologists can also help manage renewable resources that can be replaced or regenerated, such as solar or wind energy, and timber.

A class looks at rocks in Zion National Park.

Hoover Dam provides hydroelectric energy and stores water for southern Nevada.
Resource extraction and usage impacts our environment, which can negatively affect human health. For example, burning fossil fuels releases chemicals into the air that are unhealthy for humans, especially children. Mining activities can release toxic heavy metals, such as lead and mercury, into the soil and waterways. Our choices will have an effect on Earth’s environment for the foreseeable future. Understanding the remaining quantity, extractability, and renewability of geologic resources will help us better sustainably manage those resources.

Geologists also study natural hazards created by geologic processes. Natural hazards are phenomena that are potentially dangerous to human life or property. No place on Earth is completely free of natural hazards, so one of the best ways people can protect themselves is by understanding geology. Geology can teach people about the natural hazards in an area and how to prepare for them. Geologic hazards include landslides, earthquakes, tsunamis, floods, volcanic eruptions, and sea-level rise.

Finally, geology is where other scientific disciplines intersect in the concept known as Earth System Science. In science, a system is a group of interactive objects and processes. Earth System Science views the entire planet as a combination of systems that interact with each other via complex relationships. This geology textbook provides an introduction to science in general and will often reference other scientific disciplines.

Earth System Science includes five basic systems (or spheres), the Geosphere (the solid body of the Earth), the Atmosphere (the gas envelope surrounding the Earth), the Hydrosphere (water in all its forms at and near the surface of the Earth), the Cryosphere (frozen water part of Earth), and the Biosphere (life on Earth in all its forms and interactions, including humankind).
Rather than viewing geology as an isolated system, earth system scientists study how geologic processes shape not only the world, but all the spheres it contains. They study how these multidisciplinary spheres relate, interact, and change in response to natural cycles and human-driven forces. They use elements from physics, chemistry, biology, meteorology, environmental science, zoology, hydrology, and many other sciences.

1.5.2 Rock Cycle

The most fundamental view of Earth materials is the rock cycle, which describes the major materials that comprise the Earth, the processes that form them, and how they relate to each other. It usually begins with hot molten liquid rock called magma or lava. Magma forms under the Earth’s surface in the crust or mantle. Lava is molten rock that erupts onto the Earth’s surface.

When magma or lava cools, it solidifies by a process called crystallization in which minerals grow within igneous rocks. *Ignis* is Latin for fire.

Igneous rocks, as well as other types of rocks, on Earth’s surface are exposed to weathering and erosion, which produces sediments. Weathering is the physical and chemical breakdown of rocks into smaller fragments. Erosion is the removal of those fragments from their original location. The broken-down and transported fragments or grains are considered sediments, such as gravel, sand, silt, and clay. These sediments may be transported by streams and rivers, ocean currents, glaciers, and wind.

Sediments come to rest in a process known as deposition. As the deposited sediments accumulate—often under water, such as in a shallow marine environment—the older sediments get buried by the new deposits. The
deposits are compacted by the weight of the overlying sediments and individual grains are cemented together by minerals in groundwater. These processes of compaction and cementation are called lithification. Lithified sediments are considered a sedimentary rock, such as sandstone and shale. Other sedimentary rocks are made by direct chemical precipitation of minerals rather than eroded sediments, and are known as chemical sedimentary rocks.

Pre-existing rocks may be transformed into a metamorphic rock; meta- means change and -morphos means form or shape. When rocks are subjected to extreme increases in temperature or pressure, the mineral crystals are enlarged or altered into entirely new minerals with similar chemical make up. High temperatures and pressures occur in rocks buried deep within the Earth’s crust or that come into contact with hot magma or lava. If the temperature and pressure conditions melt the rocks to create magma and lava, the rock cycle begins anew with the creation of new rocks.

1.5.3 Plate Tectonics and Layers of Earth

The theory of plate tectonics is the fundamental unifying principle of geology and the rock cycle. Plate tectonics describes how Earth’s layers move relative to each other, focusing on the tectonic or lithospheric plates of the outer layer. Tectonic plates float, collide, slide past each other, and split apart on an underlying mobile layer called the asthenosphere. Major landforms are created at the plate boundaries, and rocks within the tectonic plates move through the rock cycle. Plate tectonics is discussed in more detail in Chapter 2.
Earth’s three main geological layers can be categorized by chemical composition or the chemical makeup: crust, mantle, and core. The crust is the outermost layer and composed of mostly silicon, oxygen, aluminum, iron, and magnesium [29]. There are two types, continental crust and oceanic crust. Continental crust is about 50 km (30 mi) thick, composed of low-density igneous and sedimentary rocks, Oceanic crust is approximately 10 km (6 mi) thick and made of high-density igneous basalt-type rocks. Oceanic crust makes up most of the ocean floor, covering about 70% of the planet [30]. Tectonic plates are made of crust and a portion the upper mantle, forming a rigid physical layer called the lithosphere.

The mantle, the largest chemical layer by volume, lies below the crust and extends down to about 2,900 km (1,800 mi) below the Earth’s surface [31]. The mostly solid mantle is made of peridotite, a high-density composed of silica, iron, and magnesium [32]. The upper part of mantel is very hot and flexible, which allows the overlying tectonic plates to float and move about on it. Under the mantle is the Earth’s core, which is 3,500 km (2,200 mi) thick and made of iron and nickel. The core consists of two parts, a liquid outer core and solid inner core [33; 34; 35]. Rotations within the solid and liquid metallic core generate Earth’s magnetic field (see figure) [36; 37].
1.5.4 Geologic Time and Deep Time

“The result, therefore, of our present enquiry is, that we find no vestige of a beginning; no prospect of an end.” (James Hutton, 1788)[22]

One of the early pioneers of geology, James Hutton, wrote this about the age of the Earth after many years of geological study. Although he wasn’t exactly correct—there is a beginning and will be an end to planet Earth—Hutton was expressing the difficulty humans have in perceiving the vastness of geological time. Hutton did not assign an age to the Earth, although he was the first to suggest the planet was very old.

Today we know Earth is approximately 4.54 ± 0.05 billion years old. This age was first calculated by Caltech professor Clair Patterson in 1956, who measured the half-lives of lead isotopes to radiometrically date a meteorite recovered in Arizona [38]. Studying geologic time, also known as deep time, can help us overcome a perspective of Earth that is limited to our short lifetimes. Compared to the geologic scale, the human lifespan is very short, and we struggle to comprehend the depth of geologic time and slowness of geologic processes. For example, the study of earthquakes only goes back about 100 years; however, there is geologic evidence of large earthquakes occurring thousands of years ago. And scientific evidence indicates earthquakes will continue for many centuries into the future.

Eons are the largest divisions of time, and from oldest to youngest are named Hadean, Archean, Proterozoic, and Phanerozoic. The three oldest eons are sometimes collectively referred to as Precambrian time.

Life first appeared more than 3,800 million of years ago (Ma). From 3,500 Ma to 542 Ma, or 88% of geologic time, the predominant life forms were single-celled organisms such as bacteria. More complex organisms appeared only more recently, during the current Phanerozoic Eon, which includes the last 542 million years or 12% of geologic time.
Geologic time scale showing time period names and ages. (Source: Belinda Madsen)
The name Phanerozoic comes from *phaneros*, which means visible, and *zoic*, meaning life. This eon marks the proliferation of multicellular animals with hard body parts, such as shells, which are preserved in the geological record as fossils. Land-dwelling animals have existed for 360 million years, or 8% of geologic time. The demise of the dinosaurs and subsequent rise of mammals occurred around 65 Ma, or 1.5% of geologic time. Our human ancestors belonging to the genus *Homo* have existed since approximately 2.2 Ma—0.05% of geological time or just 1/2,000th the total age of Earth.

The Phanerozoic Eon is divided into three eras: Paleozoic, Mesozoic, and Cenozoic. Paleozoic means *ancient life*, and organisms of this era included invertebrate animals, fish, amphibians, and reptiles. The Mesozoic (*middle life*) is popularly known as the Age of Reptiles and is characterized by the abundance of dinosaurs, many of which evolved into birds. The mass extinction of the dinosaurs and other apex predator reptiles marked the end of the Mesozoic and beginning of the Cenozoic. Cenozoic means *new life* and is also called the Age of Mammals, during which mammals evolved to become the predominant land-dwelling animals. Fossils of early humans, or hominids, appear in the rock record only during the last few million years of the Cenozoic. The geologic time scale, geologic time, and geologic history are discussed in more detail in chapters 7 and 8.

### 1.5.5 The Geologist’s Tools

In its simplest form, a geologist’s tool may be a rock hammer used for sampling a fresh surface of a rock. A basic tool set for fieldwork might also include:

- Magnifying lens for looking at mineralogical details
- Compass for measuring the orientation of geologic features
- Map for documenting the local distribution of rocks and minerals
- Magnet for identifying magnetic minerals like magnetite
- Dilute solution of hydrochloric acid to identify carbonate-containing minerals like calcite or limestone.

In the laboratory, geologists use optical microscopes to closely examine rocks and soil for mineral composition and grain size. Laser and mass spectrometers precisely measure the chemical composition and geological age of minerals. Seismographs record and locate earthquake activity, or when used in conjunction with ground penetrating radar, locate objects buried beneath the surface of the earth. Scientists apply computer simulations to turn their collected data into testable, theoretical models.
Hydrogeologists drill wells to sample and analyze underground water quality and availability. Geochemists use scanning electron microscopes to analyze minerals at the atomic level, via x-rays. Other geologists use gas chromatography to analyze liquids and gases trapped in glacial ice or rocks.

Technology provides new tools for scientific observation, which leads to new evidence that helps scientists revise and even refute old ideas. Because the ultimate technology will never be discovered, the ultimate observation will never be made. And this is the beauty of science—it is ever-advancing and always discovering something new.

**Quiz: 1.5 Did I Get It?**

This quiz is for you to check your comprehension of this section.

1. **Igneous rocks form by ____________.**
   - [ ] lithification
   - [ ] erosion
   - [ ] crystallization
   - [ ] heat and pressure
   - [ ] melting

2. **Which layer of the Earth is liquid?**
   - [ ] Outer core
   - [ ] Inner core
   - [ ] Asthenosphere
   - [ ] Lithosphere
   - [ ] Mantle
1.6 Science Denial and Evaluating Sources

Introductory science courses usually deal with accepted scientific theory and do not include opposing ideas, even though these alternate ideas may be credible. This makes it easier for students to understand the complex material. Advanced students will encounter more controversies as they continue to study their discipline.

Some groups of people argue that some established scientific theories are wrong, not based on their scientific merit but rather on the ideology of the group. This section focuses on how to identify evidence based information and differentiate it from pseudoscience.

1.6.1 Science Denial

Science denial happens when people argue that established scientific theories are wrong, not based on scientific merit but rather on subjective ideology—such as for social, political, or economic reasons. Organizations and people use science denial as a rhetorical argument against issues or ideas they oppose. Three examples of science denial versus science are: 1) teaching evolution in public schools, 2) linking tobacco smoke to cancer, and 3) linking human activity to climate change. Among these, denial of climate change is strongly connected with geology. A climate denier specifically denies or doubts the objective conclusions of geologists and climate scientists.

Science denial generally uses three false arguments. The first argument tries to undermine the credibility of the scientific conclusion by claiming the research methods...
are flawed or the theory is not universally accepted—the science is unsettled. The notion that scientific ideas are not absolute creates doubt for non-scientists; however, a lack of universal truths should not be confused with scientific uncertainty. Because science is based on falsifiability, scientists avoid claiming universal truths and use language that conveys uncertainty. This allows scientific ideas to change and evolve as more evidence is uncovered.

The second argument claims the researchers are not objective and motivated by an ideology or economic agenda. This is an *ad hominem* argument in which a person’s character is attacked instead of the merit of their argument. They claim results have been manipulated so researchers can justify asking for more funding. They claim that because the researchers are funded by a federal grant, they are using their results to lobby for expanded government regulation.

The third argument is to demand a balanced view, equal time in media coverage and educational curricula, to engender the false illusion of two equally valid arguments. Science deniers frequently demand equal coverage of their proposals, even when there is little scientific evidence supporting their ideology. For example, science deniers might demand religious explanations be taught as an alternative to the well-established theory of evolution \[39; 40\]. Or that all possible causes of climate change be discussed as equally probable, regardless of the body of evidence. Conclusions derived using the scientific method should not be confused with those based on ideologies.

Furthermore, conclusions about nature derived from ideologies have no place in science research and education. For example, it would be inappropriate to teach the flat earth model in a modern geology course because this idea has been disproved by the scientific method. Unfortunately, widespread scientific illiteracy allows these arguments to be used to suppress scientific knowledge and spread misinformation.

The formation of new conclusions based on the scientific method is the only way to change scientific conclusions. We wouldn’t teach Flat Earth geology along with plate tectonics because Flat Earthers don’t follow the scientific method. The fact that scientists avoid universal truths and change their ideas as more evidence is uncovered shouldn’t be seen as meaning that the science is unsettled. Because of widespread scientific illiteracy, these arguments are used by those who wish to suppress science and misinform the general public.
In a classic case of science denial, beginning in the 1960s and for the next three decades, the tobacco industry and their scientists used rhetorical arguments to deny a connection between tobacco usage and cancer. Once it became clear scientific studies overwhelmingly found that using tobacco dramatically increased a person’s likelihood of getting cancer, their next strategy was to create a sense of doubt about the science. The tobacco industry suggested the results were not yet fully understood and more study was needed. They used this doubt to lobby for delaying legislative action that would warn consumers of the potential health hazards [39; 41]. This same tactic is currently being employed by those who deny the significance of human involvement in climate change.

1.6.2 Evaluating Sources of Information

In the age of the internet, information is plentiful. Geologists, scientists, or anyone exploring scientific inquiry must discern valid sources of information from pseudoscience and misinformation. This evaluation is especially important in scientific research because scientific knowledge is respected for its reliability [42]. Textbooks such as this one can aid this complex and crucial task. At its roots, quality information comes from the scientific method [43], beginning with the empirical thinking of Aristotle. The application of the scientific method helps produce unbiased results. A valid inference or interpretation is based on objective evidence or data. Credible data and inferences are clearly labeled, separated, and differentiated. Anyone
looking over the data can understand how the author’s conclusion was derived or come to an alternative conclusion. Scientific procedures are clearly defined so the investigation can be replicated to confirm the original results or expanded further to produce new results. These measures make a scientific inquiry valid and its use as a source reputable. Of course, substandard work occasionally slips through and retractions are published from time to time. An infamous article linking the MMR vaccine to autism appeared in the highly reputable journal *Lancet* in 1998. Journalists discovered the author had multiple conflicts of interest and fabricated data, and the article was retracted in 2010.

In addition to methodology, data, and results, the authors of a study should be investigated. When looking into any research, the author(s) should be investigated [44]. An author’s credibility is based on multiple factors, such as having a degree in a relevant topic or being funded from an unbiased source.

The same rigor should be applied to evaluating the publisher, ensuring the results reported come from an unbiased process [45]. The publisher should be easy to discover. Good publishers will show the latest papers in the journal and make their contact information and identification clear. Reputable journals show their peer review style. Some journals are predatory, where they use unexplained and unnecessary fees to submit and access journals. Reputable journals have recognizable editorial boards. Often, a reliable journal will associate with a trade, association, or recognized open source initiative.

One of the hallmarks of scientific research is peer review. Research should be transparent to peer review. This allows the scientific community to reproduce experimental results, correct and retract errors, and validate theories. This allows reproduction of experimental results, corrections of errors, and proper justification of the research to experts.

Citation is not only imperative to avoid plagiarism, but also allows readers to investigate an author’s line of thought and conclusions. When reading scientific works, it is important to confirm the citations are from reputable scientific research. Most often, scientific citations are used to reference paraphrasing rather than quotes. The number of times a work is cited is said to measure of the influence an investigation has within the scientific community, although this technique is inherently biased [46].
Quiz: 1.6 Did I Get It

This quiz is for you to check your comprehension of this section.

1. Science deniers commonly use what three rhetorical arguments?
   - [ ] The scientific methods are flawed
   - [ ] Attack the scientists personally
   - [ ] Present alternative scientific data to disprove scientific conclusions
   - [ ] Demand equal time for "balanced" view

2. Which three of the following makes a source more credible?
   - [ ] Inferences clearly distinguished from data in report
   - [ ] Produced by an institution with a long history of being trustworthy
   - [ ] Made by scientists who have never been wrong before
   - [ ] Made by scientists who have been working for a long time
   - [ ] Research was reviewed by peers who have expertise in the field

Summary

Science is a process, with no beginning and no end. Science is never finished because a full truth can never be known. However, science and the scientific method are the best way to understand the universe we live in. Scientists draw conclusions based on objective evidence; they consolidate these conclusions into unifying models. Geologists likewise understand studying the Earth is an ongoing process, beginning with James Hutton who declared the Earth has “...no vestige of a beginning, no prospect of an end.” Geologists explore the 4.5 billion-year history of Earth, its resources, and its many hazards. From a larger viewpoint, geology can teach people how to develop credible conclusions, as well as identify and stop misinformation.
Chapter 1 Review Quiz

Take this quiz for a general review of this chapter.

1. In the scientific method, which step would normally follow observation?
   - Hypothesis development
   - Theory development
   - Peer review
   - Analysis
   - Testing/experimentation

2. Why are objective observations so important to science?
   - They can be stated by anyone
   - They are helpful in removing bias
   - They produce the numbers used in scientific calculations
   - They are 100% free of bias
   - They can only be done by trained scientists

3. Why do scientists prefer quantitative data?
   - Give a higher degree of certainty
   - More aesthetically pleasing
   - Reveal trends and used in calculations
   - The data last longer and can be stored better
   - Easier to look at and think about

4. Deductive reasoning focuses on ________________, while inductive reasoning deals with ________________.
   - intelligence; observation
   - observation; inference
   - inference; observation
   - intelligence; inference
   - observation; intelligence
5. Which of the following geologic phenomena would be outside the realm of uniformitarianism? SELECT TWO

- Rounded pebbles in conglomerates formed like rounded pebbles today
- Ophiolites are parts of the ocean floor brought to the surface
- Diamonds come from strange, deep volcanoes that do not erupt any longer
- Banded iron formed as oxygen entered the atmosphere
- Landslides typically occur where they have in the past
- When sea levels are high, marine rocks form on continents

6. The observation that “23% of the sandstone is composed of the mineral quartz” is best characterized as a ________ observation.

- quantitative and subjective
- qualitative and objective
- quantitative and deductive
- qualitative and objective
- qualitative and deductive
- quantitative and subjective

7. What paradigm shift in geology most changed the way geologists look at the world?

- Extinction
- Deep time
- Uniformitarianism
- Plate tectonics
- Evolution
8. Why did Aristotelian empiricism fall out of favor as science advanced?

- It was based outside the moral fabric of the church
- It stated only scholars could progress science
- It relied on evidence observable by human senses
- It was made illegal by dictators
- It did not allow theories to change

9. Which large chunk of geologic time is characterized by the lack of easy-to-find fossils?

- Precambrian
- Paleozoic
- Hadean
- Phanerozoic
- Archean

10. As metamorphism progresses and intensifies in the rock cycle, what event or process is likely to take place next?

- Weathering
- Melting
- Igneous rock
- Lithification
- Crystallization
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2 Plate Tectonics

A layer of shallow ocean limestone (white) has been brought to the top of a mountain by the convergent forces of the Sevier Orogeny. Near Sun River Canyon, Montana.

KEY CONCEPTS

At the end of this chapter, students should be able to:

- Describe how the ideas behind plate tectonics started with Alfred Wegener’s hypothesis of continental drift
- Describe the physical and chemical layers of the Earth and how they affect plate movement
- Explain how movement at the three types of plate boundaries causes earthquakes, volcanoes, and mountain building
- Identify convergent boundaries, including subduction and collisions, as places where plates come together
- Identify divergent boundaries, including rifts and mid-ocean ridges, as places where plates separate
- Explain transform boundaries as places where adjacent plates shear past each other
- Describe the Wilson Cycle, beginning with continental rifting, ocean basin creation, plate subduction, and ending with ocean basin closure
- Explain how the tracks of hotspots, places that have continually rising magma, is used to calculate plate motion
Revolution is a word usually reserved for significant political or social changes. Several of these idea revolutions forced scientists to re-examine their entire field, triggering a paradigm shift that shook up their conventionally held knowledge. Charles Darwin’s book on evolution, *On the Origin of Species*, published in 1859; Gregor Mendel’s discovery of the genetic principles of inheritance in 1866; and James Watson, Francis Crick, and Rosalind Franklin’s model for the structure of DNA in 1953 did that for biology. Albert Einstein’s relativity and quantum mechanics concepts in the early twentieth century did the same for Newtonian physics.

The concept of plate tectonics was just as revolutionary for geology. The theory of plate tectonics attributes the movement of massive sections of the Earth’s outer layers with creating earthquakes, mountains, and volcanoes. Many earth processes make more sense when viewed through the lens of plate tectonics. Because it is so important in understanding how the world works, plate tectonics is the first topic of discussion in this textbook.

### 2.1 Alfred Wegener’s Continental Drift Hypothesis

Alfred Wegener (1880-1930) was a German scientist who specialized in meteorology and climatology. His knack for questioning accepted ideas started in 1910 when he disagreed with the explanation that the Bering Land Bridge was formed by isostasy, and that similar land bridges once connected the continents. After reviewing the scientific literature, he published a hypothesis stating the continents were originally connected,
and then drifted apart. While he did not have the precise mechanism worked out, his hypothesis was backed up by a long list of evidence.

### 2.1.1 Early Evidence for Continental Drift Hypothesis

Wegener’s first piece of evidence was that the coastlines of some continents fit together like pieces of a jigsaw puzzle. People noticed the similarities in the coastlines of South America and Africa on the first world maps, and some suggested the continents had been ripped apart. Antonio Snider-Pellegrini did preliminary work on continental separation and matching fossils in 1858.

What Wegener did differently was synthesize a large amount of data in one place. He used true edges of the continents, based on the shapes of the continental shelves. This resulted in a better fit than previous efforts that traced the existing coastlines.

Wegener also compiled evidence by comparing similar rocks, mountains, fossils, and glacial formations across oceans. For example, the fossils of the primitive aquatic reptile *Mesosaurus* were found on the separate coastlines of Africa and South America. Fossils of another reptile, *Lystrosaurus*, were found on Africa, India, and Antarctica. He pointed out these were land-dwelling creatures could not have swum across an entire ocean.

![Map of world elevations. Note the light blue, which are continental shelves flooded by shallow ocean water. These show the true shapes of the continents.](image1)

![Image showing fossils that connect the continents of Gondwana (the southern continents of Pangea).](image2)
Opponents of continental drift insisted trans-oceanic land bridges allowed animals and plants to move between continents. The land bridges eventually eroded away, leaving the continents permanently separated. The problem with this hypothesis is the improbability of a land bridge being tall and long enough to stretch across a broad, deep ocean.

More support for continental drift came from the puzzling evidence that glaciers once existed in normally very warm areas in southern Africa, India, Australia, and Arabia. These climate anomalies could not be explained by land bridges. Wegener found similar evidence when he discovered tropical plant fossils in the frozen region of the Arctic Circle. As Wegener collected more data, he realized the explanation that best fit all the climate, rock, and fossil observations involved moving continents.

2.1.2 Proposed Mechanism for Continental Drift

Wegener’s work was considered a fringe science theory for his entire life. One of the biggest flaws in his hypothesis was an inability to provide a mechanism for how the continents moved. Obviously, the continents did not appear to move, and changing the conservative minds of the scientific community would require exceptional evidence that supported a credible mechanism. Other pro-continental drift followers used expansion, contraction, or even the moon’s origin to explain how the continents moved. Wegener used centrifugal forces and precession, but this model was proven wrong. He also speculated about seafloor spreading, with hints of convection, but could not substantiate these proposals. As it turns out, current scientific knowledge reveals convection is the major force in driving plate movements.

2.1.3 Development of Plate Tectonic Theory

Wegener died in 1930 on an expedition in Greenland. Poorly respected in his lifetime, Wegener and his ideas about moving continents seemed destined to be lost in history as
fringe science. However, in the 1950s, evidence started to trickle in that made continental drift a more viable idea. By the 1960s, scientists had amassed enough evidence to support the missing mechanism—namely, seafloor spreading—for Wegener’s hypothesis of continental drift to be accepted as the theory of plate tectonics. Ongoing GPS and earthquake data analyses continue to support this theory. The next section provides the pieces of evidence that helped transform one man’s wild notion into a scientific theory.

**MAPPING OF THE OCEAN FLOORS**

In 1947 researchers started using an adaptation of SONAR to map a region in the middle of the Atlantic Ocean with poorly-understood topographic and thermal properties. Using this information, Bruce Heezen and Marie Tharp created the first detailed map of the ocean floor to reveal the Mid-Atlantic Ridge, a basaltic mountain range that spanned the length of the Atlantic Ocean, with rock chemistry and dimensions unlike the mountains found on the continents. Initially scientists thought the ridge was part of a mechanism that explained the expanding Earth or ocean-basin growth hypotheses. In 1959, Harry Hess proposed the hypothesis of seafloor spreading — that the mid-ocean ridges represented tectonic plate factories, where new oceanic plate was issuing from these long volcanic ridges. Scientists later included transform faults perpendicular to the ridges to better account for varying rates of movement between the newly formed plates. When earthquake epicenters were discovered along the ridges, the idea that earthquakes were linked to plate movement took hold.

Seafloor sediment, measured by dredging and drilling, provided another clue. Scientists once believed sediment accumulated on the ocean floors over a very long time in a static environment. When some studies showed less sediment than expected, these results were initially used to argue against continental movement. With more time, researchers discovered these thinner sediment layers were located close to mid-ocean ridges,
indicating the ridges were younger than the surrounding ocean floor. This finding supported the idea that the sea floor was not fixed in one place.

**PALEOMAGNETISM**

The seafloor was also mapped magnetically. Scientists had long known of strange magnetic anomalies that formed a striped pattern of symmetrical rows on both sides of mid-oceanic ridges. What made these features unusual was the north and south magnetic poles within each stripe was reversed in alternating rows. By 1963, Harry Hess and other scientists used these magnetic reversal patterns to support their model for seafloor spreading (see also Lawrence W. Morley).

Paleomagnetism is the study of magnetic fields frozen within rocks, basically a fossilized compass. In fact, the first hard evidence to support plate motion came from paleomagnetism.

Igneous rocks containing magnetic minerals like magnetite typically provide the most useful data. In their liquid state as magma or lava, the magnetic poles of the minerals align themselves with the Earth’s magnetic field. When the rock cools and solidifies, this alignment is frozen into place, creating a permanent paleomagnetic record that includes magnetic inclination related to global latitude, and declination related to magnetic north.

Scientists had noticed for some time the alignment of magnetic north in many rocks was nowhere close to the earth’s current magnetic north. Some explained this away are part of the normal movement of earth’s magnetic north pole. Eventually, scientists realized adding the idea of continental movement explained the data better than pole movement alone.
Around the same time mid-ocean ridges were being investigated, other scientists linked the creation of ocean trenches and island arcs to seismic activity and tectonic plate movement. Several independent research groups recognized earthquake epicenters traced the shapes of oceanic plates sinking into the mantle. These deep earthquake zones congregated in planes that started near the surface around ocean trenches and angled beneath the continents and island arcs. Today these earthquake zones called Wadati-Benioff zones.

Based on the mounting evidence, the theory plate tectonics continued to take shape. J. Tuzo Wilson was the first scientist to put the entire picture together by proposing that the opening and closing of the ocean basins. Before long, scientists proposed other models showing plates moving with respect to each other, with clear boundaries between them. Others started piecing together complicated histories of tectonic plate movement. The plate tectonic revolution had taken hold.
Which of the following are evidence for continental drift, and which are evidence for plate tectonics?

Matching fossils and rocks
GPS measurements
Mid-ocean ridge found
Ocean trenches found
Matching coastlines
Lined-up earthquakes
Warm places glaciated
Cooler places with tropical fossils
Paleomagnetism showing moving rocks

2.1 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. Which of the following are evidence Wegener used to construct the idea of Continental Drift? SELECT ALL THAT APPLY

- [ ] Matching the edges of the continental shelves
- [ ] Matching fossils across the ocean
- [ ] Evidence of climate change in the geologic record
- [ ] Paleomagnetism
- [ ] Earthquake locations lined up with certain features
- [ ] Deep ocean features like trenches and mid-ocean ridges
2. Which of the following are evidence that was used to refine continental drift into the modern Theory of Plate Tectonics? **SELECT ALL THAT APPLY**

- ☐ Evidence of drastic climate shifts in the geologic record
- ☐ Matching fossils across the ocean
- ☐ Matching the edges of the continental shelves
- ☐ Earthquake locations lined up with certain features
- ☐ Large deep ocean features like trenches and mid-ocean ridges
- ☐ Paleomagnetism

3. **How did scientists first figure out plates could sink into the interior of the planet, since no one can see this happening?**

- ☒ Isostasy states that as mountains move upwards, land must also sink elsewhere
- ☒ Measurements via GPS showed ocean basins closing rapidly
- ☒ It was an inference based on expansion around mid-ocean ridges
- ☒ Lines of progressively-deeper earthquakes near arcs and trenches
- ☒ Earthquake waves mapped the liquid interior of Earth and showed movement
2.2 Layers of the Earth

In order to understand the details of plate tectonics, it is essential to first understand the layers of the earth. Firsthand information about what is below the surface is very limited; most of what we know is pieced together from hypothetical models, and analyzing seismic wave data and meteorite materials. In general, the Earth can be divided into layers based on chemical composition and physical characteristics.

2.2.1 Chemical Layers

Certainly the earth is composed of a countless combination of elements. Regardless of what elements are involved two major factors—temperature and pressure—are responsible for creating three distinct chemical layers.

CRUST

The outermost chemical layer and the one we currently reside on, is the crust. There are two types of crust. Continental crust has a relatively low density and composition similar to granite. Oceanic crust has a relatively high density, especially when cold and old, and composition similar to basalt. The surface levels of crust are relatively brittle. The deeper parts of the crust are subjected to higher temperatures and pressure, which makes them more ductile. Ductile materials are like soft plastics or putty, they move under force. Brittle materials are like solid glass or pottery, they break under force, especially when it is applied quickly. Earthquakes, generally occur in the upper crust and are caused by the rapid movement of relatively brittle materials.

The base of the crust is characterized by a large increase in seismic velocity, which measures how fast earthquake waves travel through solid matter. Called the Mohorovičić Discontinuity, or Moho for short, this zone was discovered by Andrija Mohorovičić (pronounced mo-ho-ro-vee-cheech; audio pronunciation) in 1909 after studying earthquake wave paths in his native Croatia. The change in wave direction and
speed is caused by dramatic chemical differences of the crust and mantle. Underneath the oceans, the Moho is found roughly 5 km below the ocean floor. Under the continents, it is located about 30-40 km below the surface. Near certain large mountain-building events known as orogenies, the continental Moho depth is doubled.

**MANTLE**

The mantle sits below the crust and above the core. It is the largest chemical layer by volume, extending from the base of the crust to a depth of about 2900 km. Most of what we know about the mantle comes from seismic wave analysis, though information is gathered by studying ophiolites and xenoliths. Ophiolites are pieces of mantle that have risen through the crust until they are exposed as part of the ocean floor. Xenoliths are carried within magma and brought to the Earth’s surface by volcanic eruptions. Most xenoliths are made of peridotite, an ultramafic class of igneous rock (see chapter 4.2 for explanation). Because of this, scientists hypothesize most of the mantle is made of peridotite.

**CORE**

The core of the Earth, which has both liquid and solid layers, and consists mostly of iron, nickel, and possibly some oxygen. Scientists looking at seismic data first discovered this innermost chemical layer in 1906. Through a union of hypothetical modeling, astronomical insight, and hard seismic data, they concluded the core is mostly metallic iron. Scientists studying meteorites, which typically contain more iron than surface rocks, have proposed the earth was formed from meteoric material. They believe the liquid
component of the core was created as the iron and nickel sank into the center of the planet, where it was liquefied by intense pressure.

2.2.2 Physical Layers

The Earth can also be broken down into five distinct physical layers based on how each layer responds to stress. While there is some overlap in the chemical and physical designations of layers, specifically the core-mantle boundary, there are significant differences between the two systems.

**LITHOSPHERE**

Lithos is Greek for stone, and the lithosphere is the outermost physical layer of the Earth. It is grouped into two types: oceanic and continental. Oceanic lithosphere is thin and relatively rigid. It ranges in thickness from nearly zero in new plates found around mid-ocean ridges, to an average of 140 km in most other locations. Continental lithosphere is generally thicker and considerably more plastic, especially at the deeper levels. Its thickness ranges from 40 to 280 km.

The lithosphere is not continuous. It is broken into segments called plates. A plate boundary is where two plates meet and move relative to each other. Plate boundaries are where we see plate tectonics in action—mountain building, triggering earthquakes, and generating volcanic activity.

**ASTHENOSPHERE**

The asthenosphere is the layer below the lithosphere. Astheno- means lacking strength, and the most distinctive property of the asthenosphere is movement. Because it is mechanically weak, this layer moves and flows due to convection currents created by heat coming from the earth’s core cause. Unlike the lithosphere that consists of multiple plates, the asthenosphere is relatively unbroken. Scientists have determined this by analyzing seismic waves
that pass through the layer. The depth of at which the asthenosphere is found is temperature-dependent. It tends to lie closer to the earth’s surface around mid-ocean ridges and much deeper underneath mountains and the centers of lithospheric plates.

**MESOSPHERE**

The mesosphere, sometimes known as the lower mantle, is more rigid and immobile than the asthenosphere. Located at a depth of approximately 410 and 660 km below the earth’s surface, the mesosphere is subjected to very high pressures and temperatures. These extreme conditions create a transition zone in the upper mesosphere where minerals continuously change into various forms, or pseudomorphs. Scientists identify this zone by changes in seismic velocity and sometimes physical barriers to movement. Below this transitional zone, the mesosphere is relatively uniform until it reaches the core.

**INNER AND OUTER CORE**

The outer core is the only entirely liquid layer within the Earth. It starts at a depth of 2,890 km and extends to 5,150 km, making it about 2,300 km thick. In 1936, the Danish geophysicist Inge Lehmann analyzed seismic data and was the first to prove a solid inner core existed within a liquid outer core. The solid inner core is about 1,220 km thick, and the outer core is about 2,300 km thick.

It seems like a contradiction that the hottest part of the Earth is solid, as the minerals making up the core should be liquified or vaporized at this temperature. Immense pressure keeps the minerals of the inner core in a solid phase. The inner core grows slowly from the lower outer core solidifying as heat escapes the interior of the Earth and is dispersed to the outer layers.
The earth’s liquid outer core is critically important in maintaining a breathable atmosphere and other environmental conditions favorable for life. Scientists believe the earth’s magnetic field is generated by the circulation of molten iron and nickel within the outer core. If the outer core were to stop circulating or become solid, the loss of the magnetic field would result in Earth getting stripped of life-supporting gases and water. This is what happened, and continues to happen, on Mars.

Match the layer of the Earth with the description that fits it best!

- The lowest density layer ________________________________
- The highest density layer ________________________________
- The only liquid layer ________________________________
- The largest layer by volume ________________________________
- The layer plates are made from ________________________________
- The layer that moves the plates around ________________________________

2.2.3 Plate Tectonic Boundaries

At passive margins the plates don’t move—the continental lithosphere transitions into oceanic lithosphere and forms plates made of both types. A tectonic plate may be made of both oceanic and continental lithosphere connected by a passive margin. North and South America’s eastern coastlines are examples of passive margins. Active margins are places where
the oceanic and continental lithospheric tectonic plates meet and move relative to each other, such as the western coasts of North and South America. This movement is caused by frictional drag created between the plates and differences in plate densities. The majority of mountain-building events, earthquake activity and active volcanism on the Earth’s surface can be attributed to tectonic plate movement at active margins.

In a simplified model, there are three categories of tectonic plate boundaries. Convergent boundaries are places where plates move toward each other. At divergent boundaries, the plates move apart. At transform boundaries, the plates slide past each other.
Quiz: 2.2 Did I Get It?
This quiz is for you to check your comprehension of this section.

1. What makes continental plates different than oceanic plates?
   - ☐ Oceanic plates are thicker
   - ☐ Continental plates can flow internally
   - ☐ Continental plates have more volcanoes
   - ☐ Oceanic plates are more brittle
   - ☐ Oceanic plates are older

2. What term is used for a boundary between a continent and a ocean basin without relative motion between them?
   - ☐ Passive
   - ☐ Convergent
   - ☐ Transform
   - ☐ Active
   - ☐ Divergent

3. Which layers of the Earth can move internally or flow? SELECT TWO
   - ☐ Mantle
   - ☐ Asthenosphere
   - ☐ Outer core
   - ☐ Inner core
   - ☐ Lithosphere
2.3 Convergent Boundaries

Convergent boundaries, also called destructive boundaries, are places where two or more plates move toward each other. Convergent boundary movement is divided into two types, subduction and collision, depending on the density of the involved plates. Continental lithosphere is of lower density and thus more buoyant than the underlying asthenosphere. Oceanic lithosphere is more dense than continental lithosphere, and, when old and cold, may even be more dense than asthenosphere.

When plates of different densities converge, the higher density plate is pushed beneath the more buoyant plate in a process called subduction. When continental plates converge without subduction occurring, this process is called collision.

2.3.1. Subduction

Subduction occurs when a dense oceanic plate meets a more buoyant plate, like a continental plate or warmer/younger oceanic plate, and descends into the mantle. The worldwide average rate of oceanic plate subduction is 25 miles per million years, about a half-inch per year. As an oceanic plate descends, it pulls the ocean floor down into a trench. These trenches can be more than twice as deep as the average depth of the adjacent ocean basin, which is usually three to four km. The Mariana Trench, for example, approaches a staggering 11 km.
Within the trench, ocean floor sediments are scraped together and compressed between the subducting and overriding plates. This feature is called the accretionary wedge, mélangé, or accretionary prism. Fragments of continental material, including microcontinents, riding atop the subducting plate may become sutured to the accretionary wedge and accumulate into a large area of land called a terrane. Vast portions of California are comprised of accreted terranes.

When the subducting oceanic plate, or slab, sinks into the mantle, the immense heat and pressure pushes volatile materials like water and carbon dioxide into an area below the continental plate and above the descending plate called the mantle wedge. The volatiles are released mostly by hydrated minerals that revert to non-hydrated minerals in these higher temperature and pressure conditions. When mixed with asthenospheric material above the plate, the volatile lower the melting point of the mantle wedge, and through a process called flux melting it becomes liquid magma. The molten magma is more buoyant than the lithospheric plate above it and migrates to the Earth’s surface where it emerges as volcanism. The resulting volcanoes frequently appear as curved mountain chains, volcanic arcs, due to the curvature of the earth. Both oceanic and continental plates can contain volcanic arcs.
How subduction is initiated is still a matter of scientific debate. It is generally accepted that subduction zones start as passive margins, where oceanic and continental plates come together, and then gravity initiates subduction and converts the passive margin into an active one. One hypothesis is gravity pulls the denser oceanic plate down or the plate can start to flow ductility at a low angle. Scientists seeking to answer this question have collected evidence that suggests new subduction zone is forming off the coast of Portugal. Some scientists have proposed large earthquakes like the 1755 Lisbon earthquake may even have something to do with this process of creating a subduction zone, although the evidence is not definitive.

Another hypothesis proposes subduction happens at transform boundaries involving plates of different densities.

Some plate boundaries look like they should be active, but show no evidence of subduction. The oceanic lithospheric plates on either side of the Atlantic Ocean for example, are denser than the underlying asthenosphere and are not subducting beneath the continental plates. One hypothesis is the bond holding the oceanic and continental plates together is stronger than the downwards force created by the difference in plate densities.

Subduction zones are known for having the largest earthquakes and tsunamis; they are the only places with fault surfaces large enough to create magnitude-9 earthquakes. These subduction-zone earthquakes not only are very large, but also are very deep. When a subducting slab becomes stuck and cannot descend, a massive amount of energy builds up between the stuck plates. If this energy is not gradually dispersed, it may force the plates to suddenly release along several hundred kilometers of the subduction zone. Because subduction-zone faults are located on the ocean floor, this massive amount of movement can generate giant tsunamis such as those that followed the 2004
Indian Ocean Earthquake and 2011 Tōhoku Earthquake in Japan.

All subduction zones have a forearc basin, a feature of the overriding plate found between the volcanic arc and oceanic trench. The forearc basin experiences a lot of faulting and deformation activity, particularly within the accretionary wedge.

In some subduction zones, tensional forces working on the continental plate create a backarc basin on the interior side of the volcanic arc. Some scientists have proposed a subduction mechanism called oceanic slab rollback creates extension faults in the overriding plates. In this model, the descending oceanic slab does not slide directly under the overriding plate but instead rolls back, pulling the overlying plate seaward. The continental plate behind the volcanic arc gets stretched like pizza dough until the surface cracks and collapses to form a backarc basin. If the extension activity is extensive and deep enough, a backarc basin can develop into a continental rifting zone. These continental divergent boundaries may be less symmetrical than their mid-ocean ridge counterparts.

In places where numerous young buoyant oceanic plates are converging and subducting at a relatively high velocity, they may force the overlying continental plate to buckle and crack. This is called back-arc faulting. Extensional back-arc faults pull rocks and chunks of plates apart. Compressional back-arc faults, also known as thrust faults, push them together.

The dual spines of the Andes Mountain range include an example of compressional thrust faulting. The western spine is part of a volcanic arc. Thrust faults have deformed the non-volcanic eastern spine, pushing rocks and pieces of continental plate on top of each other.

There are two styles of thrust fault deformation: thin-skinned faults that occur in superficial rocks lying on top of the continental plate and thick-skinned faults that reach deeper into the crust. The Sevier Orogeny in the western U.S. is a notable thin-skinned type of deformation created during the Cretaceous Period. The Laramide Orogeny, a thick-skinned type of deformation, occurred near the end of and slightly after the Sevier Orogeny in the same region.
Flat-slab, or shallow, subduction caused the Laramide Orogeny. When the descending slab subducts at a low angle, there is more contact between the slab and the overlying continental plate than in a typical subduction zone. The shallowly-subducting slab pushes against the overriding plate and creates an area of deformation on the overriding plate many kilometers away from the subduction zone.

**OCEANIC-CONTINENTAL SUBDUCTION**

Oceanic-continental subduction occurs when an oceanic plate dives below a continental plate. This convergent boundary has a trench and mantle wedge and frequently, a volcanic arc. Well-known examples of continental volcanic arcs are the Cascade Mountains in the Pacific Northwest and western Andes Mountains in South America.

**OCEANIC-OCEANIC SUBDUCTION**

The boundaries of oceanic-oceanic subduction zones show very different activity from those involving oceanic-continental plates. Since both plates are made of oceanic lithosphere, it is usually the older plate that subducts because it is colder and denser. The volcanism on the overlying oceanic plate may remain hidden underwater. If the volcanoes rise high enough the reach the ocean surface, the chain
of volcanism forms an island arc. Examples of these island arcs include the Aleutian Islands in the northern Pacific Ocean, Lesser Antilles in the Caribbean Sea, and numerous island chains scattered throughout the western Pacific Ocean.

2.3.2. Collisions

When continental plates converge, during the closing of an ocean basin for example, subduction is not possible between the equally buoyant plates. Instead of one plate descending beneath another, the two masses of continental lithosphere slam together in a process known as collision. Without subduction, there is no magma formation and no volcanism. Collision zones are characterized by tall, non-volcanic mountains; a broad zone of frequent, large earthquakes; and very little volcanism.

Two continental plates colliding.

When oceanic crust connected by a passive margin to continental crust completely subducts beneath a continent, an ocean basin closes, and continental collision begins. Eventually, as ocean basins close, continents join together to form a massive accumulation of continents called a supercontinent, a process that has taken place in ~500 million year old cycles over earth’s history.

The process of collision created Pangea, the supercontinent envisioned by Wegener as the key component of his continental drift hypothesis. Geologists now have evidence that continental plates have been continuously converging into supercontinents and splitting into smaller basin-separated continents throughout Earth’s existence, calling this process the supercontinent cycle, a process that takes place in approximately 500 million years. For example, they estimate Pangea began separating 200 million years ago. Pangea was preceded by an earlier supercontinents, one of which being Rodinia, which existed 1.1 billion years ago and started breaking apart 800 million to 600 million years ago.
A foreland basin is a feature that develops near mountain belts, as the combined mass of the mountains forms a depression in the lithospheric plate. While foreland basins may occur at subduction zones, they are most commonly found at collision boundaries. The Persian Gulf is possibly the best modern example, created entirely by the weight of the nearby Zagros Mountains.

If continental and oceanic lithosphere are fused on the same plate, it can partially subduct but its buoyancy prevents it from fully descending. In very rare cases, part of a continental plate may become trapped beneath a descending oceanic plate in a process called obduction. When a portion of the continental crust is driven down into the subduction zone, due to its buoyancy it returns to the surface relatively quickly.

As pieces of the continental lithosphere break loose and migrate upward through the obduction zone, they bring along bits of the mantle and ocean floor and amend them on top of the continental plate. Rocks composed of this mantle and ocean-floor material are called ophiolites and they provide valuable information about the composition of the mantle.

The area of collision-zone deformation and seismic activity usually covers a broader area because continental lithosphere is plastic and malleable. Unlike subduction-zone earthquakes, which tend to be located along a narrow swath near the convergent boundary, collision-zone earthquakes may occur hundreds of kilometers from the boundary between the plates.

The Eurasian continent has many examples of collision-zone deformations covering vast areas. The Pyrenees mountains begin in the Iberian Peninsula and cross into France. Also, there are the Alps stretching from Italy to central Europe; the Zagros mountains from Arabia to Iran; and Himalaya mountains from the Indian subcontinent to central Asia.
2.3 Did I Get it?

This quiz is for you to check your comprehension of this section.

1. **What type of motion occurs at a transform boundary?** Plates move ____________.
   - on top of each other
   - side to side
   - underneath each other
   - together
   - apart

2. **Why do continents generally not subduct?**
   - Continents are pushed up by mantle convection, preventing subduction
   - Continents are too ductile to subduct
   - Ocean plates move faster and do not allow continents to subduct
   - Continents are too low in density to subduct
   - Continents are too strongly attached to ocean plates to subduct

3. **What features are associated with subduction?** SELECT FOUR
   - Tsunamis
   - Volcanic arc
   - Mid-ocean ridge
   - Trench
   - Rift
   - Largest earthquakes

4. **As a rift forms, what feature commonly can form next?**
   - Collision
   - Supercontinent
   - Mid-ocean ridge
   - Rift
   - Transform fault
2.4 Divergent Boundaries

At divergent boundaries, sometimes called constructive boundaries, lithospheric plates move away from each other. There are two types of divergent boundaries, categorized by where they occur: continental rift zones and mid-ocean ridges. Continental rift zones occur in weak spots in the continental lithospheric plate. A mid-ocean ridge usually originates in a continental plate as a rift zone that expands to the point of splitting the plate apart, with seawater filling in the gap. The separate pieces continue to drift apart and become individual continents. This process is known as rift-to-drift.

2.4.1. Continental Rifting

In places where the continental plates are very thick, they reflect so much heat back into the mantle it develops strong convection currents that push superheated mantle material up against the overlying plate, softening it. Tensional forces created by this convective upwelling begin to pull the weakened plate apart. As it stretches, it becomes thinner and develops deep cracks called extension or normal faults. Eventually plate sections located between large faults drop into deep depressions known as rift valleys, which often contain keystone-shaped blocks of down-dropped crust known as grabens. The shoulders of these grabens are called horsts. If only one side of a section drops, it is called a half-graben. Depending on the conditions, rifts can grow into very large lakes and even oceans.

While seemingly occurring at random, rifting is dictated by two factors. Rifting does not occur in continents with older and more stable interiors, known as cratons. When continental rifting does occur, the break-up pattern resembles the seams of a soccer ball, also called a truncated icosahedron. This is the most common surface-fracture pattern to develop on an evenly expanding sphere because it uses the least amount of energy.

The Afar Triangle (center) has the Red Sea ridge (center to upper left), Gulf of Aden ridge (center to right), and East African Rift (center to lower left) form a triple junction that are about 120° apart.
Using the soccer ball model, rifting tends to lengthen and expand along a particular seam while fizzling out in the other directions. These seams with little or no tectonic activity are called failed rift arms. A failed rift arm is still a weak spot in the continental plate; even without the presence of active extension faults, it may develop into a called an aulacogen. One example of a failed rift arm is the Mississippi Valley Embayment, a depression through which the upper end of the Mississippi River flows. Occasionally connected rift arms do develop concurrently, creating multiple boundaries of active rifting. In places where the rift arms do not fail, for example the Afar Triangle, three divergent boundaries can develop near each other forming a triple junction.

Rifts come in two types: narrow and broad. Narrow rifts are characterized by a high density of highly active divergent boundaries. The East African Rift Zone, where the horn of Africa is pulling away from the mainland, is an excellent example of an active narrow rift. Lake Baikal in Russia is another. Broad rifts also have numerous fault zones, but they are distributed over wide areas of deformation. The Basin and Range region located in the western United States is a type of broad rift. The Wasatch Fault, which also created the Wasatch Mountain Range in the state of Utah, forms the eastern divergent boundary of this broad rift (Animation 1 and Animation 2).

Rifts have earthquakes, although not of the magnitude and frequency of other boundaries. They may also exhibit volcanism. Unlike the flux-melted magma found in subduction zones, rift-zone magma is created by decompression melting. As the continental plates are pulled apart, they create a region of low pressure that melts the lithosphere and draws it upwards. When this molten magma reaches the weakened and fault-riddled rift zone, it migrates to surface by breaking through the plate or escaping via an open fault. Examples of young rift volcanoes dot the Basin and Range region in the United States. Rift-zone activity is responsible for generating some unique volcanism, such as the Ol Doinyo Lengai in Tanzania.
This volcano erupts lava consisting largely of carbonatite, a relatively cold, liquid carbonate mineral.

2.4.2. Mid-ocean ridges

As rifting and volcanic activity progress, the continental lithosphere becomes more mafic (see Chapter 4) and thinner, with the eventual result transforming the plate under the rifting area into oceanic lithosphere. This is the process that gives birth to a new ocean, much like the narrow Red Sea emerged with the movement of Arabia away from Africa. As the oceanic lithosphere continues to diverge, a mid-ocean ridge is formed.

Mid-ocean ridges, also known as spreading centers, have several distinctive features. They are the only places on earth that create new oceanic lithosphere. Decompression melting in the rift zone changes asthenosphere material into new lithosphere, which oozes up through cracks in oceanic plate. The amount of new lithosphere being created at mid-ocean ridges is highly significant. These undersea rift volcanoes produce more lava than all other types of volcanism combined. Despite this, most mid-ocean ridge volcanism remains unmapped because the volcanoes are located deep on the ocean floor.

In rare cases, such as a few locations in Iceland, rift zones display the type of volcanism, spreading, and ridge formation found on the ocean floor.

The ridge feature is created by the accumulation of hot lithosphere material, which is lighter than the dense underlying asthenosphere. This chunk of isostatically buoyant lithosphere sits partially submerged and partially exposed on the asthenosphere, like an ice cube floating in a glass of water.

As the ridge continues to spread, the lithosphere material is pulled away from the area of volcanism and becomes colder and denser. As it continues to spread and

Age of oceanic lithosphere, in millions of years. Notice the differences in the Atlantic Ocean along the coasts of the continents.
cool, the lithosphere settles into wide swathes of relatively featureless topography called abyssal plains with lower topography.

This model of ridge formation suggests the sections of lithosphere furthest away from the mid-ocean ridges will be the oldest. Scientists have tested this idea by comparing the age of rocks located in various locations on the ocean floor. Rocks found near ridges are younger than those found far away from any ridges. Sediment accumulation patterns also confirm the idea of sea-floor spreading. Sediment layers tend to be thinner near mid-ocean ridges, indicating it has had less time to build up.

As mentioned in the section on paleomagnetism and the development of plate tectonic theory, scientists noticed mid-ocean ridges contained unique magnetic anomalies that show up as symmetrical striping on both sides of the ridge. The Vine-Matthews-Morley hypothesis proposes these alternating reversals are created by the earth’s magnetic field being imprinted into magma after it emerges from the ridge. Very hot magma has no magnetic field. As the oceanic plates get pulled apart, the magma cools below the Curie point, the temperature below which a magnetic field gets locked into magnetic minerals. The alternating magnetic reversals in the rocks reflects the periodic swapping of earth’s magnetic north and south poles. This paleomagnetic pattern provides a great historical record of ocean-floor movement, and is used to reconstruct past tectonic activity and determine rates of ridge spreading.

Thanks to their distinctive geology, mid-ocean ridges are home to some of the most unique ecosystems ever discovered. The ridges are often studded with hydrothermal vents, deep fissures that allow seawater to circulate through the upper portions of the oceanic plate and
interact with hot rock. The super-heated seawater rises back up to the surface of the plate, carrying dissolved gasses and minerals, and small particulates. The resulting emitted hydrothermal water looks like black underwater smoke.

Scientists had known about these geothermal areas on the ocean floor for some time. However, it was not until 1977, when scientists piloting a deep submergence vehicle, the Alvin, discovered a thriving community of organisms clustered around these hydrothermal vents. These unique organisms, which include 10-foot-long tube worms taller than people, live in the complete darkness of the ocean floor deprived of oxygen and sunlight. They use geothermal energy provided by the vents and a process called bacterial chemosynthesis to feed on sulfur compounds. Before this discovery, scientists believed life on earth could not exist without photosynthesis, a process that requires sunlight. Some scientists suggest this type of environment could have been the origin of life on Earth, and perhaps even extraterrestrial life elsewhere in the galaxy, such as on Jupiter’s moon Europa.
2.4 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. Where on Earth is the best example of current (active) rifting?

- [ ] Central Australia
- [ ] Mariana Trench
- [ ] East Africa
- [ ] Andes
- [ ] Japan

2. Which of these are features found at rift zones? SELECT TWO

- [ ] Trench
- [ ] Faults and rifts at 120° angles
- [ ] Graben
- [ ] Arc
- [ ] Tsunami

3. How is magma generated at divergent boundaries?

- [ ] Added sediment
- [ ] Added water
- [ ] Decreased pressure
- [ ] Chemical reactions
- [ ] Friction

4. What happens as newly formed oceanic crust moves away from the mid-ocean ridge?

- [ ] The seafloor increases in height
- [ ] Sediment gets thinner
- [ ] The crust gets warmer
- [ ] The crust thickens
- [ ] The crust gets colder
2.5 Transform Boundaries

A transform boundary, sometimes called a strike-slip or conservative boundary, is where the lithospheric plates slide past each other in the horizontal plane. This movement is described based on the perspective of an observer standing on one of the plates, looking across the boundary at the opposing plate. Dextral, also known as right-lateral, movement describes the opposing plate moving to the right. Sinistral, also known as left lateral, movement describe the opposing plate moving to the left.

Most transform boundaries are found on the ocean floor, around mid-ocean ridges. These boundaries form aseismic fracture zones, filled with earthquake-free transform faults, to accommodate different rates of spreading occurring at the ridge.

Some transform boundaries produce significant seismic activity, primarily as earthquakes, with very little mountain-building or volcanism. This type of transform boundary may contain a single fault or series of faults, which develop in places where plate tectonic stresses are transferred to the surface. As with other types of active boundaries, if the plates are unable to shear past each other the tectonic forces will continue to build up. If the built up energy between the plates is suddenly released, the result is an earthquake.

In the eyes of humanity, the most significant transform faults occur within continental plates, and have a shearing motion that frequently produces moderate-to-large magnitude earthquakes. Notable examples include the San Andreas Fault in California, Northern and Eastern Anatolian Faults in Turkey, Altyn Tagh Fault in central Asia, and Alpine Fault in New Zealand.
2.5.1. Transpression and Transtension

Bends along transform faults may create compressional or extensional forces that cause secondary faulting zones. Transpression occurs where there is a component of compression in addition to the shearing motion. These forces build up around the area of the bend, where the opposing plates are restricted from sliding past each other. As the forces continue to build up, they create mountains in the restraining bend around the fault. The Big Bend area, located in the southern part of the San Andreas Fault includes a large area of transpression where many mountains have been built, moved, and even rotated.

Transtension zones require a fault that includes a releasing bend, where the plates are being pulled apart by extensional forces. Depressions and sometimes volcanism develop in the releasing bend, along the fault. The Dead Sea found between Israel and Jordan, and the Salton Sea of California are examples of basins formed by transtensional forces.

2.5.2. Piercing Points

When a geological feature is cut by a fault, it is called a piercing point. Piercing points are very useful for recreating past fault movement, especially along transform boundaries. Transform faults are unique because their horizontal motion keeps a geological feature relatively intact, preserving the record of what happened. Other types of faults—normal and reverse—tend to be more destructive, obscuring or destroying these features. The best type of piercing point includes unique patterns that are used to match the parts of a geological feature separated by fault movement. Detailed studies of piercing points show the San Andreas Fault has experienced over 225 km of movement in the last 20 million years, and this movement occurred at three different fault traces.
2.5 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. **What makes transform boundaries different than other boundaries?**
   - Transform has fewer earthquakes
   - Transform are less common
   - Transform are older
   - Transform has almost no volcanoes
   - Transform makes more mountains

2. **Why are piercing points important to transform boundaries?**
   - They create earthquakes
   - They prevent volcanoes
   - They turn into mid-ocean ridges
   - They help with erosion
   - They track fault movement

3. **What famous transform fault is known for being the boundary between the Pacific Plate and North American Plate in California?**
   - Garlock fault
   - San Andreas fault
   - Alpine fault
   - Denali fault
   - Altyn Tagh fault

4. **What are the two ways transform faults move?**
   - Left and right
   - Top to bottom
   - Over and under
   - Up and down
   - In and out
2.6 The Wilson Cycle

The Wilson Cycle is named for J. Tuzo Wilson who first described it in 1966, and it outlines the ongoing origin and breakup of supercontinents, such as Pangea and Rodinia. Scientists have determined this cycle has been operating for at least three billion years and possibly earlier.

There are a number of hypotheses about how the Wilson Cycle works. One mechanism proposes that rifting happens because continental plates reflect the heat much better than oceanic plates. When continents congregate together, they reflect more of the Earth’s heat back into the mantle, generating more vigorous convection currents that then start the continental rifting process. Some geologists believe mantle plumes are remnants of these periods of increased mantle temperature and convection upwelling, and study them for clues about the origin of continental rifting.

The mechanism behind how supercontinents are created is still largely a mystery. There are three schools of thought about what continues to drive the continents further apart and eventually bring them together. The ridge-push hypothesis suggests after the initial rifting event, plates continue to be pushed apart by mid-ocean spreading centers and their underlying convection currents. Slab-pull proposes the plates are pulled apart by descending slabs in the subduction zones of the oceanic-continental margins. A third idea, gravitational sliding, attributes the movement to gravitational forces pulling the lithospheric plates down from the elevated mid-ocean ridges and across the underlying asthenosphere. Current evidence seems to support slab pull more than ridge push or gravitational sliding.

2.7 Hotspots

The Wilson Cycle provides a broad overview of tectonic plate movement. To analyze plate movement more precisely, scientists study hotspots. First postulated by J. Tuzo Wilson in 1963, a hotspot is an area in the lithospheric plate where molten magma breaks through and creates a volcanic center, islands in the ocean and mountains on land. As the plate moves across the hotspot, the volcano center becomes extinct because it is no longer over an active magma source. Instead, the magma emerges through another area in the plate to create a new active volcano. Over time, the combination of moving plate and
stationary hotspot creates a chain of islands or mountains. The classic definition of hotspots states they do not move, although recent evidence suggests that there may be exceptions.

Hotspots are the only types of volcanism not associated with subduction or rifting zones at plate boundaries; they seem totally disconnected from any plate tectonics processes, such as earthquakes. However, there are relationships between hotspots and plate tectonics. There are several hotspots, current and former, that are believed to have begun at the time of rifting. Also, scientists use the age of volcanic eruptions and shape of the chain to quantify the rate and direction of plate movement relative to the hotspot.

Scientists are divided over how magma is generated in hotspots. Some suggest that hotspots originate from super-heated material from as deep as the core that reaches the Earth's crust as a mantle plume. Others argue the molten material that feeds hotspots is sourced from the mantle. Of course, it is difficult to collect data from these deep-Earth features due to the extremely high pressure and temperature.

How hotspots are initiated is another highly debated subject. The prevailing mechanism has hotspots starting in divergent boundaries during supercontinent rifting. Scientists have identified a number of current and past hotspots believed to have begun this way. Subducting slabs have also been named as causing mantle plumes and hotspot volcanism. Some geologists have suggested another geological process not involving plate tectonics may be involved, such as a large space objects crashing into the earth. Regardless of how they are formed, dozens are on the Earth. Some well-known examples include the Tahiti Islands, Afar Triangle, Easter Island, Iceland, Galapagos Islands, and Samoan Islands. The United States is home to two of the largest and best-studied hotspots: Hawaii and Yellowstone.
2.7.1 Hawaiian hotspot

The active volcanoes in Hawaii represent one of the most active hotspot sites on earth. Scientific evidence indicates the Hawaiian hotspot is at least 80 million years old. Geologists believe it is actually much older; however any rocks with proof of this have been subducted under the ocean floor. The big island of Hawaii sits atop a large mantle plume that marks the active hotspot. The Kilauea volcano is the main vent for this hotspot and has been actively erupting since 1983.

This enormous volcanic island chain, much of which is underwater, stretches across the Pacific for almost 6,000 km. The seamount chain’s most striking feature is a sharp 60-degree bend located at the midpoint, which marks a significant change in plate movement direction that occurred 50 million years ago. The change in direction has been more often linked to a plate reconfiguration, but also to other things like plume migration.

In an attempt to map the Hawaiian mantle plume as far down as the lower mantle, scientists have used tomography, a type of three-dimensional seismic imaging. This information—along with other evidence gathered from rock ages, vegetation types, and island size—indicate the oldest islands in the chain are located the furthest away from the active hotspot.
2.7.2 YELLOWSTONE HOTSPOT

Like the Hawaiian version, the Yellowstone hotspot is formed by magma rising through the lithosphere. What makes it different is this hotspot is located under a thick, continental plate. Hawaii sits on a thin oceanic plate, which is easily breached by magma coming to the surface. At Yellowstone, the thick continental plate presents a much more difficult barrier for magma to penetrate. When it does emerge, the eruptions are generally much more violent. Thankfully they are also less frequent.

Over 15 million years of eruptions by this hotspot have carved a curved path across the western United States. It has been suggested the Yellowstone hotspot is connected to the much older Columbia River flood basalts and even to 70 million-year-old volcanism found in the Yukon region of Canada.

The most recent major eruption of this hotspot created the Yellowstone Caldera and Lava Creek tuff formation approximately 631,000 years ago. The eruption threw 1,000 cubic kilometers of ash and magma into the atmosphere, some of which was found as far away as Mississippi. Should the hotspot erupt again, scientists predict it will be another massive event. This would be a calamity reaching far beyond the western United States. These super volcanic eruptions fill the earth’s atmosphere with so much gas and ash, they block sunlight from reaching the earth. Not only would this drastically alter climates and environments around the globe, it could affect worldwide food production.

Several prominent ash beds found in North America, including three Yellowstone eruptions shaded pink (Mesa Falls, Huckleberry Ridge, and Lava Creek), the Bisho Tuff ash bed (brown dashed line), and the modern May 18th, 1980 ash fall (yellow).
2.6/7 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. What makes the Hawaiian hot spot different than the Yellowstone hot spot?

- Different types of tectonic plates
- Yellowstone’s higher elevation
- Different type of mantle below
- Hawai’i has more places for magma to come up
- Yellowstone is colder

2. What features or processes are common in hot spots?

- Volcanism
- Trenches
- Earthquakes
- Arcs
- Rifts

3. According to the Wilson Cycle, what feature or process is most likely to occur after collision?

- Ocean-ocean subduction
- Rifting
- Ocean-continent subduction
- Transform faults
- Mid-ocean ridge
Summary

Plate tectonics is a unifying theory; it explains nearly all of the major geologic processes on Earth. Since its early inception in the 1950s and 1960s, geologists have been guided by this revolutionary perception of the world. The theory of plate tectonics states the surface layer of the Earth is broken into a network of solid, relatively brittle plates. Underneath the plates is a much hotter and more ductile layer that contains zones of convective upwelling generated by the interior heat of Earth. These convection currents move the surface plates around—bringing them together, pulling them apart, and shearing them side-by-side. Earthquakes and volcanoes form at the boundaries where the plates interact, with the exception of volcanic hotspots, which are not caused by plate movement.

Chapter 2 Review Quiz

Take this quiz for a general review of this chapter.

1. Why did Alfred Wegener never get the support of the scientific community for his hypothesis of continental drift during his lifetime? CHOOSE TWO

- [ ] He had no evidence for his idea
- [ ] He could not disprove the idea of land bridges
- [ ] It is difficult to change people's minds
- [ ] He could not provide a mechanism for how continents moved
- [ ] He had an abrasive personality which made people not support him
- [ ] GPS had not been invented yet to show movement

2. Why are there not as many earthquakes or volcanoes on the east coast of North America as the west coast of North America?

- [ ] The crust on the east coast is too thick to allow volcanoes.
- [ ] The crust on the east coast is too thick to allow earthquakes.
- [ ] The Atlantic side of the continent moves slower than the Pacific side.
- [ ] The plate boundary on the east coast is purely transform.
- [ ] It is not close to a plate boundary (passive margin).
3. Which plate boundary has the largest and deepest earthquakes?
   - Collisional
   - Rift
   - Subduction
   - Mid-ocean ridge
   - Transform

4. What is the biggest difference between hot-spot volcanism in an island chain and plate tectonic volcanism in an island chain?
   - Hot spots erupt more often
   - Arcs have different magma
   - Hot spots only have tsunamis
   - Hot spots have age trends
   - Arcs have less earthquakes

5. Which plate boundary is least likely to be dangerous to humans?
   - Subduction
   - Rift
   - Collision
   - Transform
   - Mid-ocean ridge

6. Which boundaries generally produce new liquid magma?
   SELECT THREE
   - Collision
   - Transform
   - Mid-ocean ridge
   - Subduction
   - Rift
7. Which tectonic setting places the asthenosphere farthest from the surface?

- ☐ Collision
- ☐ Transform
- ☐ Subduction
- ☐ Mid-ocean ridge
- ☐ Rift

8. As you move towards the mid-ocean ridge, __________.

- ☐ sediment gets thicker
- ☐ the crust gets thicker
- ☐ the seafloor decreases in height
- ☐ the crust gets colder
- ☐ the crust gets younger

9. Which layer of the earth makes up the plates of plate tectonics?

- ☐ Lithosphere
- ☐ Mantle
- ☐ Crust
- ☐ Mesosphere
- ☐ Asthenosphere

10. A line of shallow earthquakes with little or no volcanism is likely evidence of what type of plate boundary?

- ☐ ocean-continent convergent
- ☐ ocean-ocean convergent
- ☐ slow-rifting divergent
- ☐ transform
- ☐ fast-rifting divergent
11. We are not able to get rocks from the deep within the Earth. What is the source of information that allows us to draw conclusions about the interior? SELECT TWO

- Diamond incusions
- Volcanic eruptions
- Seismic waves
- Drilling
- Meteorites
- Gas measurements

References

References are available at: https://opengeology.org/textbook/2-plate-tectonics/#References
These selenite (gypsum) crystals, found in The Cave of the Crystals in Naica, Mexico, have some of the largest minerals ever found. The largest crystal found here is 39 feet (12 meters) and 55 tones.

KEY CONCEPTS

At the end of this chapter, students should be able to:

- Define mineral.
- Describe the basic structure of the atom.
- Derive basic atomic information from the Periodic Table of Elements.
- Describe chemical bonding related to minerals.
- Describe the main ways minerals form.
- Describe the silicon-oxygen tetrahedron and how it forms common silicate minerals.
- List common non-silicate minerals in oxide, sulfide, sulfate, and carbonate groups.
- Identify minerals using physical properties and identification tables.
The term “minerals” as used in nutrition labels and pharmaceutical products is not the same as a mineral in a geological sense. In geology, the classic definition of a mineral is: 1) naturally occurring, 2) inorganic, 3) solid at room temperature, 4) regular crystal structure, and 5) defined chemical composition. Some natural substances technically should not be considered minerals, but are included by exception. For example, water and mercury are liquid at room temperature. Both are considered minerals because they were classified before the room-temperature rule was accepted as part of the definition. Calcite is quite often formed by organic processes, but is considered a mineral because it is widely found and geologically important. Because of these discrepancies, the International Mineralogical Association in 1985 amended the definition to: “A mineral is an element or chemical compound that is normally crystalline and that has been formed as a result of geological processes.” This means that the calcite in the shell of a clam is not considered a mineral. But once that clam shell undergoes burial, diagenesis, or other geological processes, then the calcite is considered a mineral. Typically, substances like coal, pearl, opal, or obsidian that do not fit the definition of mineral are called mineraloids.

A rock is a substance that contains one or more minerals or mineraloids. As is discussed in later chapters, there are three types of rocks composed of minerals: igneous (rocks crystallizing from molten material), sedimentary (rocks composed of products of mechanical weathering (sand, gravel, etc.) and chemical weathering (things precipitated from solution), and metamorphic (rocks produced by alteration of other rocks by heat and pressure).

### 3.1 Chemistry of Minerals

Rocks are composed of minerals that have a specific chemical composition. To understand mineral chemistry, it is essential to examine the fundamental unit of all matter, the atom.

#### 3.1.1 The Atom

Matter is made of atoms. Atoms consists of subatomic particles—protons, neutrons, and electrons. A simple model of the atom has a central nucleus composed of protons, which have positive charges, and neutrons which have no charge. A cloud of negatively charged electrons surrounds the nucleus, the number of electrons equaling the number of protons thus balancing the positive charge of the protons for a neutral atom. Protons and neutrons each have a mass number of 1. The mass of an electron is less than $1/1000^\text{th}$ that of a proton or neutron, meaning most of the atom’s mass is in the nucleus.
3.1.2 Periodic Table of the Elements

Matter is composed of elements which are atoms that have a specific number of protons in the nucleus. This number of protons is called the **Atomic Number** for the element. For example, an oxygen atom has 8 protons and an iron atom has 26 protons. An element cannot be broken down chemically into a simpler form and retains unique chemical and physical properties. Each element behaves in a unique manner in nature. This uniqueness led scientists to develop a periodic table of the elements, a tabular arrangement of all known elements listed in order of their atomic number.

![Periodic Table of the Elements](image)

The Periodic Table of the Elements

The first arrangement of elements into a periodic table was done by Dmitri Mendeleev in 1869 using the elements known at the time [1]. In the periodic table, each element has a chemical symbol, name, atomic number, and atomic mass. The chemical symbol is an abbreviation for the element, often derived from a Latin or Greek name for the
The atomic number is the number of protons in the nucleus. The atomic mass is the number of protons and neutrons in the nucleus, each with a mass number of one. Since the mass of electrons is so much less than the protons and neutrons, the atomic mass is effectively the number of protons plus neutrons.

The atomic mass of natural elements represents an average mass of the atoms comprising that substance in nature and is usually not a whole number as seen on the periodic table, meaning that an element exists in nature with atoms having different numbers of neutrons. The differing number of neutrons affects the mass of an element in nature and the atomic mass number represents this average. This gives rise to the concept of isotope. Isotopes are forms of an element with the same number of protons but different numbers of neutrons. There are usually several isotopes for a particular element. For example, 98.9% of carbon atoms have 6 protons and 6 neutrons. This isotope of carbon is called carbon-12 ($^{12}\text{C}$). A few carbon atoms, carbon-13 ($^{13}\text{C}$), have 6 protons and 7 neutrons. A trace amount of carbon atoms, carbon-14 ($^{14}\text{C}$), has 6 protons and 8 neutrons.

Among the 118 known elements, the heaviest are fleeting human creations known only in high energy particle accelerators, and they decay rapidly. The heaviest naturally occurring element is uranium, atomic number 92. The eight most abundant elements in Earth’s continental crust are shown in Table 1 [3; 4]. These elements are found in the most common rock forming minerals.

Element abundance pie chart for Earth’s crust by Callan Bentley.
3.1.3 Chemical Bonding

Most substances on Earth are compounds containing multiple elements. Chemical bonding describes how these atoms attach with each other to form compounds, such as sodium and chlorine combining to form NaCl, common table salt. Compounds that are held together by chemical bonds are called molecules. Water is a compound of hydrogen and oxygen in which two hydrogen atoms are covalently bonded with one oxygen.

---

<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Abundance %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>O</td>
<td>47%</td>
</tr>
<tr>
<td>Silicon</td>
<td>Si</td>
<td>28%</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Al</td>
<td>8%</td>
</tr>
<tr>
<td>Iron</td>
<td>Fe</td>
<td>5%</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca</td>
<td>4%</td>
</tr>
<tr>
<td>Sodium</td>
<td>Na</td>
<td>3%</td>
</tr>
<tr>
<td>Potassium</td>
<td>K</td>
<td>3%</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>2%</td>
</tr>
</tbody>
</table>

*Table 1. Eight Most Abundant Elements in the Earth’s Continental Crust % by weight (source: [USGS](https://www.usgs.gov)). All other elements are less than 1%.*
making the water molecule. The oxygen we breathe is formed when one oxygen atom covalently bonds with another oxygen atom to make the molecule O₂. The subscript 2 in the chemical formula indicates the molecule contains two atoms of oxygen.

Most minerals are also compounds of more than one element. The common mineral calcite has the chemical formula CaCO₃, indicating the molecule consists of one calcium, one carbon, and three oxygen atoms. In calcite, one carbon and three oxygen atoms are held together by covalent bonds to form a molecular ion, called carbonate, which has a negative charge. Calcium as an ion has a positive charge of plus two. The two oppositely charged ions attract each other and combine to form the mineral calcite, CaCO₃. The name of the chemical compound is calcium carbonate, where calcium is Ca and carbonate refers to the molecular ion CO₃²⁻.

The mineral olivine has the chemical formula (Mg,Fe)₂SiO₄, in which one silicon and four oxygen atoms are bonded with two atoms of either magnesium or iron. The comma between iron (Fe) and magnesium (Mg) indicates the two elements can occupy the same location in the crystal structure and substitute for one another.

3.1.3.1 VALENCE AND CHARGE

The electrons around the atom’s nucleus are located in shells representing different energy levels. The outermost shell is called the valence shell. Electrons in the valence shell are involved in chemical bonding. In 1913, Niels Bohr proposed a simple model of the atom that states atoms are more stable when their outermost shell is full [5; 6]. Atoms of most elements thus tend to gain or lose electrons so the outermost or valence shell is full. In Bohr’s model, the innermost shell can have a maximum of two electrons and the second and third shells can have a maximum of eight electrons. When the innermost shell is the valence shell, as in the case of hydrogen and helium, it obeys the octet rule when it is full with two electrons. For elements in higher rows, the octet rule of eight electrons in the valence shell applies.

The rows in the periodic table present the elements in order of atomic number and the columns organize elements with similar characteristics, such as the same number of electrons in their valence shells. Columns are often labeled from left to right with Roman numerals I to VIII, and Arabic numerals 1 through 18. The elements in columns I and II have 1 and 2 electrons in their respective valence shells and the elements in columns VI and VII have 6 and 7 electrons in their respective valence shells.

In row 3 and column I, sodium (Na) has 11 protons in the nucleus and 11 electrons in three shells—2 electrons in the inner shell, 8 electrons in the second shell, and 1 electron in the
valence shell. To maintain a full outer shell of 8 electrons per the octet rule, sodium readily gives up that 1 electron so there are 10 total electrons. With 11 positively charged protons in the nucleus and 10 negatively charged electrons in two shells, sodium when forming chemical bonds is an ion with an overall net charge of +1.

All elements in column I have a single electron in their valence shell and a valence of 1. These other column I elements also readily give up this single valence electron and thus become ions with a +1 charge. Elements in column II readily give up 2 electrons and end up as ions with a charge of +2. Note that elements in columns I and II which readily give up their valence electrons, often form bonds with elements in columns VI and VII which readily take up these electrons. Elements in columns 3 through 15 are usually involved in covalent bonding. The last column 18 (VIII) contains the noble gases. These elements are chemically inert because the valence shell is already full with 8 electrons, so they do not gain or lose electrons. An example is the noble gas helium which has 2 valence electrons in the first shell. Its valence shell is therefore full. All elements in column VIII possess full valence shells and do not form bonds with other elements.

As seen above, an atom with a net positive or negative charge as a result of gaining or losing electrons is called an ion. In general the elements on the left side of the table lose electrons and become positive ions, called cations because they are attracted to the cathode in an electrical device. The elements on the right side tend to gain electrons. These are called anions because they are attracted to the anode in an electrical device. The elements in the center of the periodic table, columns 3 through 15, do not consistently follow the octet rule. These are called transition elements. A common example is iron, which has a +2 or +3 charge depending on the oxidation state of the element. Oxidized Fe\(^{3+}\) carries a +3 charge and reduced Fe\(^{2+}\) is +2. These two different oxidation states of iron often impart dramatic colors to rocks containing their minerals—the oxidized form producing red colors and the reduced form producing green.
3.1.3.2 IONIC BONDING

Ionic bonds, also called electron-transfer bonds, are formed by the electrostatic attraction between atoms having opposite charges. Atoms of two opposite charges attract each other electrostatically and form an ionic bond in which the positive ion transfers its electron (or electrons) to the negative ion which takes them up. Through this transfer both atoms thus achieve a full valence shell. For example one atom of sodium (Na\(^{+1}\)) and one atom of chlorine (Cl\(^{-1}\)) form an ionic bond to make the compound sodium chloride (NaCl). This is also known as the mineral halite or common table salt. Another example is calcium (Ca\(^{+2}\)) and chlorine (Cl\(^{-1}\)) combining to make the compound calcium chloride (CaCl\(_2\)). The subscript 2 indicates two atoms of chlorine are ionically bonded to one atom of calcium.

3.1.3.3 COVALENT BONDING

Ionic bonds are usually formed between a metal and a nonmetal. Another type, called a covalent or electron-sharing bond, commonly occurs between nonmetals. Covalent bonds share electrons between ions to complete their valence shells. For example, oxygen (atomic number 8) has 8 electrons—2 in the inner shell and 6 in the valence shell. Gases like oxygen often form diatomic molecules by sharing valence electrons. In the case of oxygen, two atoms attach to each other and share 2 electrons to fill their valence shells to become the common oxygen molecule we breathe (O\(_2\)). Methane (CH\(_4\)) is another covalently bonded gas. The carbon atom needs 4 electrons and each hydrogen needs 1. Each hydrogen shares its electron with the carbon to form a molecule as shown in the figure.
3.1 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. If a magnesium ion is labeled +2, what does that mean?
   - It has gained two protons
   - It has gained two neutrons.
   - It has lost two protons
   - It has gained two electrons
   - It has lost two electrons

2. Minerals have a crystalline structure. What does this mean?
   - That the minerals are generally inorganic and not made from life.
   - That the minerals have a definite chemical composition and are made of the same elements.
   - That the atoms are arranged in an orderly, repetitive manner.
   - That all minerals form beautiful, visible crystals in the right conditions.
   - That the atoms are arranged in random order but definite chemical composition.

3. When a positively-charged sodium ion is chemically bonded with a negatively-charged chlorine ion to make sodium chloride (i.e. the mineral halite), then this is an example of _____.
   - isotopic annealing
   - ionic bonding
   - covalent bonding
   - Van der Walls bonds
   - metallic bonds
4. If an atom of the twelfth element (magnesium) has an atomic mass of 25, how many protons (p), neutrons (n), and electrons (e) does it have?

- p=12, n=12, e=13
- p=13, n=12, e=12
- p=12, n=13, e=12
- p=12, n=13, e=13
- p=13, n=12, e=13

5. Which of the following are NOT considered to be made from a mineral or minerals? SELECT THREE

- A lab-grown diamond
- A fossil baby tooth
- Glass (unordered atoms)
- Your baby teeth
- Icicle
3.2 Formation of Minerals

Minerals form when atoms bond together in a crystalline arrangement. Three main ways this occurs in nature are: 1) precipitation directly from an aqueous (water) solution with a temperature change, 2) crystallization from a magma with a temperature change, and 3) biological precipitation by the action of organisms.

3.2.1 Precipitation from aqueous solution

Solutions consist of ions or molecules, known as solutes, dissolved in a medium or solvent. In nature this solvent is usually water. Many minerals can be dissolved in water, such as halite or table salt, which has the composition sodium chloride, NaCl. The Na\(^{+1}\) and Cl\(^{-1}\) ions separate and disperse into the solution.

Precipitation is the reverse process, in which ions in solution come together to form solid minerals. Precipitation is dependent on the concentration of ions in solution and other factors such as temperature and pressure. The point at which a solvent cannot hold any more solute is called saturation. Precipitation can occur when the temperature of the solution falls, when the solute evaporates, or with changing chemical conditions in the solution. An example of precipitation in our homes is when water evaporates and leaves behind a rind of minerals on faucets, shower heads, and drinking glasses.

In nature, changes in environmental conditions may cause the minerals dissolved in water to form bonds and grow into crystals or cement grains of sediment together. In Utah, deposits of tufa formed from mineral-rich springs that emerged into the ice age Lake Bonneville. Now exposed in dry valleys, this porous tufa was a natural insulation used by pioneers to build their homes with a natural protection against summer heat and winter cold. The travertine terraces at Mammoth Hot Springs in Yellowstone Park are another example formed by calcite precipitation at the edges of the shallow spring-fed ponds.

Another example of precipitation occurs in the Great Salt Lake, Utah, where the concentration of sodium chloride and other salts is nearly eight times greater than in the
world’s oceans. Streams carry salt ions into the lake from the surrounding mountains. With no other outlet, the water in the lake evaporates and the concentration of salt increases until saturation is reached and the minerals precipitate out as sediments. Similar salt deposits include halite and other precipitates, and occur in other lakes like Mono Lake in California and the Dead Sea.

3.2.2 Crystallization from Magma

Heat is energy that causes atoms in substances to vibrate. Temperature is a measure of the intensity of the vibration. If the vibrations are violent enough, chemical bonds are broken and the crystals melt releasing the ions into the melt. Magma is molten rock with freely moving ions. When magma is emplaced at depth or extruded onto the surface (then called lava), it starts to cool and mineral crystals can form.

3.2.3 Precipitation by Organisms

Many organisms build bones, shells, and body coverings by extracting ions from water and precipitating minerals biologically. The most common mineral precipitated by organisms is calcite, or calcium carbonate (CaCO₃). Calcite is often precipitated by organisms as a polymorph called aragonite. Polymorphs are crystals with the same chemical formula but different crystal structures. Marine invertebrates such as corals and clams precipitate aragonite or calcite for their shells and structures. Upon death, their hard parts accumulate on the ocean floor as sediments, and eventually may become the sedimentary rock limestone. Though limestone can form inorganically, the vast majority is formed by this biological process. Another example is marine organisms...
called radiolaria, which are zooplankton that precipitate silica for their microscopic external shells. When the organisms die, the shells accumulate on the ocean floor and can form the sedimentary rock chert. An example of biologic precipitation from the vertebrate world is bone, which is composed mostly of a type of apatite, a mineral in the phosphate group. The apatite found in bones contains calcium and water in its structure and is called hydroxycarbonate apatite, Ca$_5$(PO$_4$)$_3$(OH). As mentioned above, such substances are not technically minerals until the organism dies and these hard parts become fossils.
3.2 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. When a mineral precipitates from solution, it ____________.
   - [ ] seeps into the ground
   - [ ] evaporates from a lake
   - [ ] crystallizes in a fluid
   - [ ] shrinks in size
   - [ ] breaks into pieces

2. What is the most common mineral formed by life?
   - [ ] Dolomite
   - [ ] Quartz
   - [ ] Feldspar
   - [ ] Apatite
   - [ ] Calcite

3. Which of the following can cause an increase in mineral growth?
   SELECT FOUR
   - [ ] Heating a fluid
   - [ ] Changing pressure
   - [ ] Cooling a fluid
   - [ ] Evaporating water
   - [ ] Organisms adding shell material
3.3 Silicate Minerals

Minerals are categorized based on their composition and structure. Silicate minerals are built around a molecular ion called the **silicon-oxygen tetrahedron**. A tetrahedron has a pyramid-like shape with four sides and four corners. Silicate minerals form the largest group of minerals on Earth, comprising the vast majority of the Earth’s mantle and crust. Of the nearly four thousand known minerals on Earth, most are rare. There are only a few that make up most of the rocks likely to be encountered by surface dwelling creatures like us. These are generally called the **rock-forming minerals**.

The silicon-oxygen tetrahedron \((\text{SiO}_4)\) consists of a single silicon atom at the center and four oxygen atoms located at the four corners of the tetrahedron. Each oxygen ion has a -2 charge and the silicon ion has a +4 charge. The silicon ion shares one of its four valence electrons with each of the four oxygen ions in a covalent bond to create a symmetrical geometric four-sided pyramid figure. Only half of the oxygen’s valence electrons are shared, giving the silicon-oxygen tetrahedron an ionic charge of -4. This silicon-oxygen tetrahedron forms bonds with many other combinations of ions to form the large group of silicate minerals.

The silicon ion is much smaller than the oxygen ions (see the figures) and fits into a small space in the center of the four large oxygen ions, seen if the top ball is removed (as shown in the figure to the right). Because only one of the valence electrons of the corner oxygens is shared, the silicon-oxygen tetrahedron has chemically active corners available to form bonds with other silica tetrahedra or other positively charged ions such as \(\text{Al}^{3+}\), \(\text{Fe}^{2+}\), \(\text{Mg}^{2+}\), \(\text{K}^{+}\), \(\text{Na}^{+}\), and \(\text{Ca}^{2+}\). Depending on many factors, such as the original magma chemistry, silica-oxygen
tetrahedra can combine with other tetrahedra in several different configurations. For example, tetrahedra can be isolated, attached in chains, sheets, or three dimensional structures. These combinations and others create the chemical structure in which positively charged ions can be inserted for unique chemical compositions forming silicate mineral groups.

### 3.3.1 The dark ferromagnesian silicates

#### The Olivine Family

Olivine is the primary mineral component in mantle rock such as peridotite and basalt. It is characteristically green when not weathered. The chemical formula is (Fe,Mg)\(_2\)SiO\(_4\). As previously described, the comma between iron (Fe) and magnesium (Mg) indicates these two elements occur in a solid solution. Not to be confused with a liquid solution, a solid solution occurs when two or more elements have similar properties and can freely substitute for each other in the same location in the crystal structure.

Olivine is referred to as a mineral family because of the ability of iron and magnesium to substitute for each other. Iron and magnesium in the olivine family indicates a solid solution forming a compositional series within the mineral group which can form crystals of all iron as one end member and all mixtures of iron and magnesium in between to all magnesium at the other end member. Different mineral names are applied to compositions between these end members. In the olivine series of minerals, the iron and magnesium ions in the solid solution are about the same size and charge, so either atom can fit into the same location in the growing crystals. Within the cooling magma, the mineral crystals continue to grow until they solidify into igneous rock. The relative amounts of iron and magnesium in the parent magma determine which minerals in the series form. Other rarer elements with similar properties to iron or magnesium, like manganese (Mn), can substitute into the olivine crystalline structure in small amounts. Such ionic substitutions in mineral crystals give rise to the great variety of minerals and are often responsible for differences in color and other properties within a group or family of minerals. Olivine has a pure iron end-member (called fayalite) and a pure magnesium ...
end-member (called forsterite). Chemically, olivine is mostly silica, iron, and magnesium and therefore is grouped among the dark-colored ferromagnesian (iron=ferro, magnesium=magnesian) or mafic minerals, a contraction of their chemical symbols Ma and Fe. Mafic minerals are also referred to as dark-colored ferromagnesian minerals. Ferro means iron and magnesian refers to magnesium. Ferromagnesian silicates tend to be more dense than non-ferromagnesian silicates. This difference in density ends up being important in controlling the behavior of the igneous rocks that are built from these minerals: whether a tectonic plate subducts or not is largely governed by the density of its rocks, which are in turn controlled by the density of the minerals that comprise them.

The crystal structure of olivine is built from independent silica tetrahedra. Minerals with independent tetrahedral structures are called neosilicates (or orthosilicates). In addition to olivine, other common neosilicate minerals include garnet, topaz, kyanite, and zircon.

Two other similar arrangements of tetrahedra are close in structure to the neosilicates and grade toward the next group of minerals, the pyroxenes. In a variation on independent tetrahedra called sorosilicates, there are minerals that share one oxygen between two tetrahedra, and include minerals like pistachio-green epidote, a gemstone. Another variation are the cyclosilicates, which as the name suggests, consist of tetrahedral rings, and include gemstones such as beryl, emerald, aquamarine, and tourmaline.
3.3.2 Pyroxene Family

Pyroxene is another family of dark ferromagnesian minerals, typically black or dark green in color. Members of the pyroxene family have a complex chemical composition that includes iron, magnesium, aluminum, and other elements bonded to polymerized silica tetrahedra. Polymers are chains, sheets, or three-dimensional structures, and are formed by multiple tetrahedra covalently bonded via their corner oxygen atoms. Pyroxenes are commonly found in mafic igneous rocks such as peridotite, basalt, and gabbro, as well as metamorphic rocks like eclogite and blue schist.

Pyroxenes are built from long, single chains of polymerized silica tetrahedra in which tetrahedra share two corner oxygens. The silica chains are bonded together into the crystal structures by metal cations. A common member of the pyroxene family is augite, itself containing several solid solution series with a complex chemical formula \((\text{Ca,Na})(\text{Mg,Fe,Al,Ti})(\text{Si,Al})_2\text{O}_6\) that gives rise to a number of individual mineral names.

This single-chain crystalline structure bonds with many elements, which can also freely substitute for each other. The generalized chemical composition for pyroxene is \(XZ(\text{Al,Si})_2\text{O}_6\). X represents the ions Na, Ca, Mg, or Fe, and Z represents Mg, Fe, or Al. These ions have similar ionic sizes, which allows many possible substitutions among them. Although the cations may freely substitute for each other in the crystal, they carry different ionic charges that must be balanced out in the final crystalline structure. For example Na has a charge of +1, but Ca has charge of +2. If a Na\(^+\) ion substitutes for a Ca\(^{+2}\) ion, it creates an unequal charge that must be balanced by other ionic substitutions elsewhere in the crystal. Note that ionic size is more important than ionic charge for substitutions to occur in solid solution series in crystals.
3.3.3 Amphibole Family

Amphibole minerals are built from polymerized double silica chains and they are also referred to as inosilicates. Imagine two pyroxene chains that connect together by sharing a third oxygen on each tetrahedra. Amphiboles are usually found in igneous and metamorphic rocks and typically have a long-bladed crystal habit. The most common amphibole, hornblende, is usually black; however, they come in a variety of colors depending on their chemical composition. The metamorphic rock, amphibolite, is primarily composed of amphibole minerals.

Amphiboles are composed of iron, magnesium, aluminum, and other cations bonded with silica tetrahedra. These dark ferromagnesian minerals are commonly found in gabbro, basalt, diorite, and often form the black specks in granite. Their chemical formula is very complex and generally written as (RSi₄O₁₁)₂, where R represents many different cations. For example, it can also be written more exactly as AX₂Z₅((Si,Al,Ti)₈O₂₂)(OH,F,Cl,O)₂. In this formula A may be Ca, Na, K, Pb, or blank; X equals Li, Na, Mg, Fe, Mn, or Ca; and Z is Li, Na, Mg, Fe, Mn, Zn, Co, Ni, Al, Cr, Mn, V, Ti, or Zr. The substitutions create a wide variety of colors such as green, black, colorless, white, yellow, blue, or brown. Amphibole crystals can also include hydroxide ions (OH⁻) which occurs from an interaction between the growing minerals and water dissolved in magma.
3.3.4 Sheet Silicates

Sheet silicates are built from tetrahedra which share all three of their bottom corner oxygens thus forming sheets of tetrahedra with their top corners available for bonding with other atoms. Micas and clays are common types of sheet silicates, also known as phyllosilicates. Mica minerals are usually found in igneous and metamorphic rocks, while clay minerals are more often found in sedimentary rocks. Two frequently found micas are dark-colored biotite, frequently found in granite, and light-colored muscovite, found in the metamorphic rock called schist.

Chemically, sheet silicates usually contain silicon and oxygen in a 2:5 ratio (Si$_4$O$_{10}$). Micas contain mostly silica, aluminum, and potassium. Biotite mica has more iron and magnesium and is considered a ferromagnesian silicate mineral. Muscovite micas belong to the felsic silicate minerals. Felsic is a contraction formed from feldspar, the dominant mineral in felsic rocks.
The illustration of the crystalline structure of mica shows the corner O atoms bonded with K, Al, Mg, Fe, and Si atoms, forming polymerized sheets of linked tetrahedra, with an octahedral layer of Fe, Mg, or Al, between them. The yellow potassium ions form Van der Waals bonds (attraction and repulsion between atoms, molecules, and surfaces) and hold the sheets together. Van der Waals bonds differ from covalent and ionic bonds, and exist here between the sandwiches, holding them together into a stack of sandwiches. The Van der Waals bonds are weak compared to the bonds within the sheets, allowing the sandwiches to be separated along the potassium layers. This gives mica its characteristic property of easily cleaving into sheets.

Clays minerals occur in sediments formed by the weathering of rocks and are another family of silicate minerals with a tetrahedral sheet structure. Clay minerals form a complex family, and are an important component of many sedimentary rocks. Other sheet silicates include serpentine and chlorite, found in metamorphic rocks.

Clay minerals are composed of hydrous aluminum silicates. One type of clay, kaolinite, has a structure like an open-faced sandwich, with the bread being a single layer of silicon-oxygen tetrahedra and a layer of aluminum as the spread in an octahedral configuration with the top oxygens of the sheets.
3.3.5 Framework Silicates

Quartz and feldspar are the two most abundant minerals in the continental crust. In fact, feldspar itself is the single most abundant mineral in the Earth’s crust. There are two types of feldspar, one containing potassium and abundant in felsic rocks of the continental crust, and the other with sodium and calcium abundant in the mafic rocks of oceanic crust. Together with quartz, these minerals are classified as framework silicates. They are built with a three-dimensional framework of silica tetrahedra in which all four corner oxygens are shared with adjacent tetrahedra. Within these frameworks in feldspar are holes and spaces into which other ions like aluminum, potassium, sodium, and calcium can fit giving rise to a variety of mineral compositions and mineral names.

Feldspars are usually found in igneous rocks, such as granite, rhyolite, and basalt as well as metamorphic rocks and detrital sedimentary rocks. Detrital sedimentary rocks are composed of mechanically weathered rock particles, like sand and gravel. Quartz is especially abundant in detrital sedimentary rocks because it is very resistant to disintegration by weathering. While quartz is the most abundant mineral on the Earth’s surface, due to its durability, the feldspar minerals are the most abundant minerals in the Earth’s crust, comprising roughly 50% of the total minerals that make up the crust.

Quartz is composed of pure silica, SiO₂, with the tetrahedra arranged in a three dimensional framework. Impurities consisting of atoms within this framework give rise to many varieties of quartz among which are gemstones like amethyst, rose quartz, and citrine. Feldspars are mostly silica with aluminum, potassium, sodium, and calcium. Orthoclase feldspar (KAlSi₃O₈), also called potassium feldspar or K-spar, is made of...
silica, aluminum, and potassium. Quartz and orthoclase feldspar are felsic minerals. Felsic is the compositional term applied to continental igneous minerals and rocks that contain an abundance of silica. Another feldspar is plagioclase with the formula \((\text{Ca}, \text{Na})\text{AlSi}_3\text{O}_8\), the solid solution \((\text{Ca}, \text{Na})\) indicating a series of minerals, one end of the series with calcium \(\text{CaAl}_2\text{Si}_2\text{O}_8\), called anorthite, and the other end with sodium \(\text{NaAlSi}_3\text{O}_8\), called albite. Note how the mineral accommodates the substitution of \(\text{Ca}^{++}\) and \(\text{Na}^+\). Minerals in this solid solution series have different mineral names.

Note that aluminum, which has a similar ionic size to silicon, can substitute for silicon inside the tetrahedra (see figure). Because potassium ions are so much larger than sodium and calcium ions, which are very similar in size, the inability of the crystal lattice to accommodate both potassium and sodium/calcium gives rise to the two families of feldspar, orthoclase and plagioclase respectively. Framework silicates are called tectosilicates and include the alkali metal-rich feldspathoids and zeolites.
3.3 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. Why are mica minerals “like a sandwich”?

- Because they have many strong atomic bonds similar to bread.
- Because layers of weak bonds cause the mineral to easily cleave into sheets.
- Because they are found in the structures of wheat.
- Because they taste really good and smell really good.
- Because there are so many different ways they stack on each other.

2. Which of the following are arrangements of silica tetrahedra in silicate minerals? SELECT ALL THAT APPLY

- 3-D framework
- Sheet
- Chain
- Double chain
- Triple chain
- Isolated
- Ring

3. What elements are in the silica tetrahedra, the basic unit of silicate minerals?

- 2 oxygens and 2 silicons
- 4 oxygens and 1 silicon
- 1 oxygen and 4 silicons
- 4 oxygens and 4 silicons
- 1 oxygen and 1 silicon
3.4 Non-Silicate Minerals

The crystal structure of non-silicate minerals (see table) does not contain silica-oxygen tetrahedra. Many non-silicate minerals are economically important and provide metallic resources such as copper, lead, and iron. They also include valuable non-metallic products such as salt, construction materials, and fertilizer.

<table>
<thead>
<tr>
<th>Mineral Group</th>
<th>Examples</th>
<th>Formula</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Native elements</td>
<td>gold, silver, copper</td>
<td>Au, Ag, Cu</td>
<td>Jewelry, coins, industry</td>
</tr>
<tr>
<td>Carbonates</td>
<td>calcite, dolomite</td>
<td>CaCO₃, CaMg(CO₃)₂</td>
<td>Lime, Portland cement</td>
</tr>
<tr>
<td>Oxides</td>
<td>hematite, magnetite, bauxite</td>
<td>Fe₂O₃, Fe₃O₄, a mixture of aluminum oxides</td>
<td>Ores of iron &amp; aluminum, pigments</td>
</tr>
<tr>
<td>Halides</td>
<td>halite, sylvite</td>
<td>NaCl, KCl</td>
<td>Table salt, fertilizer</td>
</tr>
<tr>
<td>Sulfides</td>
<td>galena, chalcopyrite, cinnabar</td>
<td>PbS, CuFeS₂, HgS</td>
<td>Ores of lead, copper, mercury</td>
</tr>
<tr>
<td>Sulphates</td>
<td>gypsum, epsom salts</td>
<td>Ca₅(PO₄)₃(F,Cl,OH)</td>
<td>Sheetrock, therapeutic soak</td>
</tr>
<tr>
<td>Phosphates</td>
<td>apatite</td>
<td></td>
<td>Fertilizer, teeth, bones</td>
</tr>
</tbody>
</table>

Hanksite, Na₂₂K(SO₄)₉(CO₃)₂Cl, one of the few minerals that is considered a member of two groups: carbonate and sulfate.

Common non-silicate mineral groups.
3.4.1 Carbonates

Calcite (CaCO₃) and dolomite (CaMg(CO₃)₂) are the two most frequently occurring carbonate minerals, and usually occur in sedimentary rocks, such as limestone and dolostone rocks, respectively. Some carbonate rocks, such calcite and dolomite, are formed via evaporation and precipitation. However, most carbonate-rich rocks, such as limestone, are created by the lithification of fossilized marine organisms. These organisms, including those we can see and many microscopic organisms, have shells or exoskeletons consisting of calcium carbonate (CaCO₃). When these organisms die, their remains accumulate on the floor of the water body in which they live and the soft body parts decompose and dissolve away.

The calcium carbonate hard parts become included in the sediments, eventually becoming the sedimentary rock called limestone. While limestone may contain large, easy to see fossils, most limestones contain the remains of microscopic creatures and thus originate from biological processes.

Calcite crystals show an interesting property called *birefringence*, meaning they polarize light into two wave components vibrating at right angles to each other. As the two light waves pass through the crystal, they travel at different velocities and are separated by refraction into two different travel paths. In other words, the crystal produces a double image of objects viewed through it. Because they polarize light, calcite crystals are used in special petrographic microscopes for studying minerals and rocks.

Many non-silicate minerals are referred to as salts. The term *salts* used here refers to compounds made by replacing the hydrogen in natural acids. The most abundant natural acid is carbonic acid that forms by
the solution of carbon dioxide in water. Carbonate minerals are salts built around the carbonate ion (CO$_3^{2-}$) where calcium and/or magnesium replace the hydrogen in carbonic acid (H$_2$CO$_3$). Calcite and a closely related polymorph aragonite are secreted by organisms to form shells and physical structures like corals. Many such creatures draw both calcium and carbonate from dissolved bicarbonate ions (HCO$_3^{-}$) in ocean water. As seen in the mineral identification section below, calcite is easily dissolved in acid and thus effervesces in dilute hydrochloric acid (HCl). Small dropper bottles of dilute hydrochloric acid are often carried by geologists in the field as well as used in mineral identification labs.

Other salts include halite (NaCl) in which sodium replaces the hydrogen in hydrochloric acid and gypsum (Ca[SO$_4$] • 2 H$_2$O) in which calcium replaces the hydrogen in sulfuric acid. Note that some water molecules are also included in the gypsum crystal. Salts are often formed by evaporation and are called evaporite minerals.

The figure shows the crystal structure of calcite (CaCO$_3$). Like silicon, carbon has four valence electrons. The carbonate unit consists of carbon atoms (tiny white dots) covalently bonded to three oxygen atoms (red), one oxygen sharing two valence electrons with the carbon and the other two sharing one valence electron each with the carbon, thus creating triangular units with a charge of -2. The negatively charged carbonate unit forms an ionic bond with the Ca ion (blue), which as a charge of +2.
3.4.2 Oxides, Halides, and Sulfides

After carbonates, the next most common non-silicate minerals are the oxides, halides, and sulfides.

Oxides consist of metal ions covalently bonded with oxygen. The most familiar oxide is rust, which is a combination of iron oxides ($\text{Fe}_2\text{O}_3$) and hydrated oxides. Hydrated oxides form when iron is exposed to oxygen and water. Iron oxides are important for producing metallic iron. When iron oxide or ore is smelted, it produces carbon dioxide ($\text{CO}_2$) and metallic iron.

The red color in rocks is usually due to the presence of iron oxides. For example, the red sandstone cliffs in Zion National Park and throughout Southern Utah consist of white or colorless grains of quartz coated with iron oxide which serve as cementing agents holding the grains together.

Other iron oxides include limonite, magnetite, and hematite. Hematite occurs in many different crystal forms. The massive form shows no external structure. Botryoidal hematite shows large concentric blobs. Specular hematite looks like a mass of shiny metallic crystals. Oolitic hematite looks like a mass of dull red fish eggs. These different forms of hematite are polymorphs and all have the same formula, $\text{Fe}_2\text{O}_3$.

Other common oxide minerals include:

- ice ($\text{H}_2\text{O}$), an oxide of hydrogen
- bauxite ($\text{Al}_2\text{H}_2\text{O}_4$), hydrated oxides of aluminum, an ore for producing metallic aluminum
- corundum ($\text{Al}_2\text{O}_3$), which includes ruby and sapphire gemstones.
The **halides** consist of halogens in column VII, usually fluorine or chlorine, ionically bonded with sodium or other cations. These include halite or sodium chloride (NaCl), common table salt; sylvite or potassium chloride (KCl); and fluorite or calcium fluoride (CaF₂).

Halide minerals usually form from the evaporation of sea water or other isolated bodies of water. A well-known example of halide mineral deposits created by evaporation is the Bonneville Salt Flats, located west of the Great Salt Lake in Utah (see figure).

Many important metal ores are **sulfides**, in which metals are bonded to sulfur. Significant examples include: galena (lead sulfide), sphalerite (zinc sulfide), pyrite (iron sulfide, sometimes called “fool’s gold”), and chalcopyrite (iron-copper sulfide). Sulfides are well known for being important ore minerals. For example, galena is the main source of lead, sphalerite is the main source of zinc, and chalcopyrite is the main copper ore mineral mined in porphyry deposits like the Bingham mine (see chapter 16). The largest sources of nickel, antimony, molybdenum, arsenic, and mercury are also sulfides.
3.4.3 Sulfates

Sulfate minerals contain a metal ion, such as calcium, bonded to a sulfate ion. The sulfate ion is a combination of sulfur and oxygen (SO$_4^{-2}$). The sulfate mineral gypsum (CaSO$_4$·2H$_2$O) is used in construction materials such as plaster and drywall. Gypsum is often formed from evaporating water and usually contains water molecules in its crystalline structure. The ·2H$_2$O in the formula indicates the water molecules are whole H$_2$O. This is different from minerals like amphibole, which contain a hydroxide ion (OH$^-$) that is derived from water, but is missing a hydrogen ion (H$^+$). The calcium sulfate without water is a different mineral than gypsum called anhydrite (CaSO$_4$).

3.4.4 Phosphates

Phosphate minerals have a tetrahedral phosphate unit (PO$_4^{-3}$) combined with various anions and cations. In some cases arsenic or vanadium can substitute for phosphorus. Phosphates are an important ingredient of fertilizers as well as detergents, paint, and other products. The best known phosphate mineral is apatite, Ca$_5$(PO$_4$)$_3$(F,Cl,OH), variations of which are found in teeth and bones. The gemstone turquoise [CuAl$_6$(PO$_4$)$_4$(OH)$_8$·4H$_2$O] is a copper-rich phosphate mineral that, like gypsum, contains water molecules.
3.4.5 Native Element Minerals

Native element minerals, usually metals, occur in nature in a pure or nearly pure state. Gold is an example of a native element mineral; it is not very reactive and rarely bonds with other elements so it is usually found in an isolated or pure state. The non-metallic and poorly-reactive mineral carbon is often found as a native element, such as graphite and diamonds. Mildly reactive metals like silver, copper, platinum, mercury, and sulfur sometimes occur as native element minerals. Reactive metals such as iron, lead, and aluminum almost always bond to other elements and are rarely found in a native state.
3.4 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. Why are only some minerals found as native minerals? For example, iron and aluminum are almost never found as native elements in nature.

- Earth's crust is too acidic for aluminum/iron
- Native aluminum/iron only forms in the core.
- Some elements are too reactive
- They formed at the start of earth and are only found in altered states
- Earth is too cold for native aluminum/iron

2. What is the most common origin of carbonate molecules in nature?

- Made by desert life
- By heating
- Made by marine life
- By evaporation
- By cooling

3. Which mineral group provides important sources of ores of copper, lead, and zinc, among others?

- Oxides
- Phosphates
- Native elements
- Sulfates
- Sulfides
3.5 Identifying Minerals

Geologists identify minerals by their physical properties. In the field, where geologists may have limited access to advanced technology and powerful machines, they can still identify minerals by testing several physical properties: luster and color, streak, hardness, crystal habit, cleavage and fracture, and some special properties. Only a few common minerals make up the majority of Earth’s rocks and are usually seen as small grains in rocks. Of the several properties used for identifying minerals, it is good to consider which will be most useful for identifying them in small grains surrounded by other minerals.

3.5.1 Luster and Color

The first thing to notice about a mineral is its surface appearance, specifically luster and color. Luster describes how the mineral looks. Metallic luster looks like a shiny metal such as chrome, steel, silver, or gold. Submetallic luster has a duller appearance. Pewter, for example, shows submetallic luster.

Nonmetallic luster doesn’t look like a metal and may be described as vitreous (glassy), earthy, silky, pearly, and other surface qualities. Nonmetallic minerals may be shiny, although their vitreous shine is different from metallic luster. See the table for descriptions and examples of nonmetallic luster.
<table>
<thead>
<tr>
<th>Luster</th>
<th>Image</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitreous/glassy</td>
<td><img src="image" alt="Quartz crystals" /></td>
<td>Surface is shiny like glass</td>
</tr>
<tr>
<td>Earthy/dull</td>
<td><img src="image" alt="Kaolin specimen showing dull or earthy luster" /></td>
<td>Dull, like dried mud or clay</td>
</tr>
<tr>
<td>Silky</td>
<td><img src="image" alt="Specimen showing silky luster" /></td>
<td>Soft shine like silk fabric</td>
</tr>
<tr>
<td>Pearly</td>
<td><img src="image" alt="Specimen showing pearly luster" /></td>
<td>Like the inside of a clam shell or mother-of-pearl</td>
</tr>
<tr>
<td>Submetallic</td>
<td><img src="image" alt="Submetallic luster on sphalerite" /></td>
<td>Has the appearance of dull metal, like pewter. These minerals would usually still be considered metallic. Submetallic appearance can occur in metallic minerals because of weathering.</td>
</tr>
</tbody>
</table>
Surface color may be helpful in identifying minerals, although it can be quite variable within the same mineral family. Mineral colors are affected by the main elements as well as impurities in the crystals. These impurities may be rare elements—like manganese, titanium, chromium, or lithium—even other molecules that are not normally part of the mineral formula. For example, the incorporation of water molecules gives quartz, which is normally clear, a milky color.

Some minerals predominantly show a single color. Malachite and azurite are green and blue, respectively, because of their copper content. Other minerals have a predictable range of colors due to elemental substitutions, usually via a solid solution. Feldspars, the most abundant minerals in the earth’s crust, are complex, have solid solution series, and present several colors including pink, white, green, gray and others. Other minerals also come in several colors, influenced by trace amounts of several elements. The same element may show up as different colors, in different minerals. With notable exceptions, color is usually not a definitive property of minerals. For identifying many minerals, a more reliable indicator is streak, which is the color of the powdered mineral.

Azurite is ALWAYS a dark blue color, and has been used for centuries for blue pigment.
3.5.2 Streak

Streak examines the color of a powdered mineral, and can be seen when a mineral sample is scratched or scraped on an unglazed porcelain streak plate. A paper page in a field notebook may also be used for the streak of some minerals. Minerals that are harder than the streak plate will not show streak, but will scratch the porcelain. For these minerals, a streak test can be obtained by powdering the mineral with a hammer and smearing the powder across a streak plate or notebook paper.

While mineral surface colors and appearances may vary, their streak colors can be diagnostically useful. An example of this property is seen in the iron-oxide mineral hematite. Hematite occurs in a variety of forms, colors and lusters, from shiny metallic silver to earthy red-brown, and different physical appearances. A hematite streak is consistently reddish brown, no matter what the original specimen looks like. Iron sulfide or pyrite, is a brassy metallic yellow. Commonly named fool’s gold, pyrite has a characteristic black to greenish-black streak.
3.5.3 Hardness

Hardness measures the ability of a mineral to scratch other substances. The Mohs Hardness Scale gives a number showing the relative scratch-resistance of minerals when compared to a standardized set of minerals of increasing hardness. The Mohs scale was developed by German geologist Fredrick Mohs in the early 20th century, although the idea of identifying minerals by hardness goes back thousands of years. Mohs hardness values are determined by the strength of a mineral’s atomic bonds.

The figure shows the minerals associated with specific hardness values, together with some common items readily available for use in field testing and mineral identification. The hardness values run from 1 to 10, with 10 being the hardest; however, the scale is not linear. Diamond defines a hardness of 10 and is actually about four times harder than corundum, which is 9. A steel pocketknife blade, which has a hardness value of 5.5, separates between hard and soft minerals on many mineral identification keys.
3.5.4 Crystal Habit

Minerals can be identified by **crystal habit**, how their crystals grow and appear in rocks. Crystal shapes are determined by the arrangement of the atoms within the crystal structure. For example, a cubic arrangement of atoms gives rise to a cubic-shaped mineral crystal. Crystal habit refers to typically observed shapes and characteristics; however, they can be affected by other minerals crystallizing in the same rock. When minerals are constrained so they do not develop their typical crystal habit, they are called **anhedral**. **Subhedral** crystals are partially formed shapes. For some minerals characteristic crystal habit is to grow crystal faces even when surrounded by other crystals in rock. An example is garnet. Minerals grown freely where the crystals are unconstrained and can take characteristic shapes often form crystal faces. **A euhedral crystal** has a perfectly formed, unconstrained shape. Some minerals crystallize in such tiny crystals, they do not show a specific crystal habit to the naked eye. Other minerals, like pyrite, can have an array of different crystal habits, including cubic, dodecahedral, octahedral, and massive. The table lists typical crystal habits of various minerals.

<table>
<thead>
<tr>
<th>Habit</th>
<th>Image</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bladed</strong></td>
<td><img src="image" alt="Bladed kyanite" /></td>
<td>kyanite, amphibole, gypsum</td>
</tr>
<tr>
<td>long and flat crystals</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Botryoidal/mammillary</strong></td>
<td><img src="image" alt="Malachite from the Congo" /></td>
<td>hematite, malachite, smithsonite</td>
</tr>
<tr>
<td>blobby, circular crystals</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Coating/laminae/druse</strong></td>
<td><img src="image" alt="Quartz (var. amethyst) in a geode" /></td>
<td>quartz, calcite, malachite, azurite</td>
</tr>
<tr>
<td>crystals that are small and coat surfaces</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Habit</td>
<td>Image</td>
<td>Examples</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td><strong>Cubic</strong></td>
<td><img src="image1.png" alt="Cubic crystals of galena" /></td>
<td>pyrite, galena, halite</td>
</tr>
<tr>
<td>cube-shaped crystals</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dodecahedral</strong></td>
<td><img src="image2.png" alt="Pyrite crystals with dodecahedral habit" /></td>
<td>garnet, pyrite</td>
</tr>
<tr>
<td>12-sided polygon shapes</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dendritic</strong></td>
<td><img src="image3.png" alt="Manganese dendrites, scale in mm." /></td>
<td>Mn-oxides, copper, gold</td>
</tr>
<tr>
<td>branching crystals</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Equant</strong></td>
<td><img src="image4.png" alt="Olivine crystal" /></td>
<td>olivine, garnet, pyroxene</td>
</tr>
<tr>
<td>crystals that do not have a long direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fibrous</strong></td>
<td><img src="image5.png" alt="Tremolite, a type of amphibole" /></td>
<td>serpentine, amphibole, zeolite</td>
</tr>
<tr>
<td>thin, very long crystals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Habit</td>
<td>Image</td>
<td>Examples</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td><strong>Layered, sheets</strong></td>
<td><img src="image" alt="Sheet crystals of muscovite" /></td>
<td>mica (biotite, muscovite, etc.)</td>
</tr>
<tr>
<td>stacked, very thin, flat crystals</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lenticular/platy</strong></td>
<td><img src="image" alt="Orange wulfenite on calcite" /></td>
<td>selenite roses, wulfenite, calcite</td>
</tr>
<tr>
<td>crystals that are plate-like</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hexagonal</strong></td>
<td><img src="image" alt="Hexagonal hanksite" /></td>
<td>quartz, hanksite, corundum</td>
</tr>
<tr>
<td>crystals with six sides</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Massive/granular</strong></td>
<td><img src="image" alt="Limonite, a hydrated oxide of iron" /></td>
<td>limonite, pyrite, azurite, bornite</td>
</tr>
<tr>
<td>Crystals with no obvious shape, microscopic crystals</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Octahedral</strong></td>
<td><img src="image" alt="Octahedral fluorite" /></td>
<td>diamond, fluorite, magnetite, pyrite</td>
</tr>
<tr>
<td>4-sided double pyramid crystals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Habit</td>
<td>Image</td>
<td>Examples</td>
</tr>
<tr>
<td>-----------------------</td>
<td>--------------------------------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td><strong>Prismatic/columnar</strong></td>
<td><img src="image" alt="Columnar tourmaline" /></td>
<td>tourmaline, beryl, barite</td>
</tr>
<tr>
<td>very long, cylindrical crystals</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Radiating</strong></td>
<td><img src="image" alt="Pyrophyllite" /></td>
<td>pyrite “suns”, pyrophyllite</td>
</tr>
<tr>
<td>crystals that grow from a point and fan out</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rhombohedral</strong></td>
<td><img src="image" alt="Calcite crystal in shape of rhomb" /></td>
<td>calcite, dolomite</td>
</tr>
<tr>
<td>crystals shaped like slanted cubes</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tabular/blocky/stubby</strong></td>
<td><img src="image" alt="Crystals of diopside" /></td>
<td>feldspar, pyroxene, calcite</td>
</tr>
<tr>
<td>sharp-sided crystals with no long direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tetrahedral</strong></td>
<td><img src="image" alt="Tetrahedrite" /></td>
<td>magnetite, spinel, tetrahedrite</td>
</tr>
<tr>
<td>three-sided, pyramid-shaped crystals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Another crystal habit that may be used to identify minerals is striations, which are dark and light parallel lines on a crystal face. Twinning is another, which occurs when the crystal structure replicates in mirror images along certain directions in the crystal.

Striations are optical lines on a cleavage surface. Because of twinning in the crystal, striations show up on one of the two cleavage faces of the plagioclase crystal.

**3.5.5 Cleavage and Fracture**

Minerals often show characteristic patterns of breaking along specific cleavage planes or show characteristic fracture patterns. Cleavage planes are smooth, flat, parallel planes within the crystal. The cleavage planes may show as reflective surfaces on the crystal, as parallel cracks that penetrate into the crystal, or show on the edge or side of the crystal as a series of steps like rice terraces. Cleavage arises in crystals where the atomic bonds between atomic layers are weaker along some directions than others, meaning they will break preferentially along these planes. Because they develop on atomic surfaces in the crystal, cleavage planes are optically smooth and reflect light, although the actual break on the crystal may appear jagged or uneven. In such cleavages, the cleavage surface may appear like rice terraces on a mountainside that all reflect sunlight from a particular sun angle. Some minerals have a strong cleavage, some minerals only have weak cleavage or do not typically demonstrate cleavage.
For example, quartz and olivine rarely show cleavage and typically break into conchoidal fracture patterns.

Graphite has its carbon atoms arranged into layers with relatively strong bonds within the layer and very weak bonds between the layers. Thus graphite cleaves readily between the layers and the layers slide easily over one another giving graphite its lubricating quality.

Mineral fracture surfaces may be rough and uneven or they may be show conchoidal fracture. Uneven fracture patterns are described as irregular, splintery, fibrous. A conchoidal fracture has a smooth, curved surface like a shallow bowl or conch shell, often with curved ridges. Natural volcanic glass, called obsidian, breaks with this characteristic conchoidal pattern.

To work with cleavage, it is important to remember that cleavage is a result of bonds separating along planes of atoms in the crystal structure. On some minerals, cleavage planes may be confused with crystal faces. This will usually not be an issue for crystals of minerals that grew together within rocks. The act of breaking the rock to expose a fresh face will most likely break the crystals along cleavage planes. Some cleavage planes are parallel with crystal faces but many are not. Cleavage planes are smooth, flat, parallel planes within the crystal. The cleavage planes may show as parallel cracks that penetrate into the crystal (see amphibole below), or show on the edge or side of...
the crystal as a series of steps like rice terraces. For some minerals characteristic crystal habit is to grow crystal faces even when surrounded by other crystals in rock. An example is garnet. Minerals grown freely where the crystals are unconstrained and can take characteristic shapes often form crystal faces (see quartz below).

In some minerals, distinguishing cleavage planes from crystal faces may be challenging for the student. Understanding the nature of cleavage and referring to the number of cleavage planes and cleavage angles on identification keys should provide the student with enough information to distinguish cleavages from crystal faces. Cleavage planes may show as multiple parallel cracks or flat surfaces on the crystal. Cleavage planes may be expressed as a series of steps like terraced rice paddies. See the cleavage surfaces on galena above or plagioclase below. Cleavage planes arise from the tendency of mineral crystals to break along specific planes of weakness within the crystal favored by atomic arrangements. The number of cleavage planes, the quality of the cleavage surfaces, and the angles between them are diagnostic for many minerals and cleavage is one of the most useful properties for identifying minerals. Learning to recognize cleavage is an especially important and useful skill in studying minerals.

As an identification property of minerals, cleavage is usually given in terms of the quality of the cleavage (perfect, imperfect, or none), the number of cleavage surfaces, and the angles between the surfaces. The most common number of cleavage plane directions in the common rock-forming minerals are: one perfect cleavage (as in mica), two cleavage planes (as in feldspar, pyroxene, and amphibole), and three cleavage
planes (as in halite, calcite, and galena). One perfect cleavage (as in mica) develops on the top and bottom of the mineral specimen with many parallel cracks showing on the sides but no angle of intersection. Two cleavage planes intersect at an angle. Common cleavage angles are 60°, 75°, 90°, and 120°. Amphibole has two cleavage planes at 60° and 120°. Galena and halite have three cleavage planes at 90° (cubic cleavage). Calcite cleaves readily in three directions producing a cleavage figure called a rhomb that looks like a cube squashed over toward one corner giving rise to the approximately 75° cleavage angles. Pyroxene has an imperfect cleavage with two planes at 90°.

**Cleavages on common rock-forming minerals**

- Quartz—none (conchoidal fracture)
- Olivine—none (conchoidal fracture)
- Mica—1 perfect
- Feldspar—2 perfect at 90°
- Pyroxene—2 imperfect at 90°
- Amphibole—2 perfect at 60°/120°
- Calcite—3 perfect at approximately 75°
- Halite, galena, pyrite—3 perfect at 90°

### 3.5.6 Special Properties

Special properties are unique and identifiable characteristics used to identify minerals or that allow some minerals to be used for special purposes. Ulexite has a fiber-optic property that can project images through the crystal like a high-definition television screen (see figure). A simple identifying special property is taste, such as the salty flavor of halite or common table salt (NaCl). Sylvite is potassium chloride (KCl) and has a more bitter taste.

Another property geologists may use to identify minerals is a property related to density called **specific gravity**. Specific gravity measures the weight of a mineral specimen relative to the weight of an equal volume of water. The value is expressed as a ratio between the mineral and water weights. To measure specific gravity, a mineral specimen is first weighed in grams then submerged in a graduated cylinder filled with pure water at room temperature. The rise in water level is noted using the

**Native gold has one of the highest specific gravities.**
cylinder’s graduated scale. Since the weight of water at room temperature is 1 gram per cubic centimeter, the ratio of the two weight numbers gives the specific gravity. Specific gravity is easy to measure in the laboratory but is less useful for mineral identification in the field than other more easily observed properties, except in a few rare cases such as the very dense galena or native gold. The high density of these minerals gives rise to a qualitative property called “heft.” Experienced geologists can roughly assess specific gravity by heft, a subjective quality of how heavy the specimen feels in one’s hand relative to its size.

A simple test for identifying calcite and dolomite is to drop a bit of dilute hydrochloric acid (10-15% HCl) on the specimen. If the acid drop effervesces or fizzes on the surface of the rock, the specimen is calcite. If it does not, the specimen is scratched to produce a small amount of powder and test with acid again. If the acid drop fizzes slowly on the powdered mineral, the specimen is dolomite. The difference between these two minerals can be seen in the video. Geologists who work with carbonate rocks carry a small dropper bottle of dilute HCl in their field kit. Vinegar, which contains acetic acid, can be used for this test and is used to distinguish non-calcite fossils from limestone. While acidic, vinegar produces less of a fizzing reaction because acetic acid is a weaker acid.

Some iron-oxide minerals are magnetic and are attracted to magnets. A common name for a naturally magnetic iron oxide is lodestone. Others include magnetite (Fe₃O₄) and ilmenite (FeTiO₃). Magnetite is strongly attracted to magnets and can be magnetized. Ilmenite and some types of hematite are weakly magnetic.

Some minerals and mineraloids scatter light via a phenomenon called iridescence. This property occurs in labradorite (a variety of plagioclase) and opal. It is also seen in biologically created substances like pearls and seashells. Cut diamonds show iridescence and the jeweler’s diamond cut is designed to maximize this property.

Striations on mineral cleavage faces are an optical property that can be used to separate plagioclase feldspar from potassium feldspar (K-spar). A process called twinning creates parallel zones in the crystal that are repeating mirror images. The actual cleavage angle in plagioclase is slightly different than 90° and the alternating mirror images in these twinned zones
produce a series of parallel lines on one of plagioclase’s two cleavage faces. Light reflects off these twinned lines at slightly different angles which then appear as light and dark lines called striations on the cleavage surface. Potassium feldspar does not exhibit twinning or striations but may show linear features called exsolution lamellae, also known as perthitic lineation or simply perthite. Because sodium and potassium do not fit into the same feldspar crystal structure, the lines are created by small amounts of sodium feldspar (albite) separating from the dominant potassium feldspar (K-spar) within the crystal structure. The two different feldspars crystallize out into roughly parallel zones within the crystal, which are seen as these linear markings.

One of the most interesting special mineral properties is fluorescence. Certain minerals, or trace elements within them, give off visible light when exposed to ultraviolet radiation or black light. Many mineral exhibits have a fluorescence room equipped with black lights so this property can be observed. An even rarer optical property is phosphorescence. Phosphorescent minerals absorb light and then slowly release it, much like a glow-in-the-dark sticker.

Fluorite. Lower image shows fluorescence of fluorite under UV light
3.5 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. What luster determination is a common starting point for mineral identification?
   - [ ] Vitreous/non-vitreous
   - [ ] Glassy/non-glassy
   - [ ] Metallic/non-metallic
   - [ ] Earthy/dull
   - [ ] Metallic/submetallic

2. Which mineral property involves observing the powdered color of a mineral?
   - [ ] Color
   - [ ] Luster
   - [ ] Hardness
   - [ ] Streak
   - [ ] Cleavage

3. Regarding the Mohs Hardness Scale table, if a mineral scratches the copper penny but NOT the glass plate, then the hardness is around _____.
   - [ ] 4.5
   - [ ] 3
   - [ ] 6
   - [ ] 7.5
   - [ ] 1
4. Cleavage is a product of _____________ in a mineral’s atomic structure.

- ○ strength
- ○ softness
- ○ weakness
- ○ carbon
- ○ hardness
Summary

Minerals are the building blocks of rocks and essential to understanding geology. Mineral properties are determined by their atomic bonds. Most minerals begin in a fluid, and either crystallize out of cooling magma or precipitate as ions and molecules out of a saturated solution. The silicates are largest group of minerals on Earth, by number of varieties and relative quantity, making up a large portion of the crust and mantle. Based on the silicon-oxygen tetrahedra, the crystal structure of silicates reflects the fact that silicon and oxygen are the top two of Earth’s most abundant elements. Non-silicate minerals are also economically important, and providing many types of construction and manufacturing materials. Minerals are identified by their unique physical properties, including luster, color, streak, hardness, crystal habit, fracture, cleavage, and special properties.

Chapter 3 Review Quiz

Take this quiz for a general review of this chapter.

1. What are the two (2) most common elements in Earth’s crust? SELECT ALL THAT APPLY

- ☐ Carbon (C)
- ☐ Iron (Fe)
- ☐ Silicon (Si)
- ☐ Silver (Ag)
- ☐ Oxygen (O)

2. What makes native elements different than all other elements?

- ☒ They are more dense
- ☐ They contain only one element
- ☒ They formed early in Earth's history
- ☐ They are more pure
- ☐ They are more valuable
3. Dark silicate minerals that are black and green have a lot of ________; while light-colored silicate minerals such as quartz and feldspar have abundant ________.

- □ aluminum; magnesium
- □ protons and neutrons; potassium and feldspar
- □ silica; protons and neutrons
- □ silica; iron and nickel
- □ iron and magnesium; silica

4. Which of the following is true about minerals? SELECT ALL THAT APPLY

- □ A single mineral must include more than one chemical element
- □ Minerals can only be made naturally
- □ Minerals can be derived from living things if fossilized
- □ Specific minerals are always composed of predictable elements
- □ All rocks have more than one mineral

5. What controls a mineral’s color?

- □ Density
- □ Strength of bonds
- □ Types of elements
- □ Weakness of bonds
- □ Temperature of formation

6. Why would one mineral (like pyrite) have several different crystal habits?

- □ Current pressure of the mineral changes the habit
- □ Atoms in its structure can be arranged differently
- □ Current temperature of the mineral changes the habit
- □ Different trace elements make different habits
- □ Different solid solutions make different habits
7. Which mineral(s) are composed of a 3-D framework of silica tetrahedra? SELECT TWO

- ☐ Quartz
- ☐ Feldspar
- ☐ Pyroxene
- ☐ Olivine
- ☐ Mica
- ☐ Amphibole

8. What are the three processes by which minerals are made? SELECT THREE

- ☐ Precipitating from water
- ☐ Acid reactions in rain
- ☐ Cooling from magma
- ☐ Precipitating from water via river currents
- ☐ Precipitating from water via organisms
- ☐ Organic processes within plants
- ☐ Precipitating from air
- ☐ Movement of sediments

9. Which special mineral properties relate to light? SELECT THREE

- ☐ iridescence
- ☐ phosphorescence
- ☐ florescence
- ☐ exsolution lamellae
- ☐ specific gravity
10. What is the chemical formula of the silica tetrahedra, the building block of all silicate minerals?

- SiO₂
- Si₂O₄
- SiO₄
- SiO
- Si₄O₄
- Si₄O₂

References


4 Igneous Processes and Volcanoes

KEY CONCEPTS

By the end of this chapter, students should be able to:

- Explain the origin of magma it relates to plate tectonics
- Describe how the Bowen’s Reaction Series relates mineral crystallization and melting temperatures
- Explain how cooling of magma leads to rock compositions and textures, and how these are used to classify igneous rocks
- Analyze the features of common igneous landforms and how they relate to their origin
- Explain partial melting and fractionation, and how they change magma compositions
- Describe how silica content affects magma viscosity and eruptive style of volcanoes
- Describe volcano types, eruptive styles, composition, and their plate tectonic settings
- Describe volcanic hazards
Igneous rock is formed when liquid rock freezes into a solid rock. This molten material is called magma when it is in the ground and lava when it is on the surface. Only the Earth’s outer core is liquid; the Earth’s mantle and crust is naturally solid. However, there are a few minor pockets of magma that form near the surface where geologic processes cause melting. It is this magma that becomes the source for volcanoes and igneous rocks. This chapter will describe the classification of igneous rocks, the unique processes that form magmas, types of volcanoes and volcanic processes, volcanic hazards, and igneous landforms.

Lava cools quickly on the surface of the earth and forms tiny microscopic crystals. These are known as fine-grained extrusive, or volcanic, igneous rocks. Extrusive rocks are often vesicular, filled with holes from escaping gas bubbles. Volcanism is the process in which lava is erupted. Depending on the properties of the lava that is erupted, the volcanism can be drastically different, from smooth and gentle to dangerous and explosive. This leads to different types of volcanoes and different volcanic hazards.

In contrast, magma that cools slowly below the earth’s surface forms larger crystals which can be seen with the naked eye. These are known as coarse-grained intrusive, or plutonic, igneous rocks. This relationship between cooling rates and grain sizes of the solidified minerals in igneous rocks is important for interpreting the rock’s geologic history.

4.1 Classification of Igneous Rocks

Igneous rocks are classified based on texture and composition. Texture describes the physical characteristics of the minerals, such as grain size. This relates to the cooling history of the molten magma from which it came. Composition refers to the rock’s
specific mineralogy and chemical composition. Cooling history is also related to changes that can occur to the composition of igneous rocks.

### 4.1.1 Texture

If magma cools slowly, deep within the crust, the resulting rock is called intrusive or plutonic. The slow cooling process allows crystals to grow large, giving intrusive igneous rock a coarse-grained or **phaneritic** texture. The individual crystals in phaneritic texture are readily visible to the unaided eye.

When lava is extruded onto the surface, or intruded into shallow fissures near the surface and cools, the resulting igneous rock is called extrusive or volcanic. Extrusive igneous rocks have a fine-grained or **aphanitic** texture, in which the grains are too small to see with the unaided eye. The fine-grained texture indicates the quickly cooling lava did not have time to grow large crystals. These tiny crystals can be viewed under a petrographic microscope [1]. In some cases, extrusive lava cools so rapidly it does not develop crystals at all. This non-crystalline material is not classified as minerals, but as volcanic glass. This is a common component of volcanic ash and rocks like obsidian.
Some igneous rocks have a mix of coarse-grained minerals surrounded by a matrix of fine-grained material in a texture called **porphyritic**. The large crystals are called **phenocrysts** and the fine-grained matrix is called the **groundmass** or **matrix**. Porphyritic texture indicates the magma body underwent a multi-stage cooling history, cooling slowly while deep under the surface and later rising to a shallower depth or the surface where it cooled more quickly.

Residual molten material expelled from igneous intrusions may form veins or masses containing very large crystals of minerals like feldspar, quartz, beryl, tourmaline, and mica. This texture, which indicates a very slow crystallization, is called **pegmatitic**. A rock that chiefly consists of pegmatitic texture is known as a **pegmatite**. To give an example of how large these crystals can get, transparent cleavage sheets of pegmatitic muscovite mica were used as windows during the Middle Ages.

All magmas contain gases dissolved in solution called **volatiles**. As the magma rises to the surface, the drop in pressure causes the dissolved volatiles to come bubbling out of solution, like the fizz in an opened bottle of soda. The gas bubbles become trapped in the solidifying lava to create a **vesicular** texture, with the holes specifically called **vesicles**. The type of volcanic rock with common vesicles is called **scoria**.

An extreme version of scoria occurs when volatile-rich lava is very quickly quenched and becomes a meringue-like froth of glass called **pumice**. Some pumice is so full of vesicles that the density of the rock drops low enough that it will float.
Lava that cools extremely quickly may not form crystals at all, even microscopic ones. The resulting rock is called **volcanic glass**. **Obsidian** is a rock consisting of volcanic glass. Obsidian as a glassy rock shows an excellent example of conchoidal fracture similar to the mineral quartz (see Chapter 3).

When volcanoes erupt explosively, vast amounts of lava, rock, ash, and gases are thrown into the atmosphere. The solid parts, called tephra, settle back to earth and cool into rocks with **pyroclastic** textures. *Pyro*, meaning fire, refers to the igneous source of the tephra and *clastic* refers to the rock fragments. Tephra fragments are named based on size—**ash** (<2 mm), **lapilli** (2-64 mm), and **bombs or blocks** (>64 mm). Pyroclastic texture is usually recognized by the chaotic mix of crystals, angular glass shards, and rock fragments. Rock formed from large deposits of tephra fragments is called **tuff**. If the fragments accumulate while still hot, the heat may deform the crystals and weld the mass together, forming a welded tuff.

### 4.1.2 Composition

Composition refers to a rock’s chemical and mineral make-up. For igneous rock, composition is divided into four groups: **felsic**, **intermediate**, **mafic**, and **ultramafic**. These groups refer to differing amounts of silica, iron, and magnesium found in the minerals that make up the rocks. It is important to realize these groups do not have sharp boundaries in nature, but rather lie on a continuous spectrum with many transitional compositions and names that refer to specific quantities of minerals. As an example, granite is a commonly-used term, but has a very specific definition which includes exact quantities of minerals like feldspar and quartz. Rocks labeled as 'granite' in laymen applications can be several other rocks, including syenite, tonalite, and monzonite. To avoid these complications, the following figure presents a simplified version of igneous rock nomenclature focusing on the four main groups, which is adequate for an introductory student.
Felsic refers to a predominance of the light-colored (felsic) minerals feldspar and silica in the form of quartz. These light-colored minerals have more silica as a proportion of their overall chemical formula. Minor amounts of dark-colored (mafic) minerals like amphibole and biotite mica may be present as well. Felsic igneous rocks are rich in silica (in the 65-75% range, meaning the rock would be 65-75% weight percent SiO₂) and poor in iron and magnesium.

Intermediate is a composition between felsic and mafic. It usually contains roughly-equal amounts of light and dark minerals, including light grains of plagioclase feldspar and dark minerals like amphibole. It is intermediate in silica in the 55-60% range.
Mafic refers to a abundance of ferromagnesian minerals (with magnesium and iron, chemical symbols Mg and Fe) plus plagioclase feldspar. It is mostly made of dark minerals like pyroxene and olivine, which are rich in iron and magnesium and relatively poor in silica. Mafic rocks are low in silica, in the 45-50% range.

Ultramafic refers to the extremely mafic rocks composed of mostly olivine and some pyroxene which have even more magnesium and iron and even less silica. These rocks are rare on the surface, but make up peridotite, the rock of the upper mantle. It is poor in silica, in the 40% or less range.

On the figure above, the top row has both plutonic and volcanic igneous rocks arranged in a continuous spectrum from felsic on the left to intermediate, mafic, and ultramafic toward the right. Rhyolite thus refers to the volcanic and felsic igneous rocks, and granite thus refer to intrusive and felsic igneous rocks. Andesite and diorite likewise refer to extrusive and intrusive intermediate rocks (with dacite and granodiorite applying to those rocks with composition between felsic and intermediate). Basalt and gabbro are the extrusive and intrusive names for mafic igneous rocks, and peridotite is ultramafic, with komatiite as the fine-grained extrusive equivalent. Komatiite is a rare rock because volcanic material that comes direct from the mantle is not common, although some examples can be found in ancient Archean rocks [2]. Nature rarely has sharp boundaries and the classification and naming of rocks often imposes what appear to be sharp boundary names onto a continuous spectrum.
Classification of IGNEOUS ROCKS

Match the texture with the composition of the rock to identify it.

**TEXTURE**

- **Phaneritic** (coarse grained)
  - Granite
  - Diorite
  - Gabbro
  - Peridotite

- **Aphanitic** (fine grained)
  - Rhyolite
  - Andesite
  - Basalt

- **Porphyritic** (large crystals in a fine matrix)
  - Porphyritic Rhyolite
  - Porphyritic Andesite
  - Porphyritic Basalt

- **Vesicular** (bubbly or frothy)
  - Pumice
  - Scoria

- **Glassy**
  - Obsidian

- **Pyroclastic** (fragmental)
  - Rhyolitic Tuff or Volcanic Breccia
  - Andesitic Tuff or Volcanic Breccia
  - Basaltic Tuff or Volcanic Breccia

**COMPOSITION**

- **Felsic**
  - >10% quartz
  - >50% feldspar
  - <15% mafic minerals

- **Intermediate**
  - >10% quartz
  - >50% plagioclase
  - >10% orthoclase
  - <50% mafic minerals

- **Mafic**
  - 20-85% plagioclase
  - 15-50% pyroxene
  - >15% olivine

- **Ultramafic**
  - Olivine & pyroxene

_Igneous rock classification table with composition as vertical columns and texture as horizontal rows._
Granite is a coarse-crystalline felsic intrusive rock. The presence of quartz is a good indicator of granite. Granite commonly has large amounts of salmon pink potassium feldspar and white plagioclase crystals that have visible cleavage planes. Granite is a good approximation for the continental crust, both in density and composition.

Rhyolite is a fine-crystalline felsic extrusive rock. Rhyolite is commonly pink and will often have glassy quartz phenocrysts. Because felsic lavas are less mobile, it is less common than granite. Examples of rhyolite include several lava flows in Yellowstone National Park and the altered rhyolite that makes up the Grand Canyon of the Yellowstone.
### Intermediate Composition

<table>
<thead>
<tr>
<th>Diorite</th>
<th>Andesite</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diorite" /></td>
<td><img src="image2" alt="Andesite" /></td>
</tr>
</tbody>
</table>

**Diorite** is a coarse-crystalline intermediate intrusive igneous rock. Diorite is identifiable by its Dalmatian-like appearance of black hornblende and biotite and white plagioclase feldspar. It is found in its namesake, the Andes Mountains as well as the Henry and Abajo mountains of Utah.

**Andesite** is a fine crystalline intermediate extrusive rock. It is commonly grey and porphyritic. It can be found in the Andes Mountains and in some island arcs (see [Chapter 2](#)). It is the fine grained compositional equivalent of diorite.
### Mafic Composition

<table>
<thead>
<tr>
<th>Gabbro</th>
<th>Vesicular Basalt</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.jpg" alt="Gabbro" /></td>
<td><img src="image2.jpg" alt="Vesicular Basalt" /></td>
</tr>
</tbody>
</table>

**Gabbro** is a coarse-grained mafic igneous rock, made with mainly mafic minerals like pyroxene and only minor plagioclase. Because mafic lava is more mobile, it is less common than basalt. Gabbro is a major component of the lower oceanic crust.

**Basalt** is a fine-grained mafic igneous rock. It is commonly vesicular and aphanitic. When porphyritic, it often has either olivine or plagioclase phenocrysts. Basalt is the main rock which is formed at mid-ocean ridges, and is therefore the most common rock on the Earth’s surface, making up the entirety of the ocean floor (except where covered by sediment).
4.1.3 Igneous Rock Bodies

Igneous rocks are common in the geologic record, but surprisingly, it is the intrusive rocks that are more common. Extrusive rocks, because of their small crystals and glass, are less durable. Plus, they are, by definition, exposed to the elements of erosion immediately. Intrusive rocks, forming underground with larger, stronger crystals, are more likely to last. Therefore, most landforms and rock groups that owe their origin to igneous rocks are intrusive bodies. A significant exception to this is active volcanoes, which are discussed in a later section on volcanism. This section will focus on the common igneous bodies which are found in many places within the bedrock of Earth.

When magma intrudes into a weakness like a crack or fissure and solidifies, the resulting cross-cutting feature is called a dike (sometimes spelled dyke). Because of this, dikes are often vertical or at an angle relative to the pre-existing rock layers that they intersect. Dikes are therefore discordant intrusions, not following any layering that was present. Dikes are important to geologists, not only for the study of igneous rocks themselves but also for dating rock sequences and interpreting the geologic history of an area. The dike is younger than the rocks it cuts across and, as discussed in the chapter on Geologic Time (Chapter 7), may be used to assign actual numeric ages to sedimentary sequences, which are notoriously difficult to age date.

Sills are another type of intrusive structure. A sill is a concordant intrusion that runs parallel to the sedimentary layers in the country rock. They are formed when magma exploits a weakness between these layers, shouldering them apart and squeezing between them. As with dikes, sills are younger than the surrounding layers and may be radioactively dated to study the age of sedimentary strata.
A magma chamber is a large underground reservoir of molten rock. The path of rising magma is called a diapir. The processes by which a diapir intrudes into the surrounding native or country rock are not well understood and are the subject of ongoing geological inquiry. For example, it is not known what happens to the pre-existing country rock as the diapir intrudes. One theory is the overriding rock gets shouldered aside, displaced by the increased volume of magma. Another is the native rock is melted and consumed into the rising magma or broken into pieces that settle into the magma, a process known as stoping. It has also been proposed that diapirs are not a real phenomenon, but just a series of dikes that blend into each other. The dikes may be intruding over millions of years, but since they may be made of similar material, they would be appearing to be formed at the same time. Regardless, when a diapir cools, it forms a mass of intrusive rock called a pluton. Plutons can have irregular shapes, but can often be somewhat round.

When many plutons merge together in an extensive single feature, it is called a batholith. Batholiths are found in the cores of many mountain ranges, including the granite formations of Yosemite National Park in the Sierra Nevada of California. They are typically more than 100 km² in area, associated with subduction zones, and mostly felsic in composition. A stock is a type of pluton with less surface exposure than a batholith, and may represent a narrower neck of material emerging from the top of a batholith. Batholiths and stocks are discordant intrusions that cut across and through surrounding country rock.
Laccoliths are blister-like, concordant intrusions of magma that form between sedimentary layers. The Henry Mountains of Utah are a famous topographic landform formed by this process. Laccoliths bulge upwards; a similar downward-bulging intrusion is called a lopolith.

The Henry Mountains in Utah are interpreted to be a laccolith, exposed by erosion of the overlying layers.
4.1 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. Where do igneous rocks with a coarse-grained (phaneritic) texture form?
   - Deep under the surface
   - Close to the surface but also just below it
   - On top of the surface after being ejected into the air
   - On top of the surface
   - Contact with water

2. Using the classification table, if an igneous rock has a coarse-grained texture AND has a felsic composition (abundant silica), then the igneous rock is called ________.
   - granite
   - basalt
   - pumice
   - rhyolite
   - obsidian

3. Which rock composition has the most amount of silica?
   - ultramafic
   - mafic
   - ultrafelsic
   - intermediate
   - felsic
4. A basaltic intrusion that cuts across layers of sedimentary rocks is called a _______.

- laccolith
- batholith
- sill
- dike
- pluton
4.2 Bowen’s Reaction Series

Bowen’s Reaction Series describes the temperature at which minerals crystallize when cooled, or melt when heated. The low end of the temperature scale where all minerals crystallize into solid rock, is approximately 700°C (1292°F). The upper end of the range where all minerals exist in a molten state, is approximately 1,250°C (2,282°F). These numbers reference minerals that crystallize at standard sea-level pressure, 1 bar. The values will be different for minerals located deep below the Earth’s surface due to the increased pressure, which affects crystallization and melting temperatures (see Chapter 4.4). However, the order and relationships are maintained.

In the figure, the righthand column lists the four groups of igneous rock from top to bottom: ultramafic, mafic, intermediate, and felsic. The down-pointing arrow on the far right shows increasing amounts of silica, sodium, aluminum, and potassium as the mineral composition goes from ultramafic to felsic. The up-pointing arrow shows increasing ferromagnesian components, specifically iron, magnesium, and calcium. To the far left of the diagram is a temperature scale. Minerals near the top of diagram, such as olivine, crystallize at higher temperatures and are found in ultramafic rocks, whereas minerals near the bottom, such as quartz, crystallize at lower temperatures and are found in felsic rocks. (Source Colivine, modified from Bowen, 1922)
as olivine and anorthite (a type of plagioclase), crystallize at higher temperatures. Minerals near the bottom, such as quartz and muscovite, crystallize at lower temperatures.

The most important aspect of Bowen’s Reaction Series is to notice the relationships between minerals and temperature. Norman L. Bowen (1887-1956) was an early 20th Century geologist who studied igneous rocks. He noticed that in igneous rocks, certain minerals always occur together and these mineral assemblages exclude other minerals. Curious as to why, and with the hypothesis in mind that it had to do with the temperature at which the rocks cooled, he set about conducting experiments on igneous rocks in the early 1900s. He conducted experiments on igneous rock—grinding combinations of rocks into powder, sealing the powders into metal capsules, heating them to various temperatures, and then cooling them.

When he opened the quenched capsules, he found a glass surrounding mineral crystals that he could identify under his petrographic microscope. The results of many of these experiments, conducted at different temperatures over a period of several years, showed that the common igneous minerals crystallize from magma at different temperatures. He also saw that minerals occur together in rocks with others that crystallize within similar temperature ranges, and never crystallize with other minerals. This relationship can explain the main difference between mafic and felsic igneous rocks. Mafic igneous rocks contain more mafic minerals, and therefore, crystallize at higher temperatures than felsic igneous rocks. This is even seen in lava flows, with felsic lavas erupting hundreds of degrees cooler than their mafic counterparts. Bowen’s work laid the foundation for understanding igneous petrology (the study of rocks) and resulted in his book, *The Evolution of the Igneous Rocks* in 1928 [5].

![Norman L. Bowen working with his petrographic microscope](image)
4.2 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. Examine Bowen’s Reaction Series diagram. As a felsic magma cools, which mineral would be the last to crystallize?

- muscovite
- k-spar
- olivine
- biotite
- quartz

2. Examine Bowen’s Reaction Series diagram. If a rock contained amphibole, potassium feldspar (orthoclase), and quartz, as the rock is heated, which mineral would melt first?

- quartz
- pyroxene
- olivene
- potassium feldspar (orthoclase)
- amphibole

3. Examine Bowen’s Reaction Series diagram. Which mineral has the highest temperature of crystallization?

- pyroxene
- quartz
- orthoclase
- olivine
- k-spar
4.3 Magma Generation

Magma and lava contain three components: melt, solids, and volatiles. The melt is made of ions from minerals that have liquefied. The solids are made of crystallized minerals floating in the liquid melt. These may be minerals that have already cooled. Volatiles are gaseous components—such as water vapor, carbon dioxide, sulfur, and chlorine—dissolved in the magma [6]. The presence and amount of these three components affect the physical behavior of the magma and will be discussed more below.

4.3.1 Geothermal Gradient

Below the surface, the temperature of the Earth rises. This heat is caused by residual heat left from the formation of Earth and ongoing radioactive decay. The rate at which temperature increases with depth is called the geothermal gradient.

The average geothermal gradient in the upper 100 km (62 mi) of the crust is about 25°C per kilometer of depth. So for every kilometer of depth, the temperature increases by about 25°C.

The depth-temperature graph (see figure) illustrates the relationship between the geothermal gradient (geotherm, red line) and the start of rock melting (solidus, green line). The geothermal gradient changes with depth (which has a direct relationship to pressure) through the crust into upper mantle. The area to the left of the green line includes solid components; to the right is where liquid components start to form. The increasing temperature with depth makes the
depth of about 125 kilometers (78 miles) where the natural geothermal gradient is closest to the solidus.

The temperature at 100 km (62 mi) deep is about 1,200°C (2,192°F). At bottom of the crust, 35 km (22 mi) deep, the pressure is about 10,000 bars \[7\]. A bar is a measure of pressure, with 1 bar being normal atmospheric pressure at sea level. At these pressures and temperatures, the crust and mantle are solid. To a depth of 150 km (93 mi), the geothermal gradient line stays to the left of the solidus line. This relationship continues through the mantle to the core-mantle boundary, at 2,880 km (1,790 mi).

The solidus line slopes to the right because the melting temperature of any substance depends on pressure. The higher pressure created at greater depth increases the temperature needed to melt rock. In another example, at sea level with an atmospheric pressure close to 1 bar, water boils at 100°C. But if the pressure is lowered, as shown on the video below, water boils at a much lower temperature.

There are three principal ways rock behavior crosses to the right of the green solidus line to create molten magma: 1) decompression melting caused by lowering the pressure, 2) flux melting caused by adding volatiles (see more below), and 3) heat-induced melting caused by increasing the temperature. The Bowen’s Reaction Series shows that minerals melt at different temperatures. Since magma is a mixture of different minerals, the solidus boundary is more of a fuzzy zone rather than a well-defined line; some minerals are melted and some remain solid. This type of rock behavior is called partial melting and represents real-world magmas, which typically contain solid, liquid, and volatile components.

The figure below uses P-T diagrams to show how melting can occur at three different plate tectonic settings. The green line is called the solidus, the melting point temperature of the rock at that pressure. Setting A is a situation (called “normal”) in the middle of a stable plate in which no magma is generated. In the other three situations, rock at a lettered location with a temperature at the geothermal gradient is moved to a new P-T situation on the diagram. This shift is indicated by the arrow and its temperature relative to the solidus is shown by the red line. Partial melting occurs where the red line temperature of the rock crosses the green solidus on the diagram. Setting B is at a mid-ocean ridge (decompression melting) where reduction of pressure carries the rock at its temperature across the solidus. Setting C is a hotspot where decompression melting plus addition of heat carries the rock across the solidus, and setting D is a subduction zone where a process called flux melting takes place where the solidus (melting point) is actually shifted to below the temperature of the rock.

Graphs A-D below, along with the side view of the Earth’s layers in various tectonic settings (see figure), show how melting occurs in different situations. Graph A illustrates a normal situation, located in the middle of a stable plate, where no melted rock can be found. The remaining three graphs illustrate rock behavior relative
to shifts in the geothermal gradient or solidus lines. Partial melting occurs when the geothermal gradient line crosses the solidus line. Graph B illustrates behavior of rock located at a mid-ocean ridge, labeled X in the graph and side view. Reduced pressure shifts the geotherm to the right of the solidus, causing decompression melting. Graph C and label Y illustrate a hotspot situation. Decompression melting, plus an addition of heat, shifts the geotherm across the solidus. Graph D and label Z show a subduction zone, where an addition of volatiles lowers the melting point, shifting the solidus to the left of the geothermal gradient. B, C, and D all show different ways the Earth produces intersections of the geothermal gradient and the solidus, which results in melting each time.

Four P-T diagrams show temperature in degrees Celsius on x-axis and depth below the surface in kilometers (km) on the y-axis. The red line is the geothermal gradient and green solidus line represents at temperature and pressure regime at which melting begins. Each of the four P-T diagrams are associated a tectonic setting as shown by a side-view (cross-section) of the lithosphere and mantle.
4.3.2 Decompression Melting

Magma is created at mid-ocean ridges via **decompression melting**. Strong convection currents cause the solid asthenosphere to slowly flow beneath the lithosphere. The upper part of the lithosphere (crust) is a poor heat conductor, so the temperature remains about the same throughout the underlying mantle material. Where the convection currents cause mantle material to rise, the pressure decreases, which causes the melting point to drop. In this situation, the rock at the temperature of the geothermal gradient is rising toward the surface, thus hotter rock is now shallower, at a lower pressure, and the rock, still at the temperature of the geothermal gradient at its old location, shifts past the its melting point (shown as the red line crossing over the solidus or green line in example B in previous figure) and partial melting starts. As this magma continues to rise, it cools and crystallizes to form new lithospheric crust.

4.3.3 Flux Melting

Diagram of ocean-continent subduction. Note water vapor driven out of hydrated minerals in the descending oceanic slab.
Flux melting or fluid-induced melting occurs in island arcs and subduction zones when volatile gases are added to mantle material (see figure: graph D, label Z). Flux-melted magma produces many of the volcanoes in the circum-Pacific subduction zones, also known as the Ring of Fire. The subducting slab contains oceanic lithosphere and hydrated minerals. As covered in Chapter 2, these hydrated forms are created when water ions bond with the crystal structure of silicate minerals. As the slab descends into the hot mantle, the increased temperature causes the hydrated minerals to emit water vapor and other volatile gases, which are expelled from the slab like water being squeezed out of a sponge. The volatiles dissolve into the overlying asthenospheric mantle and decrease its melting point. In this situation the applied pressure and temperature have not changed, the mantle’s melting point has been lowered by the addition of volatile substances. The previous figure (graph D) shows the green solidus line shifting to the left of and below the red geothermal gradient line, and melting begins. This is analogous to adding salt to an icy roadway. The salt lowers the freezing temperature of the solid ice so it turns into liquid water.

**4.3.4 Heat-Induced Melting**

Heat-induced melting, transforming solid mantle into liquid magma by simply applying heat, is the least common process for generating magma (see figure: graph C, label Y). Heat-induced melting occurs at mantle plumes or hotspots. The rock surrounding the plume is exposed to higher temperatures, the geothermal gradient crosses to the right of the green solidus line, and the rock begins to melt. The mantle plume includes rising mantle material, meaning some decompression melting is occurring as well. A small amount of magma is also generated by intense regional metamorphism (see Chapter 6). This magma becomes a hybrid metamorphic-igneous rock called migmatite.

![Migmatite is a partially molten metamorphic rock. (Source: Peter Davis)](image)
4.3 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. What does a P-T diagram of the mantle show?
   - ○ It shows how pressure and temperature increase with depth.
   - ○ It shows how the mantle is liquid magma under the surface.
   - ○ It shows how temperature increases but pressure decreases with depth.
   - ○ It shows the process by which material in the mantle can react and form minerals.
   - ○ It shows how Celsius and kilobars change.

2. What is the process by which decompression melting produces magma at divergent plate boundaries?
   - ○ reduction of pressure at constant temperature
   - ○ addition of fluid at constant pressure
   - ○ addition of heat at constant depth
   - ○ additional pressure deep within the Earth
   - ○ chemical changes to things like pH and charge

3. If volatiles such as water vapor and carbon dioxide are added to a rock, what will happen to the melting temperature?
   - ○ The pressure of the rock will decrease.
   - ○ The pressure of the rock will increase.
   - ○ The melting temperature will not change; It is dependent on the pressure.
   - ○ The melting temperature of a rock will increase.
   - ○ The melting temperature of a rock will decrease.
4.4 Partial Melting and Crystallization

Even though all magmas originate from similar mantle rocks, and start out as similar magma, other things, like partial melting and crystallization processes like magmatic differentiation, can change the chemistry of the magma. This explains the wide variety of resulting igneous rocks that are found all over Earth.

4.4.1 Partial Melting

Because the mantle is composed of many different minerals, it does not melt uniformly. As minerals with lower melting points turn into liquid magma, those with higher melting points remain as solid crystals. This is known as partial melting. As magma slowly rises and cools into solid rock, it undergoes physical and chemical changes in a process called magmatic differentiation.

According to Bowen’s Reaction Series (Section 4.2), each mineral has a unique melting and crystallization temperature. Since most rocks are made of many different minerals, when they start to melt, some minerals begin melting sooner than others. This is known as partial melting, and creates magma with a different composition than the original mantle material.

The most important example occurs as magma is generated from mantle rocks (as discussed in Section 4.3). The chemistry of mantle rock (peridotite) is ultramafic, low in silicates and high in iron and magnesium. When peridotite begins to melt, the silica-rich portions melt first due to their lower melting point. If this continues, the magma becomes increasingly silica-rich, turning ultramafic mantle into mafic magma, and mafic mantle into intermediate magma. The magma rises to the surface because it is more buoyant than the mantle.

Partial melting also occurs as existing crustal rocks melt in the presence of heat from magmas. In this process, existing rocks melt, allowing the magma formed to be more felsic and less mafic than the pre-existing rock. Early in the Earth’s history when the

Geologic provinces with the Shield (orange) and Platform (pink) comprising the Craton, the stable interior of continents.
continents were forming, silica-rich magmas formed and rose to the surface and solidified into granitic continents. In the figure, the old granitic cores of the continents, called shields, are shown in orange.

### 4.4.2 Crystallization and Magmatic Differentiation

Liquid magma is less dense than the surrounding solid rock, so it rises through the mantle and crust. As magma begins to cool and crystallize, a process known as magmatic differentiation changes the chemistry of the resultant rock towards a more felsic composition. This happens via two main methods: assimilation and fractionation.

During assimilation, pieces of country rock with a different, often more felsic, composition are added to the magma. These solid pieces may melt, which changes the composition of the original magma. At times, the solid fragments may remain intact within the cooling magma and only partially melt. The unmelted country rocks within an igneous rock mass are called xenoliths.

Xenoliths are also common in the processes of magma mixing and rejuvenation, two other processes that can contribute to magmatic differentiation. Magma mixing occurs when two different magmas come into contact and mix, though at times, the magmas can remain heterogeneous and create xenoliths, dikes, and other features. Magmatic rejuvenation happens when a cooled and crystallized body of rock is remelted and pieces of the original rock may remain as xenoliths.

Much of the continental lithosphere is felsic (i.e. granitic), and normally more buoyant than the underlying mafic/ultramafic mantle. When mafic magma rises through thick continental crust, it does so slowly, more slowly than when magma rises through oceanic plates. This gives the magma lots of time to react with the surrounding country rock. The mafic magma tends to assimilate felsic rock, becoming more silica-rich as it migrates through the lithosphere and changing into intermediate or felsic magma by the time it reaches the surface. This is why felsic magmas are much more common within continents.
Fractionation or fractional crystallization is another process that increase magma silica content, making it more felsic. As the temperature drops within a magma diapir rising through the crust, some minerals will crystallize and settle to the bottom of the magma chamber, leaving the remaining melt depleted of those ions. Olivine is a mafic mineral at the top of the Bowen’s Reaction series with a high melting point and a smaller percentage of silica verses other common igneous minerals. When ultramafic magma cools, the olivine crystallizes first and settles to the bottom of the magma chamber (see figure). This means the remaining melt becomes more silica-rich and felsic. As the mafic magma further cools, the next minerals on Bowen’s Reaction Series (plagioclase and pyroxene) crystallize next, removing even more low-silica components from the magma, making it even more felsic. This crystal fractionation can occur in oceanic lithosphere, but the formation of more differentiated, highly evolved felsic magmas is largely confined to continental regions where the longer time to the surface allows more fractionation to occur.

Rising magma diapirs in mantle and crust. Fractional crystallization occurs in the diapirs in the crust. (Source: Woudloper)

Schematic diagram illustrating fractional crystallization. If magma at composition A is ultramafic, as the magma cools it changes composition as different minerals crystallize from the melt and settle to the bottom of the magma chamber. In section 1, olivine crystallizes; section 2: olivine and pyroxene crystallize; section 3: pyroxene and plagioclase crystallize; and section 4: plagioclase crystallizes. The crystals are separated from the melt and the remaining magma (composition B) is more silica-rich. (Source: Woudloper)
4.4 Did I Get It?

This quiz is for you to check your comprehension of this section.

1. The crystallization process in which a rising magma diapir incorporates some of the surrounding country rock so that the chemistry of the magma changes is called _____.
   - [ ] fractional crystallization
   - [ ] xenolith
   - [ ] lower density magma rising through higher density country rock
   - [ ] differentiation
   - [ ] assimilation

2. Unmelted pieces of country rock within the igneous rock mass are called _______.
   - [ ] assimilation material
   - [ ] partial melting
   - [ ] basalt nuggets
   - [ ] xenoliths
   - [ ] assimilated rock

3. As magma travels up from the asthenosphere through the lithosphere into continental crust, how will fractional crystallization/magmatic differentiation change the chemistry of an ultramafic magma?
   - [ ] It will become more felsic.
   - [ ] It will become more mafic.
   - [ ] It will contain more volatiles.
   - [ ] It will have higher temperature.
   - [ ] It will have higher pressure.
4.5 Volcanism

When magma emerges onto the Earth’s surface, the molten rock is called lava. A volcano is a type of land formation created when lava solidifies into rock. Volcanoes have been an important part of human society for centuries, though their understanding has greatly increased as our understanding of plate tectonics has made them less mysterious. This section describes volcano location, type, hazards, and monitoring.

4.5.1. Distribution and Tectonics

Most volcanoes are interplate volcanoes. Interplate volcanoes are located at active plate boundaries created by volcanism at mid-ocean ridges, subduction zones, and continental rifts. The prefix “inter-” means between. Some volcanoes are intraplate volcanoes. The prefix “intra-” means within, and intraplate volcanoes are located within tectonic plates, far removed from plate boundaries. Many intraplate volcanoes are formed by hotspots.
Most volcanism on Earth occurs on the ocean floor along mid-ocean ridges, a type of divergent plate boundary (see Chapter 2). These interplate volcanoes are also the least observed and famous, since most of them are located under 3,000-4,500 m (10,000-15,000 ft) of ocean and the eruptions are slow, gentle, and oozing. One exception is the interplate volcanoes of Iceland. The diverging and thinning oceanic plates allow hot mantle rock to rise, releasing pressure and causing decompression melting. Ultramafic mantle rock, consisting largely of peridotite, partially melts and generates magma that is basaltic. Because of this, almost all volcanoes on the ocean floor are basaltic. In fact, most oceanic lithosphere is basaltic near the surface, with phaneritic gabbro and ultramafic peridotite underneath [10].

When basaltic lava erupts underwater it emerges in small explosions and/or forms pillow-shaped structures called pillow basalts. These seafloor eruptions enable entire underwater ecosystems to thrive in the deep ocean around mid-ocean ridges. This ecosystem exists around tall vents emitting black, hot mineral-rich water called deep-sea hydrothermal vents, also known as black smokers.

Without sunlight to support photosynthesis, these organisms instead utilize a process called chemosynthesis. Certain bacteria are able to turn hydrogen sulfide (H₂S), a gas that smells like rotten eggs, into life-supporting nutrients and water. Larger organisms may eat these bacteria or absorb nutrients and water produced by bacteria living symbiotically inside their bodies [11]. The three videos show some of the ecosystems found around deep-sea hydrothermal vents.

- https://youtu.be/a5aQ4W9GbpU
- https://youtu.be/dXOQFnU-49k
- https://youtu.be/eUzz ilsFa0
**VOLCANOES AT SUBDUCTION ZONES**

The second most commonly found location for volcanism is adjacent to subduction zones, a type of convergent plate boundary (see Chapter 2). The process of subduction expels water from hydrated minerals in the descending slab, which causes flux melting in the overlying mantle rock. Because subduction volcanism occurs in a volcanic arc, the thickened crust promotes partial melting and magma differentiation. These evolve the mafic magma from the mantle into more silica-rich magma. The Ring of Fire surrounding the Pacific Ocean, for example, is dominated by subduction-generated eruptions of mostly silica-rich lava; the volcanoes and plutons consist largely of intermediate-to-felsic rock such as andesite, rhyolite, pumice, and tuff.

Distribution of hydrothermal vent fields

Distribution of volcanoes on the planet. Click here for an interactive map of volcano distributions.
VOLCANOES AT CONTINENTAL RIFTS

Some volcanoes are created at continental rifts, where crustal thinning is caused by diverging lithospheric plates, such as the East African Rift Basin in Africa. Volcanism caused by crustal thinning without continental rifting is found in the Basin and Range Province in North America. In this location, volcanic activity is produced by rising magma that stretches the overlying crust (see figure). Lower crust or upper mantle material rises through the thinned crust, releases pressure, and undergoes decompression-induced partial melting. This magma is less dense than the surrounding rock and continues to rise through the crust to the surface, erupting as basaltic lava. These eruptions usually result in flood basalts, cinder cones, and basaltic lava flows (see video). Relatively young cinder cones of basaltic lava can be found in south-central Utah, in the Black Rock Desert Volcanic Field, which is part of the zone of Basin and Range crustal extension. These Utah cinder cones and lava flows started erupting around 6 million years ago, with the last eruption occurring 720 years ago [12].

HOTSPOTS

Hotspots are the main source of intraplate volcanism. Hotspots occur when lithospheric plates glide over a hot mantle plume, an ascending column of solid heated rock originating from deep within the mantle. The mantle plume generates melts as material rises, with the magma rising even more. When the ascending magma reaches the lithospheric crust, it spreads out into a mushroom-shaped head that is tens to hundreds of kilometers across.

Basaltic cinder cones of the Black Rock Desert near Beaver, Utah.

Diagram showing a non-moving source of magma (mantle plume) and a moving overriding plate.
Since most mantle plumes are located beneath the oceanic lithosphere, the early stages of intraplate volcanism typically take place underwater. Over time, basaltic volcanoes may build up from the sea floor into islands, such as the Hawaiian Islands \[13\]. Where a hotspot is found under a continental plate, contact with the hot mafic magma may cause the overlying felsic rock to melt and mix with the mafic material below, forming intermediate magma. Or the felsic magma may continue to rise, and cool into a granitic batholith or erupt as a felsic volcano. The Yellowstone caldera is an example of hotspot volcanism that resulted in an explosive eruption.

A zone of actively erupting volcanism connected to a chain of extinct volcanoes indicates intraplate volcanism located over a hotspot. These volcanic chains are created by the overriding oceanic plate slowly moving over a hotspot mantle plume. These chains are seen on the seafloor and continents and include volcanoes that have been inactive for millions of years. The Hawaiian Islands on the Pacific Oceanic plate are the active end of a long volcanic chain that extends from the northwest Pacific Ocean to the Emperor Seamounts, all the way to the to the subduction zone beneath the Kamchatka Peninsula. The overriding North American continental plate moved across a mantle plume hotspot for several million years, creating a chain of volcanic calderas that extends from Southwestern Idaho to the presently active Yellowstone caldera in Wyoming.

Two three-minute videos (below) illustrates hotspot volcanoes.

- https://youtu.be/AhSaE0omw90
- https://youtu.be/t5go-78gCJU
4.5.2 Volcano Features and Types

There are several different types of volcanoes based on their shape, eruption style, magmatic composition, and other aspects.

The figure shows the main features of a typical stratovolcano: 1) magma chamber, 2) upper layers of lithosphere, 3) the conduit or narrow pipe through which the lava erupts, 4) the base or edge of the volcano, 5) a sill of magma between layers of the volcano, 6) a diapir or feeder tube to the sill, 7) layers of tephra (ash) from previous eruptions, 8 & 9) layers of lava erupting from the vent and flowing down the sides of the volcano, 10) the crater at the top of the volcano, 11) layers of lava and tephra on (12), a parasitic cone.
A parasitic cone is a small volcano located on the flank of a larger volcano such as Shastina on Mount Shasta. Kilauea sitting on the flank of Mauna Loa is not considered a parasitic cone because it has its own separate magma chamber [13]. The vents of the parasite and the main volcano, the rim of the crater, clouds of ash blown into the sky by the eruption; this settles back onto the volcano and surrounding land.

The largest craters are called calderas, such as the Crater Lake Caldera in Oregon. Many volcanic features are produced by viscosity, a basic property of a lava. Viscosity is the resistance to flowing by a fluid. Low viscosity magma flows easily more like syrup, the basaltic volcanism that occurs in Hawaii on shield volcanoes. High viscosity means a thick and sticky magma, typically felsic or intermediate, that flows slowly, similar to toothpaste.

SHIELD VOLCANO

The largest volcanoes are shield volcanoes. They are characterized by broad low-angle flanks, small vents at the top, and mafic magma chambers. The name comes from the side view, which resembles a medieval warrior’s shield. They are typically associated with hotspots, mid-ocean ridges, or continental rifts with rising upper mantle material. The low-angle flanks are built up slowly from numerous low-viscosity basaltic lava flows that spread out over long distances. The basaltic lava erupts effusively, meaning the eruptions are small, localized, and predictable.
Typically, shield volcano eruptions are not much of a hazard to human life—although non-explosive eruptions of Kilauea (Hawaii) in 2018 produced uncharacteristically large lavas that damaged roads and structures. Mauna Loa (see USGS page) and Kilauea (see USGS page) in Hawaii are examples of shield volcanoes. Shield volcanoes are also found in Iceland, the Galapagos Islands, Northern California, Oregon, and the East African Rift.

The largest volcanic edifice in the Solar System is Olympus Mons on Mars. This (possibly extinct) shield volcano covers an area the size of the state of Arizona. This may indicate the volcano erupted over a hotspot for millions of years, which means Mars had little, if any, plate tectonic activity.

Basaltic lava forms special landforms based on magma temperature, composition, and content of dissolved gases and water vapor. The two main types of basaltic volcanic rock have Hawaiian names—pahoehoe and aa. Pahoehoe might come from low-viscosity lava that flows easily into ropey strands.

Aa (sometimes spelled a’a or ‘a‘ā and pronounced “ah-ah”) is more viscous and has a crumbly blocky appearance. The exact details of what forms the two types of flows are still up for debate. Felsic lavas have lower temperatures and more silica, and thus are higher viscosity. These also form aa-style flows.
Low-viscosity, fast-flowing basaltic lava tends to harden on the outside into a tube and continue to flow internally. Once lava flow subsides, the empty outer shell may be left as a lava tube. Lava tubes, with or without collapsed roofs, make famous caves in Hawaii, Northern California, the Columbia River Basalt Plateau of Washington and Oregon, El Malpais National Monument in New Mexico, and Craters of the Moon National Monument in Idaho.

**Fissures** are cracks that commonly originate from shield-style eruptions. Lava emerging from fissures is typically mafic and very fluid. The 2018 Kiluaea eruption included fissures associated with the lava flows. Some fissures are caused by the volcanic seismic activity rather than lava flows. Some fissures are influenced by plate tectonics, such as the common fissures located parallel to the divergent boundary in Iceland.

Cooling lava can contract into columns with semi-hexagonal cross sections called **columnar jointing**. This feature forms the famous Devils Tower in Wyoming, possibly an ancient volcanic vent from which the surrounding layers of lava and ash have been removed by erosion. Another well-known exposed example of columnar jointing is the Giant’s Causeway in Ireland.
**STRATOVOLCANO**

A *stratovolcano*, also called a composite cone volcano, has steep flanks, a symmetrical cone shape, distinct crater, and rises prominently above the surrounding landscape. The term composite refers to the alternating layers of pyroclastic fragments like ash and bombs, and solidified lava flows of varying composition. Examples include Mount Rainier in Washington state and Mount Fuji in Japan.

Stratovolcanoes usually have felsic to intermediate magma chambers, but can even produce mafic lavas. Stratovolcanoes have viscous lava flows and domes, punctuated by explosive eruptions. This produces volcanoes with steep flanks. [14].

**LAVA DOMES**

*Lava domes* are accumulations of silica-rich volcanic rock, such as rhyolite and obsidian. Too viscous to flow easily, the felsic lava tends to pile up near the vent in blocky masses. Lava domes often form in a vent within the collapsed crater of a stratovolcano, and grow by internal expansion. As the dome expands, the outer surface cools, hardens, and shatters, and spills loose fragments down the sides. Mount Saint Helens has a good example of a lava dome inside of a
collapsed stratovolcano crater. Examples of stand-alone lava domes are Chaiten in Chile and Mammoth Mountain in California. [18][14].

**CALDERA**

Calderas are steep-walled, basin-shaped depressions formed by the collapse of a volcanic edifice into an empty magma chamber. Calderas are generally very large, with diameters of up to 25 km (15.5 mi). The term caldera specifically refers to a volcanic vent; however, it is frequently used to describe a volcano type. Caldera volcanoes are typically formed by eruptions of high-viscosity felsic lava having high volatiles content.

Crater Lake, Yellowstone, and the Long Valley Caldera are good examples of this type of volcanism. The caldera at Crater Lake National Park in Oregon was created about 6,800 years ago when Mount Mazama, a composite volcano, erupted in a huge explosive blast. The volcano ejected large amounts of volcanic ash and rapidly drained the magma chamber, causing the top to collapse into a large depression that later filled with water. Wizard Island in the middle of the lake is a later resurgent lava dome that formed within the caldera basin [14].

The Yellowstone volcanic system erupted three times in the recent geologic past—2.1, 1.3, and 0.64 million years ago—leaving behind three caldera basins. Each eruption created large rhyolite lava flows as well as pyroclastic flows that solidified into tuff formations. These extra-large eruptions rapidly emptied the magma chamber, causing the roof to collapse and form a caldera. The youngest of the three calderas contains most of Yellowstone National Park, as well as two resurgent lava domes. The calderas are difficult to see today due to the amount of time

Map of calderas and related rocks around Yellowstone.
since their eruptions and subsequent erosion and glaciation.

Yellowstone volcanism started about 17-million years ago as a hotspot under the North American lithospheric plate near the Oregon/Nevada border. As the plate moved to the southwest over the stationary hotspot, it left behind a track of past volcanic activities. Idaho’s Snake River Plain was created from volcanism that produced a series of calderas and lava flows. The plate eventually arrived at its current location in northwestern Wyoming, where hotspot volcanism formed the Yellowstone calderas [19].

The Long Valley Caldera near Mammoth, California, is the result of a large volcanic eruption that occurred 760,000 years ago. The explosive eruption dumped enormous amounts of ash across the United States, in a manner similar to the Yellowstone eruptions. The Bishop Tuff deposit near Bishop, California, is made of ash from this eruption. The current caldera basin is 17 km by 32 km (10 mi by 20 mi), large enough to contain the town of Mammoth Lakes, major ski resort, airport, major highway, resurgent dome, and several hot springs [20].

**CINDER CONE**

Cinder cones are small volcanoes with steep sides, and made of pyroclastic fragments that have been ejected from a pronounced central vent. The small fragments are called cinders and the largest are volcanic bombs. The eruptions are usually short-lived events, typically consisting of mafic lavas with a high content of volatiles. Hot lava is ejected into the air, cooling and solidifying into fragments that accumulate on the flank of the volcano. Cinder cones are found throughout western North America [14].
A recent and striking example of a cinder cone is the eruption near the village of Paricutin, Mexico that started in 1943 \[^{21}\]. The cinder cone started explosively shooting cinders out of the vent in the middle of a farmer’s field.

The volcanism quickly built up the cone to a height of over 90 m (300 ft) within a week, and 365 m (1,200 ft) within the first 8 months. After the initial explosive eruption of gases and cinders, basaltic lava poured out from the base of the cone. This is a common order of events for cinder cones: violent eruption, cone and crater formation, low-viscosity lava flow from the base. The cinder cone is not strong enough to support a column of lava rising to the top of the crater, so the lava breaks through and emerges near the bottom of the volcano. During nine years of eruption activity, the ashfall covered about 260 km\(^2\) (100 mi\(^2\)) and destroyed the nearby town of San Juan \[^{14}\].

**FLOOD BASALTS**

A rare volcanic eruption type, unobserved in modern times, is the flood basalt. Flood basalts are some of the largest and lowest viscosity types of eruptions known. They are not known from any eruption in human history, so the exact mechanisms of eruption are still mysterious. Some famous examples include the Columbia River Flood Basalts in Washington, Oregon, and Idaho, the Deccan Traps,
which cover about 1/3 of the country of India, and the Siberian Traps, which may have been involved in the Earth’s largest mass extinction (see chapter 8).

**CARBONATITES**

Arguably the most unusual volcanic activity are carbonatite eruptions. Only one actively erupting carbonatite volcano exists on Earth today, Ol Doinyo Lengai, in the East African Rift Zone of Tanzania. While all other volcanism on Earth originates from silicate-based magma, carbonatites are a product of carbonate-based magma and produce volcanic rocks containing greater than 50% carbonate minerals. Carbonatite lavas are very low viscosity and relatively cold for lava. The erupting lava is black, and solidifies to brown/grey rock that eventually turns white. These rocks are occasionally found in the geologic record and require special study to distinguish them from metamorphic marbles (see Chapter 6). They are mostly associated with continental rifting [22].

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*Crater of Ol Doinyo Lengai in 2011. Note the white carbonatite in the walls of the crater.*
Igneous rock types and related volcano types. Mid-ocean ridges and shield volcanoes represent more mafic compositions, and strato (composite) volcanoes generally represent a more intermediate or felsic composition and a convergent plate tectonic boundary. Note that there are exceptions to this generalized layout of volcano types and igneous rock composition.
4.5.3 Volcanic Hazards and Monitoring

While the most obvious volcanic hazard is lava, the dangers posed by volcanoes go far beyond lava flows. For example, on May 18, 1980, Mount Saint Helens (Washington, United States) erupted with an explosion and landslide that removed the upper 400 m (1,300 ft) of the mountain. The initial explosion was immediately followed by a lateral blast, which produced a pyroclastic flow that covered nearly 600 km² (230 mi²) of forest with hot ash and debris [23]. The pyroclastic flow moved at speeds of 80-130 kph (50-80 mph), flattening trees and ejecting clouds of ash into the air. The USGS video provides an account of this explosive eruption that killed 57 people [24].

- https://youtu.be/Ec3ouUoG56U

In 79 AD, Mount Vesuvius, located near Naples, Italy, violently erupted sending a pyroclastic flow over the Roman countryside, including the cities of Herculaneum and Pompeii. The buried towns were discovered in an archeological expedition in the 18th century [25]. Pompeii famously contains the remains (casts) of people suffocated by ash and covered by 10 feet (3 m) of ash, pumice lapilli, and collapsed roofs [26].
PYROCLASTIC FLOWS

The most dangerous volcanic hazard are **pyroclastic flows** [video]. These flows are a mix of lava blocks, pumice, ash, and hot gases between 200°C-700°C (400°F-1,300°F). The turbulent cloud of ash and gas races down the steep flanks at high speeds up to 193 kph (120 mph) into the valleys around composite volcanoes [24]. Most explosive, silica-rich, high viscosity magma volcanoes such as composite cones usually have pyroclastic flows. The rock tuff and welded tuff is often formed from these pyroclastic flows.
There are numerous examples of deadly pyroclastic flows. In 2014, the Mount Ontake pyroclastic flow in Japan killed 47 people. The flow was caused by magma heating groundwater into steam, which then rapidly ejected with ash and volcanic bombs. Some were killed by inhalation of toxic gases and hot ash, while others were struck by volcanic bombs [27]. Two short videos below document eye-witness video of pyroclastic flows. In the early 1990s, Mount Unzen erupted several times with pyroclastic flows. The pyroclastic flow shown in this famous short video killed 41 people. In 1902, on the Caribbean Island Martinique, Mount Pelee erupted with a violent pyroclastic flow that destroyed the entire town of St. Pierre and killing 28,000 people in moments [28].

**LANDSLIDES AND LANDSLIDE-GENERATED TSUNAMIS**

The steep and unstable flanks of a volcano can lead to slope failure and dangerous landslides. These landslides can be triggered by magma movement, explosive eruptions, large earthquakes, and/or heavy rainfall. During the 1980 Mount St. Helens eruption, the entire north flank of the volcano collapsed and released a huge landslide that moved at speeds of 160-290 kph (100-180 mph).

If enough landslide material reaches the ocean, it may cause a tsunami. In 1792, a landslide caused by the Mount Unzen eruption reached the Ariaka Sea, generating a tsunami that killed 15,000 people (see USGS page). When Mount Krakatau in Indonesia erupted in 1883, it generated ocean waves that towered 40 m (131 ft) above sea level. The tsunami killed 36,000 people and destroyed 165 villages [24].
**TEPHRA**

Volcanoes, especially composite volcanoes, eject large amounts of **tephra** (ejected rock materials), most notably **ash** (tephra fragments less than 0.08 inches [2 mm]). Larger tephra is heavier and falls closer to the vent. Larger blocks and bombs pose hazards to those close to the eruption such as at the 2014 Mount Ontake disaster in Japan discussed earlier.

Hot ash poses an immediate danger to people, animals, plants, machines, roads, and buildings located close to the eruption. Ash is fine grained (< 2mm) and can travel airborne long distances away from the eruption site. Heavy accumulations of ash can cause buildings to collapse. In people, it may cause respiratory issues like silicosis. Ash is destructive to aircraft and automobile engines, which can disrupt transportation and shipping services [24]. In 2010, the Eyjafjallajökull volcano in Iceland emitted a large ash cloud into the upper atmosphere, causing the largest air-travel disruption in northern Europe since World War II. No one was injured, but the service disruption was estimated to have cost the world economy billions of dollars [29].

**VOLCANIC GASES**

As magma rises to the surface the confining pressure decreases, and allows dissolved gases to escape into the atmosphere. Even volcanoes that are not actively erupting may emit hazardous gases, such as carbon dioxide (CO₂), sulfur dioxide (SO₂), hydrogen sulfide (H₂S), and hydrogen halides (HF, HCl, or HBr).

Carbon dioxide tends to sink and accumulate in depressions and basins. In volcanic areas known to emit carbon dioxide, low-lying areas may trap hazardous concentrations of this colorless and odorless gas. The Mammoth Mountain Ski Resort in California is located within the Long Valley Caldera, is one such area of carbon dioxide-producing volcanism. In 2006, three ski patrol members died of suffocation caused by carbon dioxide after falling into a snow depression near a fumarole (info).
In rare cases, volcanism may create a sudden emission of gases without warning. Limnic eruptions (*limne* is Greek for lake), occur in crater lakes associated with active volcanism. The water in these lakes is supercharged with high concentrations of dissolved gases. If the water is physically jolted by a landslide or earthquake, it may trigger an immediate and massive release of gases out of solution. An analogous example would be what happens to vigorously shaken bottle of carbonated soda when the cap is opened. An infamous limnic eruption occurred in 1986 at Lake Nyos, Cameroon. Almost 2,000 people were killed by a massive release of carbon dioxide [24].

**LAHARS**

*Lahar* is an Indonesian word and is used to describe a volcanic mudflow that forms from rapidly melting snow or glaciers. Lahars are slurries resembling wet concrete, and consist of water, ash, rock fragments, and other debris. These mudflows flow down the flanks of volcanoes or mountains covered with freshly-erupted ash and on steep slopes can reach speeds of up to 80 kph (50 mph).

Several major cities, including Tacoma, are located on prehistoric lahar flows that extend for many kilometers across the flood plains surrounding Mount Rainier in Washington (see map). A map of Mount Baker in Oregon shows a similar potential hazard for lahar flows (see map)[24]. A tragic scenario played out recently, in 1985, when a lahar from the Nevado del Ruiz volcano in Colombia buried the town of Armero and killed an estimated 23,000 people.

**MONITORING**

Geologists use various instruments to detect changes or indications that an eruption is imminent [30][31]. The three videos show different types of volcanic monitoring used to predict eruptions 1) earthquake activity; 2) increases in gas emission; and 3) changes in land surface orientation and elevation.

One video shows how monitoring earthquake frequency, especially special vibrational earthquakes called harmonic tremors, can detect magma movement and possible
eruption. Another video shows how gas monitoring may be used to predict an eruption. A rapid increase of gas emission may indicate magma that is actively rising to surface and releasing dissolved gases out of solution, and that an eruption is imminent. The last video shows how a GPS unit and tiltmeter can detect land surface changes, indicating the magma is moving underneath it.

- https://youtu.be/nlo-2JoNHrw
- https://youtu.be/owk4fWbw4qM
- https://youtu.be/sNYQkxxd_oQ
4.5 Did I Get It?

1. Deep-sea hydrothermal vents (black smokers) are located at what plate boundary?

- divergent boundaries of the East African Rift
- convergent boundaries with oceanic to oceanic plate subduction
- convergent boundaries with subduction zones
- transform boundaries like the San Andreas
- divergent boundaries of the mid-ocean ridge

2. Explosive silica-rich volcanoes will be located mostly at ______.

- convergent plate boundaries with subduction zones
- divergent boundaries of the East African Rift
- divergent boundaries of the mid-ocean ridge
- oceanic hot spot volcanic chains
- convergent plate boundaries with continental to continental plate collision

3. A ______ volcano has steep flanks, symmetrical cone shapes, distinct craters, and a silica-rich magma that results in an explosive eruption style.

- cinder cone
- flood basalts
- stratovolcano
- caldera

4. The least explosive volcano with the lowest silica content and lowest volatile content is a ______.

- shield
- lava dome
- caldera
- stratovolcano (composite cone)
- cinder cone
Summary

Igneous rock is divided into two major groups: intrusive rock that solidifies from underground magma, and extrusive rock formed from lava that erupts and cools on the surface. Magma is generated from mantle material at several plate tectonics situations by three types of melting: decompression melting, flux melting, or heat-induced melting. Magma composition is determined by differences in the melting temperatures of the mineral components (Bowen’s Reaction Series). The processes affecting magma composition include partial melting, magmatic differentiation, assimilation, and collision. Volcanoes come in a wide variety of shapes and sizes, and are classified by a multiple factors, including magma composition, and plate tectonic activity. Because volcanism presents serious hazards to human civilization, geologists carefully monitor volcanic activity to mitigate or avoid the dangers it presents.

Chapter 4 Review Quiz

Take this quiz for a general review of this chapter.

1. Which rock composition has the least amount of silica?
   - [ ] ultramafic
   - [ ] intermediate
   - [ ] felsic
   - [ } mafic

2. How does the silica content affect the behavior of the magma?
   - [ ] Higher silica makes the magma have less volatiles
   - [ ] Higher silica makes the cooling rate greater
   - [ ] Higher silica makes the magma more viscous
   - [ ] Higher silica makes the magma less viscous
   - [ ] Higher silica makes the magma have more volatiles
3. What is the rate of cooling for intrusive rocks?

- ☐ Fast, then slow
- ☑ Slow, then fast
- ☐ Slow
- ☐ Fast
- ☐ Variable

4. How is magma generated in the earth? SELECT THREE THAT APPLY

- ☐ Volatiles are added to the mantle to lower melting temperature
- ☐ Pressure is reduced
- ☐ Sedimentation is added to create heat
- ☐ Heat from magma partially melts adjacent rocks
- ☐ The subducting plate is melted
- ☐ Heat is created as plates thicken

5. Partially melting an ultramafic rock would immediately produce a magma of what composition?

- ☐ ultrafelsic
- ☐ felsic
- ☐ intermediate
- ☐ mafic
- ☐ ultramafic

6. Where do igneous rocks with a fine-grained (aphanitic) texture form?

- ☐ in pegmatitic dikes
- ☐ pretty much anywhere that has dissolved water
- ☐ on or near the Earth's surface
- ☐ deep in the mantle
- ☐ deep under the Earth's surface
7. Which tectonic setting generally has the least explosive volcanism?

- ☐ Transform
- ☐ Mid-ocean ridge
- ☐ Subduction
- ☐ Collision
- ☐ Rift

8. Porphyritic rocks with coarse grained crystals in a finer grained groundmass indicate what?

- ☐ The rock cooled quickly underground
- ☐ The rock cooled slowly on the surface
- ☐ The rock cooled quickly on the surface
- ☐ The rock cooled slowly underground
- ☐ The rock cooled slowly, then more quickly

9. Which volcanic hazard is LEAST likely to cause injury or death?

- ☐ Pyroclastic flow
- ☐ Lahar
- ☐ Lava flow
- ☐ Landslide
- ☐ Ash fall

10. What is the name of a volcanic hazard composed of hot gases and lapilli that runs downhill at tremendous speed (perhaps > 100 mph!)?

- ☐ Pyroclastic flow
- ☐ Ash flow
- ☐ Lahar flow
- ☐ Cinder flow
- ☐ Lava flow
References


