The Nature of Earth:
An Introduction to Geology

John J. Renton, Ph.D.
Professor John Renton received his bachelor’s degree in chemistry in 1956 from Waynesburg College, Waynesburg, Pennsylvania. Although he had originally planned to earn a master’s degree in chemistry, having had his interest piqued by a course in geology taken in his senior year and encouraged by his professor, he decided to pursue a master’s degree in geology, which he received in 1959 from West Virginia University. Commissioned as a second lieutenant in the U.S. Air Force in 1959, Dr. Renton spent his tour of duty as a Research and Development Officer in the Solid-State Physics Group at Wright-Patterson Air Force Base in Dayton, Ohio. Upon completion of his military duty and having decided on a career in university teaching, he returned to West Virginia University, where he was awarded the Ph.D. in 1963. The year Dr. Renton graduated, the Department of Geology decided to expand into the area of geochemistry and offered him a faculty position to do just that. He established and taught courses in aqueous geochemistry, instrumental analysis, x-ray analysis, and clay mineralogy. With government interest rising in coal, he and a colleague established courses in coal geology and coal geochemistry. Throughout his tenure, however, his favorite course has been introductory geology, which he has taught for 40 years.

In his specialty of coal geology and geochemistry, either alone or with co-workers, Dr. Renton has published 45 papers and has been part of more than $4 million of coal-related research grants. His current research interest is the distribution of selenium and arsenic in coal and coal-related rocks and their mobility when exposed to weathering. In addition to his scientific investigations, Dr. Renton and three colleagues have established a program to provide content, workshops, and field experiences for earth science teachers throughout West Virginia.
With few students currently interested in coal, Dr. Renton’s teaching responsibilities are primarily focused on two 280-student introductory geology courses each semester. Based on his experiences in teaching introductory students and in recognition of their special academic needs, he has written a textbook, *Planet Earth*, published by Kendall-Hunt. Dr. Renton’s success in teaching is indicated by the number of teaching awards he has received. In 1995, he won the Outstanding Educator Award from the Eastern Section of the American Association of Petroleum Geologists. In 2000, he won the Outstanding Teacher Award from the Eberly College of Arts and Sciences, and in 2001, he won the university-wide Outstanding Teacher Award from the West Virginia University Foundation and also West Virginia Professor of the Year from the Carnegie Foundation for the Advancement of Teaching and the Council for the Advancement and Support of Education (CASE Award). His most prestigious award came in 2002, when he was appointed to the Eberly Family Chair for Distinguished Teaching.
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Scope:

Geology has got to be considered the world’s number-one spectator sport. Consider the millions of people worldwide who travel millions of miles to visit and experience monuments that nature has carved out of rock. Each year, tourists stand in awe on the south rim of the Grand Canyon on the edge of a chasm that is more than a mile deep and, in places, more than 10 miles wide. Others stand among the incredible thermal features of Yellowstone Park, one of the truly unique places in all the world. Although visitors can appreciate such places with absolutely no geological knowledge, I cannot help but feel that if they had at least a basic understanding of how these features originated, they would be even more impressed. How much more would a trip to the Grand Canyon mean with the understanding that what lay before you was the result of a huge portion of the southwest that we now call the Colorado Plateau having been lifted vertically from near sea level to elevations of 10,000 feet? The result was a rejuvenated Colorado River and its tributaries that methodically cut through thousands of feet of rock to create the scenic splendor you see from Canyonlands in the east to Zion National Park in the west. Likewise, as you stand in the middle of Yellowstone Park surrounded by hundreds of hot springs, fumaroles, and geysers, the power of nature is obvious. But how much more will that experience mean if you understand that all of what you see within the park is the result of the movement of the North American continent over a hot spot that developed about 16 million years ago beneath what is now northeastern Nevada? Further, that hot spot was responsible for the volcanism that created the Snake River Valley of southern Idaho as the continent moved to the west-southwest, and it eventually ended up under the northwestern corner of Wyoming. Would it not mean more as you observed an eruption of Old Faithful to know that you were standing in the middle of an enormous collapsed structure that formed following three incredible eruptions, the likes of which have never been experienced in all of historic time? Would it not mean more to know that only a few miles beneath your feet, molten rock is rising toward the surface, creating a bulge that explains why Yellowstone Lake is being tipped to the south and that this bulging of
the surface may well be a premonition of another cataclysmic eruption? I cannot help but feel that it would.

It is my purpose in preparing this course to give you the basic knowledge you will need to understand much of what you see around you as you tour the world, whether that tour represents going to some distant exotic place or the short trip to the office or shopping center. There will be much to learn beyond what I will teach you here, but what you will gain in this course will be a sound foundation for further investigation on your part. As I will point out in my first lecture, my aim is to have you carry what you learn in this course with you wherever you go for the rest of your life so that you may more deeply understand and appreciate the landscape and the geology that surrounds you.

I have always thought that a course in introductory geology should begin by placing Earth in the context of the universe. To this end, in Lectures One and Two, we will review some of the ideas astronomers have about the universe, from its creation with the Big Bang to its possible end. In these early lectures, we will concentrate on the stars, because the elements that are the building blocks of everything are created during the deaths of stars. Having created the elements, we will discuss the origin of planets, using our own solar system as a model. We will then use the discussion describing the formation of planet Earth from its protoplanet predecessor to introduce the topic of plate tectonics.

The theory of plate tectonics revolutionized how we envision Earth. It is to geology what Darwin’s concept of organic evolution was to biology, Newton’s laws of motion were to physics, and Copernicus’s view of the heavens was to astronomy. Because plate tectonics will be the basis for many of our discussions, it is important that you have an understanding of it early in the course. Lectures Three and Four will be devoted to the theory of plate tectonics.

We will then move on to a discussion of the materials of which Earth is made in Lectures Five through Seven, namely, minerals. Minerals are the building blocks of rocks. Because much of what you will see in your travels is either composed of rocks or consists of the remains of rocks that have been exposed to the atmosphere, it is important to have a firm understanding
of basic mineralogy and how minerals combine to form the three different kinds of rocks: igneous, sedimentary, and metamorphic. It is also important to understand that the geologic history of Earth is recorded in rocks and that the primary purpose of the science of geology is to determine Earth history. To these ends, we will discuss how minerals form, what determines their relative chemical stability, and how they combine to form rocks.

Because igneous rocks make up the great portion of Earth’s surface, in particular the crust, we will introduce in Lecture Eight the process by which many types of igneous rocks form, that is, volcanic activity. We continue our discussion of rock types in Lectures Nine and Ten, where we take a look at the composition and formation of sedimentary and metamorphic rocks. In Lectures Eleven through Thirteen, we will call on plate tectonics to demonstrate how the theory allowed us to finally understand the distribution of volcanic activity, a process that had been observed for many centuries but never fully understood.

Lectures Fourteen through Sixteen will introduce the major processes that constantly change Earth’s land surface, including mass wasting and weathering. For the most part, these processes go on at such slow rates that, except for the occasional landslide or flood, few people are aware of their existence, yet their combined efforts are responsible for the sculpting of the topography that surrounds all of us. These discussions will represent a giant step toward your understanding of much of what you see as you tour your world. Lectures Seventeen and Eighteen discuss the topics of soil minerals and soil types. Lectures Nineteen through Twenty-Two take up the topic of erosion, beginning with the main agent of erosion—streams—and how they sculpt the land and ending with a look at the second most important agent of erosion—glaciers.

The topic of groundwater is introduced in Lectures Twenty-Three through Twenty-Six, mainly because it represents our major supply of readily available fresh water; in this country, more than half of our drinking water comes from groundwater sources. In many parts of the country and the world at large, obtaining fresh water is now and will become an increasingly serious problem. Unfortunately, too many people consider groundwater to be a renewable resource; you will discover in these discussions that it is not.
Lectures Twenty-Seven through Twenty-Nine discuss the various processes under which rocks are deformed and the basic geologic structures that are created by the deformational forces. During your travels, except for rocks whose layers are horizontal, the attitudes of rocks you observe in road cuts and the faces of cliffs are the result of rock deformation.

Lectures Thirty through Thirty-Two discuss perhaps the most life-threatening aspect of rock deformation, namely, earthquakes. We will again resurrect our discussions of plate tectonics to explain the worldwide distribution of earthquakes. For centuries, observers noted that the distributions of life-threatening volcanic activity and earthquakes seemed to be directly associated, a relationship that was only understood with the advent of plate tectonics. Using plate tectonics, we will explain what determines the magnitude of earthquakes and what, if anything, can be done to minimize their damage. Included in these lectures will be a discussion of how seismic waves are recorded and studied.

Lectures Thirty-Three and Thirty-Four will concentrate on what many geologists consider the essence of the science, namely the creation of mountains. Once again, we will see that until the advent of the theory of plate tectonics, we never really understood how the great mountains of the world formed. At first thought, it would seem that there should be an infinite number of ways such structures could come about. Plate tectonics shows us that all of the major mountains of the world can be explained using a few plate-dominated scenarios.

We will close the course with two lectures that concentrate on the two major sources of energy in modern society, coal and petroleum, in particular, oil. We are fast approaching a crisis in the availability of the oil that has been the world’s major energy source since early in the last century. According to the best estimates, the end of the hydrocarbon era will come before the end of this century. Certainly, our children and grandchildren will face the end of the oil era. At the present time, the only readily available long-term source of energy for the future is coal. But because coal is also a non-renewable resource, we must find one that is not. I would suggest hydrogen.
I’ve often thought that the place to start a course in geology is in the beginning. And in the beginning, the astronomers tell us, there was no need for geology, because there were no rocks. There were no minerals. There was no Earth. There were no stars. They tell us there was nothing.

The science of geology has had to go beyond the confines of our own planet to gain insight into how Earth came to be and where we fit into the big picture of the universe. To do so, we call heavily on information provided by the science of astronomy, beginning with theories about the creation of the universe, including the Big Bang theory. We see how energy was converted into matter in the form of quarks and how hydrogen atoms were converted into helium atoms to create stars and, eventually, stars play a critical role in the formation of all matter as we know it, including Earth and every living thing on it.
galaxies. We then look at theories about the future of the universe before returning to the subject of stars, their classification, and their life cycles.

This course is divided into 12 topics, of which the first is Earth and its place in space. The second topic is plate tectonics, and the third is minerals. We continue with rocks, volcanism, and mass wasting. We then deal with issues concerning soils, erosion, and groundwater. Finally, the course concludes with the topics of rock deformation, earthquakes, and mountains.

According to astronomers, in the beginning, there was no need for geology because there were no rocks, minerals, or Earth. There were no stars or galaxies. In the beginning, the universe did not exist. In the 1920s, in response to Hubble’s discovery that the universe was expanding, Georges Lemaître proposed that the universe must have originally been compressed into a golf ball–sized sphere he called the primeval atom. Because of the conditions of temperature and pressure that would have existed in such a sphere, matter as we know it could not exist. What existed within the sphere were basic atomic particles called quarks and leptons.

Another theory proposes that the entire universe was contained within a dimensionless point called a singularity containing only energy. Current estimates indicate that about 13.7 billion years ago, the universe was created by an event commonly referred to as the Big Bang. In the case of the primeval atom, the quarks and leptons were released into space in all directions. Instantly, quarks bonded to make the fundamental components of atoms, protons, neutrons, and electrons. In the case of the singularity, energy was converted into matter, according to the Einsteinian equation $E = mc^2$, in the form of quarks.

Following the Big Bang, protons, neutrons, and electrons combined to create hydrogen atoms. As the hydrogen bubble grew and roared out into space, bundles of hydrogen gas atoms, attracted by the force of gravity, began to rotate and to collapse along their rotational axes. As the rotating mass collapsed, some of the gravitational energy was converted to heat. When temperatures within the core of the collapsing mass rose to about 15 million degrees, a thermonuclear reaction was initiated that converted hydrogen atoms into helium atoms.
After a million or so years, the stars within the expanding mass of hydrogen gas became so numerous that they began to be attracted into huge groups called galaxies. Eventually, billions of galaxies were created. Although galaxies take on different shapes, most galaxies are discus-shaped as a result of their rotation, with most of the stars concentrated in the center. Our galaxy is the Milky Way. Earth is located on the outer edge of this galaxy.

It is estimated that the universe contains about 100 billion galaxies, all rotating on their axes, all rotating around some point in space, and all moving away from each other as the universe expands. The question that now arises is whether or not the universe will continue forever. According to astronomers, the fate of the universe depends on the total amount of matter it contains. The problem is that the total amount of matter in the universe is unknown, primarily because much (if not most) of it, what is called dark matter, cannot be seen. What will ultimately happen depends on the relationship between the total mass of the universe and an amount of mass called the critical mass. If the sum of the known and dark matter is less than the critical mass, the universe will expand forever. This scenario is called an open universe. If the sum of the known and dark matter exceeds the critical mass, the universe will collapse back to either another primeval atom or a singularity that will undergo another Big Bang. If the sum of the known and dark matter equals the critical mass, the universe may stop expanding but will never collapse. This scenario is called a flat universe.

Stars play a critical role in the formation of all matter as we know it, including Earth and her sister planets. A star is a thermonuclear reaction in which four hydrogen atoms bond together to make one helium atom; the residual mass is converted to energy and released.

Stars are classified into four groups based on mass, using the mass of the Sun, representing 1 solar mass (SM), as the yardstick.

- Flyweight stars are those with less than 0.5 SM.

- Lightweight stars are those with masses from 0.5 SM to about 4 SM. At 1 SM, our Sun is a relatively small lightweight star.
• Middleweight stars range from 4 SM to 8 SM.

• Heavyweight stars are those in excess of 8 SM.

Stars are fires, but like any fire, eventually, the fuel will be exhausted and the fire will go out. All stars, therefore, have a life expectancy that can be calculated. The life expectancy of a star is inverse to its mass, with flyweight stars existing for 55 billion years and the most massive stars lasting only a few million years. With a life expectancy nearly four times longer than the estimated age of the universe, all the flyweight stars ever created still exist.

Stars spend 95% of their lives as main-sequence stars, consuming hydrogen and converting it to helium while releasing enormous amounts of energy. As hydrogen is converted to more massive helium atoms and a star becomes helium-rich, the core of the star undergoes gravitational collapse and begins to heat up.

In the case of a flyweight star, the core will collapse and create a star called a white dwarf. “White” refers to the fact that the star is white-hot, and “dwarf” refers to its relatively small size, about the size of Earth (approximately 8,000 miles in diameter). Once in the white dwarf stage, the flyweight star continues to consume whatever fuel may remain and will burn out after a very long period of time.

In the case of the larger stars, as the core collapses, the shell will expand to as much as 100 times its original diameter to become a red giant. At this stage, helium starts to be converted into bigger atoms, and carbon and oxygen, among other elements, are generated. All life as we know it is based on carbon products. Every atom in your body was created in the red giant phase of a star’s death. The same is true of the oxygen we breathe; plants release oxygen, but they do not create it.

All these dead stars will be blasted out into space, into the cosmos, which is just a fancy word for space, and we’re going to create cosmic dust.
A star massive enough to create an iron-rich core may collapse catastrophically within a few seconds and explode to form a supernova. During a supernova, all of the remaining 92 natural elements are created. The core of the original massive star may further collapse to become a neutron star. If the core is quite massive, the star may collapse into a structure with a force of gravity so great that nothing, not even light, can escape from it. Of course, these structures are called black holes. Following the supernova, the remains of the star are dispersed into interstellar space to form cosmic dust that consists of particles of metals, minerals, rock, and frozen gases referred to collectively as ices. Basically, dark matter is cosmic dust. It will be from this mixture that future planets form.

**Suggested Reading**

Hawking, S., *A Brief History of Time*.

Silk, J., *A Brief History of the Universe*.

**Questions to Consider**

1. How did Hubble’s discovery that the nebulae were actually distant galaxies change our view of the universe?

2. When you view a distant star, how can it be possible that the star does not actually exist?
Now we want to talk about formation of planets and eventually, of course, end up with our own planetary system. And the astronomers tell us that, if you’re going to make planets, the first thing you have to have is a star.

Astronomers are fairly certain about the origin of stars such as our Sun, but where did the planets that orbit the Sun come from? In this lecture, we look at the formation of planets from a disc of cosmic dust rotating around a star. We note the planets’ differing compositions, explaining why the planets nearest the Sun are made of rock, while those most distant are made of gases. We next examine the features of our solar system, with its lightweight star surrounded by nine known planets and a host of asteroids, meteoroids, and comets that have been memorably described as “dirty snowballs.”

To form planets, a new star must be created within a cloud of cosmic dust. It is theorized that the energy from a nearby supernova sets a mass of hydrogen into rotational collapse to create a new star. The newly formed star has a magnetic field that attracts cosmic dust. The rotation of the star sets the surrounding cloud of cosmic dust into rotational collapse that eventually generates a disc of cosmic dust extending outward from the star’s ecliptic. Simultaneous with the collapse of the dust cloud, the solar wind (high-energy particles) emitted from the star segregates the cosmic dust.
dust by driving the low-density ices to the outer periphery of the disc while retaining the higher-density metals, minerals, and rock closer to the star.

In time, eddy currents form within the dust disc. Inside the eddy currents, cosmic dust starts to rotate and collapse toward the center. Gravitational attraction within the dust disc causes the bits of dust and ices to collide to form ever-increasing particle sizes. Eventually, the particles become planetesimals. These also collide, taking on a spherical shape and forming protoplanets.

The protoplanets nearest the star are composed of metals, minerals, and rock fragments, while the outermost protoplanets are composed mainly of the lower-density ices and gases. As the protoplanets orbit the star, they continue to grow in mass as the remaining planetesimals plunge to their surfaces. Eventually, the mass of the protoplanets is large enough to initiate a gravitational collapse, which generates temperatures sufficiently high to cause internal melting.

Once melting begins, molten materials start to segregate based on density. The densest material settles to the center to form a core overlain by successive layers of decreasing density. The density segregation of components results in the conversion of a protoplanet to a planet. The planets nearest the star are composed of the densest material—the metals, minerals, and rocks—while the planets most distant from the star consist of frozen gases. Our solar system consists of a lightweight star surrounded by nine known planets possessing more than 31 satellites (“moons”), millions of asteroids, probably billions of meteoroids, and about 100 known comets.

The four innermost planets—Mercury, Venus, Earth, and Mars—are grouped together as the terrestrial planets because of certain similarities. Because of its near absence of an atmosphere, Mercury is characterized by having the greatest range of temperatures from day to night. Venus is the brightest planet due to its thick cloud cover, which reflects light from the Sun. The clouds surrounding Venus are primarily carbon dioxide, a greenhouse gas that keeps the planet’s temperature at about 485° C. Surface features on Mars indicate quite clearly that water existed on the Martian surface sometime during its primeval history. Like Earth, they’re all relatively small, ranging from 3,000
to 8,000 miles in diameter, and they all have an average density of about 6 gm/cm³.

The outer planets, including Jupiter, Saturn, Uranus, and Neptune, are collectively called the Jovian planets. The Jovian planets are giants, ranging in diameter from Neptune, at about 31,000 miles, to Jupiter, at nearly 90,000 miles. Because they are composed of frozen gases, the densities of the Jovian planets are low, ranging from 0.7 gm/cm³ for Saturn to 1.7 gm/cm³ for Neptune.

The asteroids are relatively small, odd-shaped rocks that orbit the Sun between the orbitals of Mars and Jupiter, the largest being about 700 miles long. Originally thought to be the remains of a terrestrial-type planet that once existed between Mars and Jupiter and was struck by some object, they are now thought to be planetesimals that would have formed terrestrial-type planets had they not been prevented from coalescing by the opposing gravitational forces of Jupiter and the Sun.

Millions, possibly billions, of meteoroids roam randomly through the solar system. A meteor is the streak of light that flashes across the sky when a meteoroid or meteorite plunges into Earth’s atmosphere. (The term “meteoroid” is used for these objects in space; “meteorite” is used when they land on Earth.) Most meteoroids never survive the trip, but it is still estimated that thousands of meteoroids plunge into Earth’s atmosphere every year. Fortunately, those that survive to become meteorites are few and small.

Meteorites are of three basic types: stony meteorites, iron meteorites, and stony-iron meteorites. Stony meteorites seem to be the most abundant. The frequency of meteorite impacts on Earth has decreased from the primeval days, when impact craters were as numerous as those now seen on the Moon. On Earth, most of the early impact craters have been removed by weathering and erosion. The last major meteorite impacted Earth about 50,000 years ago in what is now the northeastern corner of Arizona to form the Barringer Crater, commonly referred to as Meteor Crater.

A ninth planet, Pluto, is not believed to be one of the original planets but rather an object from deep space that was captured by the gravitational pull
of the Sun. Pluto has a highly elliptical orbit that is inclined about 17° to the ecliptic within which all the other planets orbit the Sun. Pluto doesn’t seem to fit anywhere in the solar system’s picture.

Comets are thought to consist mostly of ice with interspersed particles of rock. One of the foremost astronomers of the last century, Fred Whipple, called them “dirty snowballs.” The Belgian astronomer Jan Oort proposed that the comets originated in a layer that surrounds the solar system at a distance of about two light years, now called the Oort cloud. More recent studies have suggested that comets travel around the Sun in huge elliptical orbits. As a comet passes near the Sun, the solar wind causes the material facing the Sun to vaporize and ionize and be driven away from the Sun, forming the characteristic tail. Unlike the tails of meteoroids plunging into Earth’s atmosphere, the tails of comets always point away from the Sun.

Pluto is the maverick planet. It doesn’t fit anywhere in the picture.

The impacts of comets are pretty rare. We think one crashed into the Gulf of Mexico around 60 million years ago, and this one is reported to have given the death knell to the dinosaurs. Another one came down in Siberia in 1912. ■

Suggested Reading

Hawking, S., A Brief History of Time.

Silk, J., A Brief History of the Universe.

Questions to Consider

1. What role did stars play in the formation of Earth?

2. What is the significance of the larger dimensions of the Jovian planets relative to the terrestrial planets?
Continental Drift
Lecture 3

The theory of plate tectonics has to be the most significant contribution in the science of geology in its 250-year history. This one theory has changed how we look at the Earth. … What this really is all about is continental drift, the idea that the continents are moving around, which is sort of an interesting idea.

As protoplanet Earth increased in mass, heat created by gravitational collapse caused the interior of the protoplanet to melt and undergo compositional segregation based on density. Earth has a molten core, then a mantle, and finally, the outermost layer, aptly called the crust.

Molten rock below Earth’s surface is called magma; molten rock on Earth’s surface is called lava. There are three different types of magma: basaltic, granitic, and andesitic. The names refer to the type of rock that forms when the molten rock cools and solidifies. With a silica content of about 75%, granitic magma is the most viscous of all the magma types. Basaltic magma, with about 45% silica, is the least viscous of the three. Basalt is the type of rock that you see on the Hawaiian Islands. During primeval times, the less viscous basaltic magma reached the Earth’s surface first, enclosing the mantle in a layer about five miles thick. When the more viscous granitic magma reached the surface, it pushed the basaltic materials out of the way and piled up to form large globs surrounded by basalt.

As the crust continued to form, the surface of Earth was highly volcanic. The volcanic activity released enormous volumes of gas into the atmosphere consisting primarily of water vapor, which condensed to form a thick cloud cover that enclosed Earth in much the same fashion that clouds now enclose Venus. Within 3.5 to 4 billion years, Earth’s crust solidified and cooled to the point that the water vapor could condense and fall as rain. The waters ran off the granitic highs into the low regions floored with basalt to form the oceans. The basaltic crust became the oceanic crust, while the massive blobs of granitic rock became the continental crust.
Right up until the 20th century, it was taught that the size, shape, and location of the continents as we see them today were all created during the final formation of the crust 4 billion or so years ago. When medieval cartographers prepared world maps that showed the outlines of the continents with a sufficient degree of accuracy to allow individuals to make observations of the shapes of the continental margins, the first similarities to be observed were the Atlantic continental margins of South America and Africa. Intellectual curiosity prompted many to wonder whether these two continents were once joined into a single continent that broke up to create the South Atlantic Ocean. The first problem was to identify the source of energy needed to push the continent apart. The second problem was to find a scientifically sound mechanism by which such energy could be applied to create the tensional forces needed to rip a continent apart.

Late in the 19th century, Eduard Suess proposed that all the present-day southern continents were once joined into a supercontinent he named Gondwana. In the early 1900s, Alfred Wegener championed the idea of continental drift and proposed not only that South America and Africa were once joined but that all the current continents were once a single supercontinent he called Pangea, surrounded by a single superocean. About 200 million years ago, Pangea broke up to form the present-day continents.

The first evidence that would ultimately culminate with the formulation of the theory of plate tectonics came from studies of paleomagnetism. In 1917, the U.S. Navy invented SONAR (sound navigation ranging), which allowed
continuous topographic profiles to be made of the ocean bottom. After World War II came the discovery of the existence of a mountain range, called an oceanic ridge, that ran the length of each ocean and the discovery of deep-sea trenches. These deep-sea trenches were always parallel to the continental margin and were always associated with a volcanic mountain range that was either located along the margin of the continent or offshore in the form of a chain of volcanic islands.

Paleomagnetists discovered that there were successive layers of basaltic lava whose magnetic data indicated that the direction of the magnetic pole had reversed. All magmas contain the mineral magnetite. As molten basalt drops in temperature below the Curie point, the magnetite becomes magnetized and duplicates whatever magnetic field existed at the time of its formation.

Scientists working in the Columbia Plateau in Oregon and Washington discovered bands of varying magnetic width and intensity paralleling the oceanic ridge. The stronger magnetic bands were where the magnetic fields in the basaltic crust were oriented in the same direction as the existing Earth magnetic fields. The weaker magnetic bands were where the magnetic fields in the basaltic crust were reversed from the existing Earth magnetic fields. The patterns of bandwidths on opposite sides of the oceanic ridge were mirror images of each other. The only possible explanation was that each band pair formed along the summit of the oceanic ridge with the existing orientation of Earth’s magnetic field, and a new magnetic band pair formed as a reversal took place. There was no longer any doubt that the sea floor was spreading. Wegener had been right after all.

But with the new oceanic crust being formed at oceanic ridges and with the subsequent expansion of the newly formed oceans, Earth would expand unless something was being done to consume old oceanic crust. It was proposed that the most likely place for old ocean bottom to be consumed was in association with the deep-sea trenches. Around 1960, Princeton geologist Harry Hess, echoing a theory first proposed in the 1930s, postulated that the presence of heat-driven convection cells within the mantle caused the rocks within the mantle to move. The idea had initially been rejected on the grounds that the upper mantle rocks were too brittle.
According to Hess, the heat-driven convection cells within the mantle would exert tensional force on the crust as they rose to the surface, pulling apart whatever was above them. The convection cells would also exert compressional forces, breaking up the crust, as they descended back into the mantle.

The missing piece of the puzzle was provided by seismologists, who discovered a zone within the upper mantle in which seismic waves moved with decreased velocities, indicating that the zone had liquid-like properties. Called the asthenosphere, this layer is thought to be partially molten (plastic), allowing it to act overall as a liquid.

The layer above the asthenosphere—the brittle portion of the mantle and all of the brittle crust—is called the lithosphere. It is the lithosphere, not the crust, that breaks into plates, of which there are only about a dozen. A plate is bounded on one side by an oceanic ridge and on the other side by a zone of subduction (deep-sea trench); the plate moves from the oceanic ridge, where it is being created anew, to the zone of subduction, where it is being consumed. The continent is not moving—the entire plate on which the continent stands is moving. Mountains are created when one continent collides into another.

During the 1960s, all of the data were synthesized into the concept we know as the theory of plate tectonics. 

Suggested Reading


Lecture 3: Continental Drift

Questions to Consider

1. What were the basic problems faced by the early proponents of continental drift in attempting to convince early earth scientists that it existed?

2. What types of evidence did Wegener present to support his idea that South America and Africa were once joined?
I thought it would be worth our time to just go back and review a few of the things we’ve already talked about. So, let’s go all the way back. Let’s go back to the original picture we had of the structure of the Earth that was created from the proto-planet.

Earth’s core is basically molten iron, the most abundant material in the universe, with an average density of about 15 gm/cm$^3$. Surrounding the core is the mantle, made up of an iron-rich rock called peridotite. The mantle, which has a density of about 6 gm/cm$^3$, floats on Earth’s core. The outermost brittle layer, called the crust, is about 40 miles thick and made of basalt, which forms the oceanic crust, and granitic rocks—granite and granodiorite—which form the continental crust. Seismologists discovered a special plastic layer—the asthenosphere—within the upper mantle. Above the asthenosphere is the lithosphere, composed of the brittle crust and the outermost, brittle portion of the mantle.

The asthenosphere is a source of energy via convection cells. As water heats, its density decreases, causing the water to rise to the top of the convection cell. As the water cools and its density increases, the cooled water descends to the bottom of the convection cell, where it is heated all over again. A convection cell system can, perhaps, be best pictured as alternately rising and falling convection cells in a fish poacher that has been placed across two burners. A piece of wood floating in the fish poacher is subject to alternating tension and compression zones caused by two different convection-cell systems associated with each tectonic plates.
heat source. In this analogy, the piece of wood is the lithosphere and the fish poacher is the asthenosphere. The lithosphere will break up into plates under the tension of the convection systems in the asthenosphere.

Think of the rising portion of a convection cell under a continent. Tensional forces will be generated within the crust, and it will break. Cracks form at the bottom of the lithosphere and work their way to the surface. On the surface, the cracks widen under tension, creating a rift zone. Basaltic magma constantly forms under rift zones and runs into groundwater, which rises to the surface in the form of hot springs and similar phenomena. It also forms lava flows at the surface, which blow out pieces of molten rock into the air in a phenomenon called a fire fountain. These solidify and form cinder cones when they fall back to Earth.

When continents break up, they first form rift zones. Such a rift zone, called the Rio Grande Rift, can be seen coming up through the center of New Mexico and into central Colorado. This is an aborted rift that is not currently breaking North America apart. Rift valleys form when rift zones form. The East African Rift, starting in Ethiopia and extending to Mozambique, is an example. When one end of a rift valley reaches the ocean, water flows into the valley. This is called a linear ocean; it is landlocked at one end. The Red Sea is an example. Eventually, the landlocked end of the linear ocean will be severed and the continental masses will move away from each other as a new ocean is born.

Although his theory was initially rejected, Alfred Wegener already had evidence at the turn of the 20th century that there was once only one supercontinent on Earth, which he called Pangea. Wegener matched up the coastlines of South America and West Africa. He also matched up rock types, fossils, plants, and glacial deposits on both continents. When the

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You start off with a supercontinent, surrounded by a superocean. Then what happens is that supercontinent breaks up and creates new oceans at the expense of the old ocean, the great ocean.
supercontinent broke up, with the oceanic ridges recording the site of the original rift, the Atlantic, Indian, and Arctic Oceans were formed.

Harry Hess postulated that it would be possible to see an old ocean lithosphere being consumed at the site of the deep-sea trenches. The compressive forces generated within the lithosphere by the down-going portion of the convection cells break up the old oceanic lithosphere and draw it down into the mantle, where it is consumed. The site where the oceanic lithosphere is drawn down is marked on the ocean bottom by the deep-sea trench. The process by which the oceanic lithosphere is drawn down into the mantle is called subduction, and the place where subduction takes place is called the zone of subduction.

In the zone of subduction (deep-sea trenches), there are two kinds of magma: granitic and andesitic. The difference between these kinds of magma and the third, basaltic, is as follows:

- Basaltic magma has a concentration of 45% silica, giving it a viscosity akin to olive oil.

- Andesitic magma has a concentration of 55% silica, giving it a viscosity akin to pancake syrup. Andesitic magma rises to the surface and creates arc volcanoes off shore; if such a range of volcanic mountains is on land, it is called a continental arc.

- Granitic magma has a concentration of 75–80% silica, giving it a viscosity akin to cold molasses. Granitic magma rarely reaches the surface.

The oldest rocks on the ocean bottom are always next to the continent and are about 200 million years old—the time when plate tectonics began.

Now how about the Pacific? The Pacific Ocean is closing. Its ocean ridge is creating a new oceanic bottom three times faster than the Atlantic Ocean. How can a new oceanic bottom be created when the ocean is closing? The idea is that the ocean is being consumed faster than the new bottom is being created.
A Canadian geologist, J. Tuzo Wilson, took the concept of plate tectonics one step further. Wilson proposed the concept of a tectonic cycle that begins and ends with a single supercontinent surrounded by a single superocean. The supercontinent breaks up into smaller continents, creating new oceans. The new continents drift away from each other for a period of about 250 million years, at which point the process reverses. After another period of about 250 million years, the continents all collide to create a new supercontinent, and so on. A complete Wilson cycle, therefore, takes about 500 million years. Simple arithmetic indicates that we may be in the sixth Wilson cycle.

According to the Wilson cycle, we are still in the opening phase of the breakup of Pangea about 200 million years ago. The Atlantic Ocean is opening at about the growth rate of a human fingernail. The Indian Ocean is about as wide as it is going to get. The zone of subduction along the islands of Indonesia indicates that Australia has begun to move northward toward Asia. Most evidence indicates that the Arctic Ocean has stopped opening. In about 50 million years, the Atlantic Ocean will begin to close, and about 300 million years from now, all the existing continents will have collided to produce the next supercontinent.

Suggested Reading


Questions to Consider

1. Considering where we are today in a Wilson cycle and the present rate at which the Americas are moving westward, will the Pacific Ocean ever close?

2. How can you explain the fact that there are no oceanic crustal rocks older than 250 million years while continental crustal rocks have been found that are older than 4 billion years?
Minerals are very important, and if you want to really understand rocks, and how they form, and how we name them, and how they respond out there when they’re being sculpted into the landscape, you really have to know some of the minerals.

By definition, a mineral is a naturally occurring, solid, inorganic substance with a reasonably definite chemical composition and crystal structure. “Naturally occurring” means that a mineral must be created in nature rather than in a laboratory. The restriction of minerals to solids precludes the inclusion of certain natural materials, such as oil and gas, as mineral resources.

The science of chemistry is subdivided into organic chemistry and inorganic chemistry. Organic chemistry deals with compounds whose major component is carbon, while inorganic compounds are those that do not contain carbon as the dominant element. There are naturally occurring, solid, organic compounds that some geologists feel should be considered minerals, but historically, such compounds have been arbitrarily excluded.

The requirement for “a reasonably definite chemical composition and crystal structure” means that a mineral must have a diagnostic composition and crystal structure. A chemical analysis of a mineral will always show the composition to be dominated by the same elements, and an X-ray diffraction analysis will always indicate the same internal arrangement of the atomic components: a face-centered cubic lattice. The reasonably definite portion of the definition allows for some compositional impurities to be present and for some disorder to exist in the crystal structure without precluding the identification as, for example, halite.

The fundamental building block of all matter is the atom. A chemist would define an atom as a neutral system of negatively charged electrons moving around a dense, positively charged nucleus. Atoms consist of three basic components: protons, neutrons, and electrons. Protons and neutrons are
formed by combining two types of quarks with the interesting names of up (u) and down (d). The up quark has a +2/3 charge, while the down quark has a –1/3 charge. Protons form from the union of two up quarks with one down quark. This combination, uud, is the sum of +2/3, +2/3, and –1/3 for a total of +1, the charge of a proton. Neutrons are made from two down quarks and one up quark. This combination, ddu, is the sum of –1/3, –1/3, and +2/3 for a total charge of 0. Protons and neutrons are contained in the nucleus of the atom, surrounded by orbiting electrons. The number of protons in the nucleus determines the atomic number or identity of the atom. The sum of protons and neutrons in an atom determines the atom’s atomic mass.

Most elements can have different numbers of neutrons in the nucleus. Atoms with the same number of protons and different numbers of neutrons are called isotopes. Oxygen, for example, is atomic number 8 (which means it has 8 protons and 8 electrons), but it can have 8, 9, or 10 neutrons, resulting in three isotopes with atomic masses of 16, 17, and 18. For multi-isotope elements, one isotope always superdominates. Isotopes all react the same way chemically. Only the outermost electrons determine chemical reactivity. Atomic masses listed in the periodic table are not whole numbers. The reason for this is that one isotope superdominates, but others are present in lesser concentrations. To take into account the relative abundances of each isotope, the atomic masses are averaged.

The number of electrons and the number of protons in an atom are equal; that is, atoms are electrically neutral. The electrons are distributed around the nucleus in energy levels or shells designated by letters of the alphabet beginning with K. The number of levels increases with increasing atomic number. The maximum number of electrons allowed in the outermost energy level is eight. Electrons in this level are called valence electrons. Only the electrons in the outermost energy levels are involved in chemical reactions between any two atoms.

Atoms join together to form compounds by creating chemical bonds. Within a compound, the atoms may be held together by five different kinds of chemical bonds: ionic, covalent, van der Waals, metallic, and hydrogen. In the case of minerals, the most important of the five types of bonds are the ionic and covalent. In metallic bonding, the outermost electrons are allowed
to wander throughout the mass of metal atoms without being associated with any particular atom.

Metallic bonding gives metals their characteristic properties of high conductivity of heat and electricity and malleability. Geologically, metallic bonding is not too important in that few minerals exist in nature in metallic form. Van der Waals bonding is the weakest of all the bonds—just static charge. Although it is never the major type of bond in a mineral, it results in certain minerals having planes of weakness within their crystal structures.

Hydrogen bonding is fairly strong and occurs where there are, within a crystal structure, two layers of oxygens and a hydroxyl, the only difference between the hydroxyl and oxygen being a hydrogen atom.

To return to the discussion of ionic and covalent bonding, why do some atoms go together to form ionic compounds while others form covalent compounds? In the simplest of terms, and certainly in the reactions involved in the creation of minerals, the driving force is the need to satisfy the octet rule. The octet rule stipulates that if an atom can acquire the maximum eight electrons in its outermost energy level, it can “retire.” The elements that occupy column 8 in the periodic table are appropriately called the inert gases or the noble gases because they all have eight electrons in their outermost energy levels. Helium is also an inert gas because it has filled its only energy level with its maximum of two electrons.

To illustrate the operation of the octet rule in the formation of an ionic bond, let us consider the mineral halite (NaCl), common table salt. Sodium relinquishes its sole M electron to reveal a total of eight electrons in the underlying L level. Chlorine takes the electron to fill its M level with eight electrons. Although the two atoms become electrically charged ions (positively charged ions are called cations; negatively charged ions are anions), the union results in the neutralization of charges. Compounds are electrically neutral.
To illustrate the formation of a covalent bond, consider two carbon atoms, each with four electrons in the L level. With four more electrons needed to complete the filling of the L level, it is unlikely that either atom would become involved in a give-and-take scenario. However, by sharing their outer electrons, both atoms could claim to have eight electrons in their outermost shells. This sharing of outermost electrons results in the formation of the covalent bond, the strongest of all chemical bonds, explaining why diamond is the hardest substance known and the most chemically stable. Some minerals, such as halite, exhibit 100% ionic bonding, while others, such as diamond, are 100% covalently bonded. Most minerals, however, are a blend of the two.

Everyday experiences illustrate the differences in the chemical reactivity of different compounds. The bond in the mineral calcite, the major component of limestone, is equivalent to about 80% ionic and 20% covalent. Although in terms of human lifetimes, the solubility of limestone in water is very low, given geologic time, water will dissolve enough limestone to create limestone caves and caverns.

For comparison, consider another very common mineral, quartz, which is the main component of sandstones and provides the sands of your favorite beach. The effective levels of ionic and covalent bonding in quartz are the opposite of calcite, with the bonding being approximately 80% covalent. Quartz has no water solubility; in fact, it is among the most chemically resistant of all
the common rock-forming minerals. To my knowledge, the only chemical that will attack quartz is hydrofluoric acid.

In summary, the durability of the individual minerals to chemical attack is, in large part, determined by the mix of ionic and covalent bonding, with resistance to chemical attack increasing with increasing covalent bonding.

**Suggested Reading**


**Questions to Consider**

1. What is the fundamental difference between ionic and covalent bonding, and how does bonding affect chemical reactivity of a compound?

2. What changes must take place for a solute to precipitate from a solution?
We classify minerals based upon the anion group. And there are two great classes of minerals: silicate minerals and non-silicate minerals.

The silicate minerals are classified compositionally based on their anion group into silicate minerals and non-silicate minerals. The titles alone indicate quite clearly that the silicate minerals are the more important of the two. All the rocks discussed so far—the peridotite of the mantle, the basalt of the oceanic crust, and the granitic rocks of the continental crust—are composed of silicate minerals.

The basic building block for all the silicate minerals is the silicate anion, \((\text{SiO}_4)^{4-}\). A geometric figure called the silicon tetrahedron, used to illustrate the three-dimensional structure of the anion, shows four oxygen atoms located at the corners of the tetrahedron with a silicon atom at the center. The silicate anion combines with a limited number of cations. There are only six cations of any importance: calcium, magnesium, sodium, potassium, aluminum, and iron.

The anion/cation combination forms the nine most important rock-forming silicate minerals, which are subdivided compositionally into two groups. The ferromagnesian minerals are those silicate minerals that contain appreciable concentrations of iron and magnesium in addition to other elements. The major minerals of the group are olivine (from the olivine group), augite (from the pyroxene group), hornblende (from the amphibole group), and biotite (from the mica group). The nonferromagnesian minerals contain aluminum in place of the iron and magnesium. The nonferromagnesian group contains the most abundant of all the rock-forming silicate minerals, the feldspars. The feldspars are subdivided into the plagioclase (including anorthite, the calcium aluminum silicate, and albite, the sodium aluminum silicate) and potash (including orthoclase) subgroups. Additionally, we have the mica subgroup, including muscovite and quartz.
The silicate minerals are constructed by arranging the silicon tetrahedra into one of five different three-dimensional arrangements: independent tetrahedral, single chain, double chain, sheet, and network, or 3-D. The independent tetrahedral structure is characteristic of the mineral olivine (from the olivine group). As the name implies, individual silicon tetrahedra are symmetrically arranged in three-dimensional space and joined together by iron and/or magnesium atoms.

In single-chain structure, characteristic of augite (pyroxene group), the tetrahedra are joined in a chain, and the chains are stacked like cordwood, with the various cations bonding the chains together. In the double-chain structure, characteristic of hornblende (amphibole group), two single chains are joined side by side into what resembles a plank. The mineral structure is then built by stacking the double chains with the long dimensions parallel to each other and bonding them together with the cations.

In the sheet structure, characteristic of such minerals as biotite and muscovite (mica group), the silicon tetrahedra are joined into a sheet with the tetrahedra located at the corners of a repeat hexagonal pattern, similar to chicken wire or a beehive. Two sheets of tetrahedra are then bonded together by a layer of atoms, such as iron, aluminum, and magnesium, into a layer known as a 2:1 sheet. The mineral structure is then repeated by stacking the 2:1 sheets and bonding them together by relatively large atoms, such as potassium, sodium, and calcium.

The network, or 3-D, structure is characteristic of the feldspar minerals and quartz, in which each oxygen atom is shared by adjacent tetrahedra. In the feldspar minerals, electric neutrality is achieved by the inclusion of
other cations, such as aluminum, the alkali elements, and the alkaline earth elements. In the case of quartz, each oxygen atom shares an electron with two silicon atoms and, as a result, no other cations are needed to attain electric neutrality, explaining why quartz is “pure” silica. Of all the silicate minerals in Earth’s crust, the feldspars are the most abundant, with quartz being the second most abundant. Thus, the ferromagnesian minerals become increasingly complex in structure from the olivine group to the mica group. The nonferromagnesian minerals, with the exception of muscovite, have three-dimensional structures.

The non-silicate minerals do not have the silicate anion as part of their structure. Although the non-silicate minerals make up less than 10% of the Earth’s crust, they are of great importance. Perhaps the most important non-silicate is the oxide hematite, the mineral that not only brought us out of the Stone Age but is the basis for our modern iron-dominated society.

The most common carbonate is calcite, the major component in limestone and in the shells of such creatures as coral, clams, oysters, and snails. In addition to being used as a cut stone, limestone is also crushed to provide aggregate, powdered to produce agricultural lime, and used in the manufacture of cement.

Three other important minerals are halites, sulfides, and disulfides. The halites are important in that they provide the sodium that we and the vast horde of animals need for proper body functioning. And the sulfides and disulfides provide us with many of the nonferrous metals we need, including copper, zinc, and lead.

My son … tells me that every cell in your body has to have a certain concentration of salt in solution for it to work. … So, without salt, you and I wouldn’t exist.

Suggested Reading


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### Questions to Consider

1. The plagioclase feldspars, anorthite and albite, represent end members of an isomorphous series. What is an isomorphous series?

2. What different types of silicate crystal structures are represented by the ferromagnesian silicate minerals?
The Identification of Minerals

Lecture 7

So let me first of all give you just a general idea about what identification is all about. It is just so simple. “Identification” simply means that you put a name on something. … It’s just a function of two things: what it is made up of and how it’s put together, in other words—in the case of minerals, of course—composition and crystal structure.

The identification of any compound is based on two diagnostic properties: composition and crystal structure. The success of an identification depends on how precisely each of these two parameters is determined. Instrumental procedures are available that can accurately quantify the elemental composition and the exact crystal structure of an unknown. With such information, an identification can be made with an expectation of being 100% correct. Unfortunately, such instrumentation is very expensive and therefore not available to the average geologist.

On the other extreme is hand identification, which is based on the fact that the appearance of an object in reflected light is determined by the combination of composition and structure. The ability to identify minerals based on appearance requires a great deal of experience and is usually limited to those minerals seen on a day-to-day basis.

Between the two extremes are other instrumental techniques that can provide reasonably high levels of identification assurance for less cost. The two most commonly used instrumental techniques are optical microscopy and X-ray diffraction. Optical microscopy is based on the fact that the passage of polarized light through a mineral grain diagnostically responds to both composition and crystal structure. Identification consists of making visual observations, which are then matched with tables of optical responses. The problem with optical identifications is that the sample must be thin enough to transmit light, which means that it

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There are two things that you have to determine: composition and crystal structure.
must be cut and ground into a thin section. This is a time-consuming process. Another problem is that the identification process requires years of experience.

X-ray diffraction is not quite so dependent on the human influence. Each mineral produces a diagnostic diffractogram consisting of peaks, the number and location of which determine crystal structure and the combined intensities of which determine composition. These combined data represent an X-ray pattern that is a diagnostic fingerprint for the particular mineral, which can be searched in a collection of such fingerprints for a match. Although widely used, both the optical and X-ray diffraction techniques are laboratory procedures; the sample must be brought to the laboratory for identification. The field geologist who must identify a mineral immediately has to rely on hand identification.

For the average geologist, minerals are hand-identified on the basis of a series of physical properties. A physical property is any property of a mineral that can be determined by the senses. Physical properties are determined by the combined contributions of composition and crystal structure, the two diagnostic features of all minerals. There are minerals whose colors are diagnostic, such as azurite or malachite. The colors of many minerals, however, vary depending on the presence of trace-level impurities. As a result, most mineral colors are not diagnostic. A characteristic that is relatively diagnostic for certain minerals is streak, which, by definition, is the color of the powdered mineral. The name is derived from the fact that the powder is commonly attained by dragging the mineral across the surface of unglazed tile.

Mineral cleavage is the ability of certain minerals to split along planes of weakness within the crystal structure that become crystal faces. The number and orientation of the planes of cleavage depend on the crystal structure. Mica, for example, has one set of cleavage planes that develop where large atoms, such as sodium, potassium, or calcite, join the 2:1 structural layers. In the case of mica, the bonding is sufficiently weak that sheets of mica can be peeled off from what is called a “book” of mica. Halite has a cubic structure, within which are three sets of mutually perpendicular cleavage planes. If
all three are broken simultaneously, the result is smaller pieces, all with the same cubic structure.

Not all crystal faces are cleavage surfaces. Minerals lacking planes of weakness within their crystal structures break by fracturing like glass. Quartz, for example, because the bond strengths in its crystal structure are equal in all directions, breaks along random surfaces, like glass. Certain carbonate minerals, especially calcite (CaCO₃), are readily identified with effervescence produced by the application of a few drops of 5% hydrochloric acid.

One of the most often-used physical properties for identification is hardness, which is defined as “resistance to scratching.” Hardness is determined by comparing the hardness of an unknown to that of a series of 10 minerals of known hardness. The series is known as the Mohs’s scale of hardness. In order of softest to hardest on a scale of 1 to 10, these minerals are: talc, gypsum, calcite, fluorite, apatite, orthoclase, quartz, topaz, corundum, and diamond.

- Talc is a silicate mineral made of sheets, similar to mica. These sheets are held to each other by van der Waals bonding, the weakest of the chemical bonds. Talc is easily crushed between the fingers, as is graphite, which has a similar structure.

- Gypsum is used in house construction because it is inexpensive and has insulating properties.

- As mentioned earlier, calcite is used to make agricultural lime.

- Fluorite is a collector’s item; the crystals are quite beautiful.
• Apatite is used in fertilizers, as well.

• Orthoclase is used as the abrasive in most household cleansers.

• Quartz is a heavy abrasive, used in old-fashioned grinding wheels and sandpaper.

• Corundum is used as an abrasive today, in whetstones and emery paper.

Suggested Reading


Questions to Consider

1. On what criteria are minerals identified?

2. Of the various physical properties, which would be most easily determined “in the field” to identify a mineral crystal? What about a mineral contained within a rock, such as granite?
We’re going to talk about rocks. And this first lecture is going to be about igneous rocks, and igneous rocks, by definition, are those rocks that form from the molten state.

From the standpoint of volume, igneous rocks are the most important in that they constitute the mantle and the crust of Earth. Igneous rocks are classified and named based on their texture and their mineral composition.

Texture refers to the grain size of the individual minerals. A coarse-grained texture is one in which the individual mineral grains are large enough to be identified by the naked eye, usually about 0.5 mm, while the individual grains in fine-grained texture are less than 0.5 mm. Texture is determined by the rate of cooling of the molten rock.

Magmas surrounded by insulating, cold rocks undergo slow cooling, during which time individual crystals are able to grow larger than 0.5 mm before the entire molten mass solidifies. Slow cooling results in the formation of coarse-grained texture. Lavas, on the other hand, exposed to either water or the atmosphere invariably cool too fast to allow the individual crystals to grow larger than 0.5 mm before complete solidification takes place. Fast cooling promotes fine-grained texture.

Igneous rocks are composed primarily of nine silicate minerals. Every mineral has its own melting and freezing points, dependent on composition and crystal structure. In the 1930s, N. L. Bowen established that the major silicate minerals crystallized from the molten state in a recognizable order, which was originally called Bowen’s reaction series. Because it is essentially an order of crystallization, we will refer to it as

Basically, the peridotite of the mantle, and the basalt, and the granitic rocks of the crust—those are igneous rocks that form from the molten state.
Bowen’s crystallization series. The first mineral to crystallize is olivine, followed by augite, hornblende, and biotite. Of the nonferromagnesian minerals, the first mineral to precipitate out is anorthite, followed by albite, orthoclase (the potassium feldspar), muscovite, and quartz.

There is no single magma from which all of the nine major silicate minerals can form; rather, there are three basic types of magma that we introduced in our discussions of plate tectonics: granitic, andesitic, and basaltic, the names representing the major types of igneous rock that form from their cooling and solidification. From basaltic magma, we get olivine, augite, and anorthite, the minerals at the top of Bowen’s series. From granitic magma, we get orthoclase, muscovite, and quartz and, maybe, a bit of biotite and albite. The minerals in between in the series come from andesitic magma.

The terms mafic, intermediate, and felsic are used to designate specific groups of minerals. The mafic minerals are those that crystallize first at the highest temperatures (e.g., olivine, anorthite, and augite from basaltic magma); intermediate minerals are those that crystallize at intermediate temperatures from andesitic magma; and felsic are those minerals that crystallize last at the lowest temperatures (e.g., orthoclase, muscovite, and quartz from granitic magma). The same terms can be used to designate the type of magma from which the minerals form.

Individual minerals have specific freezing points, but if the mineral composition is mixed, the mineral has a range of freezing temperatures. For example, olivine is an iron-magnesium silicate. Thus, olivine does not have a specific temperature at which it crystallizes but rather a range of temperatures. No one knows why quartz precipitates out over a range of temperatures. Many minerals have complex compositions. Because of overlap in precipitation temperatures, several minerals can precipitate simultaneously.

Bowen’s crystallization series can be used as a guide to determine the mineral composition of a rock. For example, periodite is composed of olivine with, perhaps, a bit of anorthite. Interestingly, basalt and gabbro have the same composition. A basaltic magma will rise to the surface to produce basalt. If it
solidifies on the way up, it forms the lower portion of the lithosphere and is called gabbro.

Granitic rocks (orthoclase feldspar, quartz, plagioclase feldspar, and rhyolite—fine-grained granite) do not rise to the surface very often, but when they do, they produce a volcanic eruption as never seen before. What one sees in Yellowstone Park is the result of three granitic explosions. The first happened 2 million years ago, the second happened 1 million years ago, and a third explosion occurred 600,000 years ago. There is evidence that the underlying magma is rising to the surface and may well be the onset of a future eruption.

To summarize what we’ve learned so far about igneous rocks: Peridotite is what the Earth’s mantle is made of; basalt is what forms the oceanic crust; gabbro forms the lower portion of the oceanic lithosphere; andesite forms volcanoes; and granitic rocks form the continental crust.

Yellowstone Park’s geysers and hot springs are the result of three granitic explosions occurring 2 million, 1 million, and 600,000 years ago.

Suggested Reading


Winter, J. D., *Introduction to Igneous and Metamorphic Petrology*. 
1. Both igneous and metamorphic rocks form under conditions of high temperatures. How do they differ?

2. Considering Earth’s crust, which type of rock is represented in the greatest volume? In the least volume?
The sedimentary rocks, volume-wise, don’t really represent an awful lot—5% of the entire crust. But I think one of the important things about the sedimentary rocks is they cover 75% of the land.

Sedimentary rocks are the type of rock one normally sees exposed at Earth’s surface. They form from the products of weathering. Sedimentary rocks provide us with our major sources of energy. Petroleum, the major source of energy in the world today, is produced from marine plants and stored in sedimentary rocks. Petroleum represents 70% of our U.S. energy budget. Coal, the second most important source of energy in the United States at 20%, is interlayered with sedimentary rocks. And uranium, the fuel for the nuclear power industry, represents 5% of our energy budget. Uranium is found in sedimentary rocks, mostly sandstones.

The primary purpose of the science of geology is to determine the history of Earth. With few exceptions, what we know about Earth’s history has been gleaned by studying sedimentary rocks. The basic characteristic of all sedimentary rocks is that they are layered. Each layer of sedimentary rock can be compared to a page in a book entitled *History of Earth*. Of all the features preserved in sedimentary rocks, those that provide the most information about the environment at the time of sediment accumulation are fossils of animals and plants. Not only do these fossils serve to record the passage of time and the evidence of evolution, but they also record aspects of the environment in which the plants and animals originally lived. Marine fossils record water depth and temperature, while fossils of land animals and plants may chronicle changes in climate.

When rocks of any kind are exposed to the atmosphere, they undergo a process called weathering, whereby they are either ripped apart physically or decomposed chemically. Physical weathering occurs mainly from cycles of freezing and thawing, in a process called frost wedging, or from the intrusion of plant roots.
Chemical weathering is caused by oxidation and carbonation. Once oxygen is dissolved in water, it becomes an active oxidizing agent. Carbon dioxide is very water soluble and, when dissolved, makes carbonic acid. Iron “likes” to oxidize. It precipitates out of the ferromagnesian minerals as hematite, causing the collapse of the original crystal structure. Carbonic acid attacks all minerals—except olivine and quartz—creating clay minerals. Quartz does not react with dissolved oxygen (because it is already an oxide) or with carbonic acid. The major solid products of weathering are therefore clay minerals, quartz, and iron oxide.

Dissolved products of weathering are produced where carbonic acid dissolves alkali (sodium and potassium) and alkaline-earth elements (calcium and magnesium) and turns them into bicarbonates, which are ultimately carried off to the ocean. The most abundant of these is sodium bicarbonate. Silica dissolves in the form of silicic acid and, again, is carried to the ocean.

Sedimentary rocks are classified as either clastic or non-clastic. Clastic sedimentary rocks are those that form from the solid products of weathering,
while non-clastic sedimentary rocks form from dissolved products of weathering. Clastic sedimentary rocks are named based on the sizes of the individual particles, not on composition. They form from the sediments deposited by the agents of erosion, streams, glaciers, and the wind. The two major types of clastic sedimentary rocks are shales and sandstones. Shales are composed primarily of the major clastic product of weathering, the clay minerals that were formed by the chemical weathering of nearly every major rock-forming silicate mineral. As a result, of all the sedimentary rocks, shales are most abundant, making up 70% of the total. Sandstones represent 20% of all sedimentary rocks and are composed primarily of sand-sized grains of quartz. Iron oxide is simply a coloring agent in sedimentary rocks and soils.

Non-clastic sedimentary rocks are those that formed from the dissolved products of weathering. The classification scheme for non-clastic sedimentary rocks is based primarily on how the materials are removed from solution. The three major types are chemical, biochemical, and evaporite. We will treat the chemical and biochemical categories together in that, in the cases we will discuss, the chemistry is the same. The primary difference between the two categories is that, in the biochemical category, an organism is involved. Evaporites are sedimentary rocks composed of non-clastic materials that are so soluble that the water must be removed for the solid phase to precipitate. Of the evaporite rocks, rock salt, composed primarily of the mineral halite (NaCl), is probably the most abundant and commercially important.

Calcium carbonate is dissolved by carbonic acid and goes into solution as the bicarbonate ion and the calcium ion. This reaction is favored by cold water. When cold oceanic water saturated with calcium bicarbonate is warmed, the reaction is reversed. The calcite accumulates as a carbonate mud which, when converted to a rock, becomes a chemical limestone. One place where this happens is Florida Bay. The same chemical process is used by certain animals and plants that have shells and protective coatings.
Another material taken into solution during chemical weathering is silica in the form of water-soluble silicic acid; this can decompose to form hydrous silica, which then dehydrates and crystallizes to form chert. A type of chert called flint was used by paleo people and Native Americans to make tools. A striking example of evaporite formation can be seen along the southern banks of the Persian Gulf in a region called a *sabkha* (Arabic: “mixture”). This is essentially a salt flat, created by accumulation of salt deposited by high tides along a flat coastal area.

Lithification is any process whereby loose sediments of either a clastic or non-clastic origin are turned into solid rock. The two major processes are compaction and cementation. Sediments consisting primarily of clay minerals, such as mud, are lithified by the process of compaction to form shales or mudstones. Pressure exerted on the layer of mud due to the weight of the overlying rocks physically ejects the water, driving the clay platelets closer together. Most other non-clay-rich sediments, such as sands and carbonates, are lithified by the process of cementation, in which minerals precipitate out of groundwater solution. As the minerals deposit in the pores between the grains, they literally “cement” the grains together, not unlike the cement that holds bricks together in a wall.


Winter, J. D., *Introduction to Igneous and Metamorphic Petrology*.

**Questions to Consider**

1. Why is the volume of shales far greater than the combined volume of all other types of sedimentary rocks?

2. Most of what we know about Earth history has been acquired from the study of sedimentary rocks. How do they record Earth history? In comparison, what historical events do igneous or metamorphic rocks record?
Metamorphic Rocks
Lecture 10

Of all the three different kinds of rocks, I think metamorphic rocks have to be the least understood of all and mainly because we’ve never seen any of these rocks form in any fashion. No part of their formation can be seen.

Although sedimentary rocks can form under conditions of shallow burial, and lavas do solidify in plain sight, the conditions of temperature and pressure required to form metamorphic rocks exist only at significant depths below Earth’s surface. By definition, a metamorphic rock is a rock that forms by the recrystallization in the solid state of a previously existing rock in response to heat, pressure, and the presence of chemically active fluids (namely, water). The “previously existing” rock could be an igneous, a sedimentary, or another metamorphic rock. It is important to note that any change must take place in the solid state. Melting would result in the formation of a magma and the subsequent formation of an igneous rock.

In some cases, the change may be simply a recrystallization of the existing minerals with no change in composition, an example being the conversion of limestone to marble. Most often, metamorphism involves both a physical and a compositional change. A shale dominated by clay minerals and quartz subjected to high pressures will undergo a recrystallization of the clay minerals into a different suite of sheet silicate minerals and a reorientation of the platy minerals to form slate. The degree to which physical and compositional changes take place depends on the severity of the metamorphic conditions. If water is involved, minerals can be added and subtracted from the rock’s composition, resulting in a different composition.
There are three metamorphic processes: contact metamorphism, dynamothermal metamorphism, and hydrothermal metamorphism. Note that heat is a factor in each process. Contact metamorphism is primarily associated with igneous intrusions, in which the heat from the molten rock literally bakes the host rock at the contact with the magma. The thickness of the zone of alteration, called a halo, depends on the volume and temperature of the intruding magma body, the amount of water in the host rock, and the grain size and composition of the host rock. The degree of alteration depends on the amount of heat present at the contact between the magma and the host rock. Different bands of minerals can indicate what the degrees of heat were in the original contact scenario.

Dynamo-thermal metamorphism involves both pressure and heat and is primarily associated with the intense conditions that exist at the zone of subduction and the convergent plate margins, especially continent-continent collisions. One of the characteristics of both contact and dynamo-thermal metamorphism is that the elemental composition of the metamorphic rock is little changed from that of the original rock. In other words, little material is either added or removed during the metamorphic process; the existing elements were simply reprocessed into a new mineral assemblage. Because of the huge volumes of rock involved, when the mass of metamorphic rock is finally exposed by erosion, the rocks will be exposed over a very large area, giving rise to the term “regional metamorphism.” This can be seen, for example, in the Piedmont region of the Appalachian Mountains.

In contrast, hydrothermal metamorphism almost always involves a change in rock chemistry as materials are both removed from and added to the original rock by the presence of the “chemically active fluids,” or hot water, involved in the process. Hydrothermal metamorphism is primarily associated with zones of subduction, where the source of the water could be seawater drawn down along with the subducting plate or the dehydration in the zone of subduction of hydrous minerals contained within the sediments carried along with the subducted oceanic plate. As these hot solutions penetrate the host rock, elements are removed from the host rock by dissolution and replaced. When magma cools, the minerals that precipitate out do not use much water; thus, the water in the magma is concentrated. At the end of crystallization, what is left is a hot water (hydrothermal) solution full of rich elements, such
as gold or silver. This is shot out into the host rock, resulting in deposits of metals of economic value that can be mined.

The texture of metamorphic rocks is described as foliated or non-foliated. Foliated texture is the result of the development of a degree of parallelism of the platy minerals (minerals with a sheet structure, such as mica) within the rock. The foliation gives rise to planes of weakness within the rock that, in turn, result in the rock being able to split, a property called rock cleavage. The type of rock cleavage depends on the degree of orientation of the platy minerals.

Think again of shale, made up of sheet silicates in parallel layers. Under pressure, shale recrystallizes into mica and quartz, with the platy minerals realigning themselves to be perpendicular to the forces that created them. The resulting rock, slate, is basically metamorphosed shale.

The ultimate degree of rock cleavage is called slaty cleavage because it is characteristic of slate. Slaty cleavage results from the almost perfect alignment of the platy minerals. Slaty cleavage allows slate to be split into sheets of uniform thickness and smooth surfaces. Continued metamorphism of slate will result in the formation of the rock phyllite, which is characterized by phyllitic cleavage. In phyllitic cleavage, the platy minerals begin to coarsen, and non-platy minerals begin to form, both of which result in the rock being able to split into sheets but not with the uniform thickness or the smooth surfaces characteristic of slate. Further metamorphism results in the formation of the rock schist and its characteristic of schistose cleavage.
Gneiss is the most abundant of all metamorphic rocks. Gneissic banding, the poorest development of foliation, is characterized by a separation of light- and dark-colored minerals into layers. Many gneisses do not exhibit any rock cleavage.

Non-foliated metamorphic rocks consist of equidimensional, non-platy minerals. The best known example of a non-foliated metamorphic rock is marble (metamorphosed limestone).

### Suggested Reading


Winter, J. D., *Introduction to Igneous and Metamorphic Petrology*.

### Questions to Consider

1. In what important aspect do metamorphic rocks formed by hydrothermal metamorphism differ from those formed by other metamorphic processes?

2. In what geological environment would you expect most metamorphic rocks to form?
Volcanic Activity
Lecture 11

“Active” means that it’s active. Now the point is, however, that it doesn’t necessarily have to be in eruption. Obviously, an erupting volcano is an active volcano, but to be active doesn’t require active molten rock coming out. Any indication that the fire is lit down below—that’s all you really need.

Volcanoes are classified as active, dormant, or extinct. Active means that the magma chamber below is hot and liquid. Extinct means that the fire below is out—the magma chamber has cooled and solidified—and the volcano will never erupt again. Dormant means different things to different geologists. In general, it means that although there is no indication of activity, there is still reason to believe that the volcano can and will come again to life; in simpler words, it is asleep. The problem is that there have been numerous examples of “extinct” volcanoes that were, in reality, only dormant.

Mount Vesuvius, the volcano that destroyed Pompeii, was thought to have been extinct before it erupted in A.D. 79; furthermore, Vesuvius itself was created out of the eruption of another volcano, Mount Somma, also thought to have been extinct. Herculaneum, another town at the base of Mount Vesuvius, was destroyed by mudflows, called lahars, probably within hours of the eruption. The same phenomenon was responsible for much of the destruction following the eruption of Mount St. Helens.
For centuries, most of the volcanoes that have been known to be active over historic time have resided in a belt around the Pacific Ocean, aptly named the Ring of Fire. A second belt of volcanic activity extends through the Mediterranean Sea, with the third major belt following the Indonesian Peninsula to the western Pacific, where it joins the Ring of Fire. It took the advent of plate tectonics to explain the worldwide distribution of volcanism.

Earth’s volcanic activity is associated with convergent plate margins, or zones of subduction; divergent plate margins, including rift zones, rift valleys, linear oceans, and most importantly, oceanic ridges; and hot spots. The volcanism associated with divergent margins involves basaltic magmas that are almost always free of explosions. The volcanism associated with the convergent margins is represented by the island-arc and continental-arc volcanoes that form over zones of subduction. These involve andesitic magmas and always erupt explosively.

A hot spot is a point source of basaltic magma at the top of the asthenosphere that forms at the top of a heat-driven mantle plume. About 100 hot spots are currently known to exist. Hot spots appear to have nothing to do with the lithospheric plates or plate tectonics. Most hot spots are located under oceans within the plates, with a few fortuitously located along oceanic ridges. Once formed, hot spots and their associated mantle plumes do not move geographically.

The intensity of an eruptive style is determined by two directly associated factors: the composition of the magma and the amount of gas dissolved in the magma at the point of eruption. The major factor controlling the amount of gas released is the viscosity of the magma, which is dependent on its silica content. The viscosity of the magma critically controls the rate of three processes: the rate at which the magma rises to the surface, the rate of release of gas from solution to form bubbles, and the rate at which the gas bubbles rise to the surface of the magma and vent. Basaltic magma eruptions happen at divergent margins and hot spots. Because of the low viscosity of basaltic magma, most of the gas dissipates before it reaches the surface. The result is

It took plate tectonics, first of all, to understand why [volcanoes] were there.
that there is no big explosion. Andesitic magmas come to the surface at arc volcanoes. The magma’s viscosity slows down the venting of the gas, which then explodes at the surface. Granitic magmas rarely come to the surface, but when they do, their high viscosity results in huge explosions of gas.

The materials ejected from an erupting volcano include gases, solids, and liquids. A variety of gases are emitted from the erupting magma. Of all the gases ejected during the eruption of a volcano, the most abundant is water vapor. Another major gas released to Earth’s atmosphere during volcanic eruptions is carbon dioxide (CO₂), the major greenhouse gas in Earth’s atmosphere. Several other gases responsible for the rather unpleasant smells in the vicinity of active volcanic activity are the oxides of sulfur. Several acids are released in vapor form.

The solid materials ejected during the explosive eruptions are collectively called pyroclastic material. These materials are classified according to size: blocks, bombs, cinders, ash, and dust. Some of the most destructive aftermaths of a volcanic eruption involve ash and dust. In April 1815, Tambora, in Indonesia, erupted. Ash, carried around the world by the prevailing winds, blocked out the sunlight, resulting in a worldwide drop in the average atmospheric temperature. The year 1816 became known as “the year without a summer.” Growing seasons were shortened and even eliminated worldwide, resulting in famines and outbreaks of disease that resulted in the deaths of millions of people.

The liquid erupted from volcanoes is magma that has become lava. Because most lavas are basaltic, the names used to describe solid lava pertain only to basaltic lavas. The term pahoehoe is Hawaiian in origin and replaced a former English term, ropy, referring to the fact that the surface of the solidified mass has the appearance of plaited ropes. The surface of pahoehoe is very smooth, sometimes glassy smooth.

Aa (or a’a) is another Hawaiian term referring to what was originally called blocky lava. Aa lava forms when the lava flow begins to cool, becomes more viscous, and freezes at the surface, while the interior of the flow is still molten and slowly moving. Eventually, when completely cooled, the lava
surface will be an extremely rough jumble of broken blocks that, even with stout boots, is difficult or even impossible to traverse.

The third type of lava is called pillow lava, referring to its appearance of stacked pillows. Pillow lava is unique in that it solidified underwater. Because the basaltic magma erupting along the oceanic ridges solidifies underwater, all of the surface of the oceanic crust consists of pillow lava. All pillow lavas, however, do not form from lava that erupts underwater. Along the south shore of the island of Hawai‘i, for example, streams of molten lava are pouring into the ocean, where they solidify to form pillow lava. The only requirement for pillow lava is that it solidifies underwater.

**Suggested Reading**


**Questions to Consider**

1. Why are most of Earth’s active volcanoes located within the Ring of Fire?

2. The eruption of a volcano has been compared to the opening of a bottle of champagne. What did the author of that explanation have in mind?
By definition, a volcano is the conical structure that builds around a vent—a vent, of course, being a hole in the ground through which all of this stuff comes. So the conical structure that builds around a vent is a volcano. Note, in that definition there is no indication of size.

Geologists rarely concern themselves with the size of things. We’re more interested in how they got that way. Size is totally immaterial. For example, you can have a volcano that technically you could straddle with your legs; as long as it was formed by volcanic means, it would be a volcano. Obviously, most of them are a little bit bigger than that.

The three major types of volcanoes are cinder cones, shield volcanoes, and strato- or composite volcanoes. The simplest kind of volcano is the cinder cone. Cinder cones are associated with basaltic eruptions. They typically form when the molten basalt is being blown into the air as a fire fountain and breaks into small blobs that solidify in midair to form cinders; these cinders fall to accumulate around the vent. Cinder cones are seen throughout the Rio Grande Rift region and on the island of Hawaii.

Although shield volcanoes do form on land, most form on the ocean floor over hot spots where basaltic magma rises from the hot spot reservoir and erupts to the ocean floor. Because liquids cannot “pile up,” the lava flows outward from the vent to form a shallow-sloped, conical structure. Shield volcanoes that build up from the ocean floor but don’t reach the surface are called seamounts. If these volcanoes build above sea level, they become volcanic islands.

Size is totally immaterial. For example, you can have a volcano that technically you could straddle with your legs; as long as it was formed by volcanic means, it would be a volcano.
Strato- or composite volcanoes build over zones of subduction as andesitic magmas erupt to the surface. They form continental arcs and island arcs. Because of the explosive style of andesitic magma eruptions, the initial eruption generates a cone of loose, solid, odd-shaped pyroclastic material around the vent, with the characteristic steep (40°) angle of repose. The “strato-” prefix refers to the layering within the cone, while “composite” refers to the interlayering of two types of material, pyroclastic and lava. A perfect example of this type of volcano is Mount Fuji in Japan.

Volcanologists classify volcanic eruptions based on severity into one of five phases: Hawaiian, Strombolian, Volcanian, Pelean, and Plinean. The Hawaiian phase is described as “nothing but the quiet evolution of lava.” Although obviously named after eruptions on the island of Hawaii, the term is applied to any basaltic eruption anywhere in the world. Basaltic eruptions rarely involve explosions. The exception is where magma runs into groundwater, which ashes to steam and creates a phreatic explosion (meaning “related to groundwater”).

The Strombolian phase is defined as “frequent but mild explosions” and is named after the typical eruption on the volcanic island of Stromboli, just north of Sicily in the Mediterranean. Stromboli has a mild explosive eruption about every 20 minutes that is strong enough to throw blobs of molten magma over the edge of the crater and onto the slopes of the cone. Strombolian eruptions may be the result of the mixing of basaltic magma and andesitic magma at the zone of subduction.

The Volcanian phase is described as “infrequent but severe explosions.” These eruptions involve andesitic magma. Most of the volcanoes associated with zones of subduction erupt in this category. The phase is named after the typical eruptive style of a volcanic island named Volcano, also just north of Sicily, about 50 miles away from Stromboli.

The Pelean phase is named after the 1902 eruption of Mount Pelée, on the island of Martinique in the West Indies. Martinique is part of an arc chain of islands associated with the Caribbean plate. The eruption of Mount Pelée was the first witnessed occurrence of the phenomenon known as a nuée ardente, or “glowing cloud.” The glowing cloud completely overran the
town of St. Pierre and killed an estimated 30,000 people, allowing only two to survive. It consists of the contents of the magma chamber disgorged in a gigantic eruption: an incredible mass of molten rock, superheated steam, and pyroclastic material, hanging above the mountain.

The Plinian phase was named after Pliny the Younger, the young Roman historian who wrote of the final days of Pompeii. The Plinean phase is equal in violence to the Pelean except that the ejected material is blasted high into the atmosphere and does not collapse to become a nuée ardente.

Aside from the volcanoes themselves, a number of other features are created by volcanic activity. Two volcanic features are often confused because of their similar circular to elliptical shapes and their locations at the summit of volcanoes. Craters are constructional features that are created as the eruptive materials are blown out of the vent at the summit of an erupting volcano. Every volcano possesses a crater at its summit. Calderas, on the other hand, are collapse structures that form in a number of ways. Some calderas form following a massive eruption that partially or completely empties the underlying magma chamber. With the overlying cone no longer supported by the magma, the summit area of the volcano collapses into the void. It is not uncommon for calderas to subsequently fill with water, forming a lake, an example being the inappropriately named Crater Lake near the southern end of the Cascade Mountains in southern Oregon.

Some of the more spectacular features associated with active volcanism are various hydrothermal features, including hot springs, fumaroles, and geysers.
• Hot springs are, as the name implies, sites where heated groundwater comes to the surface. The temperature can range from just above body temperature to near boiling. Not all hot springs are of magmatic origin. The thermal springs at Warm Springs and Hot Springs, Virginia, for example, are the result of groundwater being heated by the geothermal gradient, which refers to the increase in temperature with depth of about 30°C per mile of depth.

• Fumaroles are vents that emit superheated gases, commonly water vapor or steam. Hydrothermal fumaroles form where the groundwater is heated to boiling by subterranean magmas and emerges as jets of steam, with temperatures reaching as high as 600°C to 700°C. Fumaroles can be harnessed to generate electricity, as has been done at Geysers, California.

• Geysers are hydrothermal features that cycle between being hot springs and fumaroles. Geysers are not common volcanic features, only being found in Iceland, New Zealand, and Yellowstone Park.


**Questions to Consider**

1. What possible explanation can you give for the difference in the eruptive styles of the volcanoes Stromboli and Volcano even though they are apparently associated with the same geologic setting?

2. What is the explanation for the glowing cloud associated with Pelean phase eruptions?
I’d like to end our discussion of volcanoes with examples of volcanic activity in the United States, one of which is one of the quietest kind of things—the Hawaiian Phase—and the other one, which there is no phase for—it has to be something we’ve never seen before: the eruption that created what is now known as Yellowstone Park.

The Hawaiian Islands consist of a string of volcanic islands and seamounts, called the Emperor Seamounts, extending from the Big Island of Hawaii at the southeastern end to Midway Island at the northwestern end and continuing all the way up to the Aleutian deep-sea trench, where the ocean bottom is being subducted.

Long before the advent of plate tectonics, two observations were made. The most obvious was the lineation of the island chain. The second was that, based on the decrease in size and apparent degrees of weathering and erosion, the islands appeared to increase in age from the island of Hawaii to Midway. The alignment of the islands was attributed to a crack that opened in the ocean floor, along which basaltic magma rose to build the shield volcanoes that eventually became individual islands. The variation in the age of the islands was explained by the fact that the crack originated in the vicinity of Midway and, over time, progressively opened east-southeastward to the island of Hawaii. The problem with the crack theory was that it could not explain why only the island of Hawaii had active volcanism.
Since the advent of plate tectonics, we now know that the Hawaiian Islands and their extension, the Emperor Seamounts, all formed over a hot spot. The lineation of the islands and Emperor Seamounts is the result of the movement of the Pacific plate over the Hawaiian hot spot. It appears that the hot spot has gone through cycles of activity and inactivity, with the individual islands being created during periods of activity lasting 100,000 or 200,000 years. These were followed by inactive periods lasting a million or so years, during which time the movement of the Pacific plate carried the island away from the hot spot, and the volcanic activity went into extinction.

After a million or so years, the hot spot resumed activity and began to create new basaltic magma, and a new island was built. Repeated cycles of activity/inactivity and continuous movement of the plate created the entire Hawaiian Island/Emperor Seamount chain. The Hawaiian hot spot has existed at its current location for at least 85 million years, as indicated by the age of the rocks at the summit of the seamount that will be the next to enter the zone of subduction.

Why does the direction of the island chain change where the Emperor Seamount turns northwest? We think that it happened about 45 million years ago, when India collided with Asia, creating the Himalayas. The theory is that this event had an impact on the direction of the Hawaiian Island chain. Most islands consist of two or more volcanoes that were created as the plate moved laterally during the period of hot spot activity. Of the five volcanoes on the island of Hawaii, three are extinct. Mauna Loa and Kilauea are active. Off the southern edge of the island, a seamount called Loihi is rising from the ocean floor; if it continues to be active, it will eventually become part of the island as the newest volcano.

Visitors can see spectacular volcanic activity at Pu`u `O`o Vent on the island of Hawaii. There, molten rock flows down the southern shore of the volcano Kilauea into the ocean. On Maui, visitors hike and ride bikes around the crater of Haleakala. On the Honolulu side of Diamondhead, on Oahu, tourists can see inside the cone of this once-active volcano.

Yellowstone Park is one of the most spectacular regions of volcanic activity in the United States. What happened at Yellowstone is something that has
never been observed in all of historic time. We are still dealing with a hot spot here, but this time, it is underneath a continental lithosphere. The hot spot formed, creating basaltic magma. It pooled under the crustal layer of granite, melting the granite, which turned into highly viscous, super-gas-charged granitic magma. This rose and broke through the surface in circular formations called annular cracks. Then it blasted through in a huge eruption, ultimately collapsing in a gigantic caldera. This event was repeated in a process starting 16 million years ago somewhere in the area of Nevada, Idaho, and Utah.

As the North American plate moved southwestward over the hot spot, at least five enormous eruptions resulted in the formation of calderas that eliminated mountain ranges that once crossed the Snake River Plain of southern Idaho. By 2 million years ago, when the first of the three eruptions that created Yellowstone occurred, the hot spot was under what is now Yellowstone Park. As the North American plate moved southwestward over the hot spot, the same scenario was repeated about 1 million years ago. The most recent eruption occurred about 600,000 years ago.

Yellowstone sits inside a gigantic caldera. There are indications that the magma underlying Yellowstone is rising, leading to speculation that another gigantic eruption may be imminent. The southern end of Yellowstone Lake is being tipped. Two bulges in the caldera are rising fast enough to be measured. We cannot predict exactly when the eruption will happen, but we are sure that it will at some point and that it will be like nothing ever seen, shutting down the entire Northern Hemisphere.

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Suggested Reading


Questions to Consider

1. Why are the rocks in the vicinity of Yellowstone Park rhyolitic while the volcanic activity is the result of an underlying basaltic hot spot?

2. Theorize an explanation for the apparent volcanic hiatus between adjacent islands/seamounts in the Hawaiian Island/Emperor Seamount chain.
Mass wasting has to be the unsung hero of all geological processes. I say “unsung” because unless it was for the occasional landslide, most people wouldn’t even know these things are going on.

Mass wasting is a very, very important process. To start our discussion, let’s go back to those products of weathering, the solid products of weathering, that mixture of rock fragments. The end product of weathering is a layer of loose material that accumulates above bedrock called regolith. From the time regolith accumulates, a series of processes is set into motion, the purpose of which is to pick the regolith up and carry it away, eventually to the ocean. The process of mass wasting starts that journey. Mostly, the regolith is carried from hilltop to valley floor, where the process of erosion begins.

The difference between mass wasting and erosion is that the main agent of erosion is water or glacial ice, whereas gravity is the primary driving force of mass wasting. Gravity was the great discovery of Isaac Newton, who postulated that every body in the universe is attracted to every other body in the universe by this force. The force of gravity is directly proportional to the product of the masses of the two bodies and inversely proportional to the square of their distance of separation. This is represented by the equation: 

\[ F_g = \frac{G m_1 m_2}{d^2}, \]

where \( G \) = the universal gravitational constant; \( m_1 \) = the mass of body 1; \( m_2 \) = the mass of body 2; and \( d \) = the distance between the centers of gravity of the two bodies.

Although this relationship is applicable throughout the universe, it can be modified to evaluate the force of gravity between Earth and any object resting on Earth’s surface. We can use it, for example, to determine the force of gravity between Earth and the largest single mass we can think of on Earth, the island of Hawaii, rising 29,000 feet from the ocean floor.

The force of gravity between Earth and any object resting on Earth’s surface is directly proportional to the product of Earth’s mass and the mass of the
object divided by the square of Earth’s radius: \( F_g = \frac{G M_E \times m_O}{R_E^2} \), where \( R_E \) = Earth’s radius.

According to the modified gravitational relationship, the force of gravity between Earth and any object on its surface is directly proportional to the mass of the object. But note that \( G \), \( M_E \), and \( R_E \) are all constants. Thus, we can combine them into another single constant—\( q \) (Earth’s gravitational constant). When substituted in our original equation, this gives \( F_g = q m_O \).

The force of gravity is the weight of the object. Note that the weight of an object is proportional to its mass and is not the same as its mass. An object’s mass is everywhere the same in the universe, while its weight is a function of the magnitude of the gravitational constant.

Mass wasting involves the downslope movement of regolith under the force of gravity. For the movement of any object residing on a surface to take place, a force must be directed parallel to the surface. When an object rests on a horizontal surface, the full force of gravity is directed perpendicular to the surface. The object will not move because there is no force directed parallel to the surface.

For objects on a sloping surface, the force of gravity is now resolved into two new forces, one parallel to the slope and directed downslope and the other directed perpendicular to the slope. The force directed downslope obviously is trying to move the object downslope. The force directed perpendicular to the slope is a force of cohesion and friction, serving to prevent any motion of the object. Whether the object will move downslope will depend on which of the two forces is the greater.

One can determine the relative magnitude of the two forces by constructing a parallelogram with the force of gravity, the object’s weight, as the diagonal, and the sides parallel and perpendicular to the surface of the slope. For simplicity, we can refer to the downslope component of gravity as the Go Force and the force of cohesion and friction as the Stay Force. As the angle of slope begins to increase from 0 slope, the Stay Force decreases and the Go Force increases. As long as the Stay Force dominates over the Go Force, the object will not move downslope. At some point, a critical balance will be
achieved in which the two forces are equal. Continued increase in slope will result in the magnitude of the Go Force exceeding that of the Stay Force, and the object will move downslope.

Although theoretically the point of critical balance between the two forces would be at a slope angle of 45°, experimentally it has been shown that for solid, odd-shaped particles of any size, the critical angle is about 40°. This angle is called the angle of repose. For this reason, slopes of less than 40° will be covered with regolith. As slopes exceed 40°, they become increasingly barren of regolith, with increasing exposures of bedrock. The angle of repose is determined to some degree by the shape of the rock: The less angular the rock, the lower the angle of repose.

Suggested Reading


Crozier, M. J., *Landslides: Causes, Consequences, and Environment*.

Questions to Consider

1. What is the difference between mass and weight?
2. Some geologists consider mass wasting a process of erosion, while others do not. What arguments would you present to substantiate each opinion?
The problem is the definition of mass wasting: It’s movement of regolith on slopes, period. It doesn’t say anything about the angle of slope. The implication is, as long as the slope is not horizontal where, remember now, nothing can move—as long as it’s not horizontal, if it has any angle at all, it’s going to be moving.

Regolith resting on slopes of less than the angle of repose will not move downslope because the Stay Force exceeds the Go Force. But the definition of mass wasting refers to the “movement of regolith on slopes.” The angle of the slope is not a consideration. The question is, how can regolith move when the Stay Force is in excess of the Go Force? For any object to move down any slope, the Go Force must exceed the Stay Force, regardless of slope angle.

An increase in the Go Force would require an increase in the force of gravity (weight of the object)—an unlikely event. However, a decrease in cohesion and/or friction would effectively decrease the Stay Force. The most likely candidate to decrease cohesion and friction is water. If sufficient water is introduced, the cohesion and friction between the object and the surface could be reduced to the point that the Stay Force would become less than the Go Force at angles as small as 1° to 2°, and the object would move downslope.

The amount of water present is so important to mass wasting that it is the basis for the classification of the processes of mass wasting into three categories: flows, requiring moderate to high amounts of water; slides, requiring moderate to low amounts of water; and falls, requiring little water.

One of the most destructive examples of a flow is a mudflow. Mudflows associated with volcanic eruptions are called lahars. It was a lahar that destroyed Herculaneum following the eruption of Mount Vesuvius in A.D. 79. Mudflows are common occurrences in many regions where steep slopes become saturated during torrential rainfalls. Because of their high fluidity, mudflows can flow for many miles. A process called solifluction, operating
in regions of permafrost, can move regolith on slopes with shallow angles of 1° to 2° when a thin layer of the permafrost thaws.

Slides, which require less water, can be of debris or rock. The two together are commonly referred to as landslides. The difference is in the size of the particles. A rockslide involves furniture-sized pieces of material, while a debris slide involves smaller fragments. Landslides typically occur on steep slopes after many cycles of freezing and thawing, terminated by heavy, soaking rainfalls in the spring. The type of slide that moves the most material worldwide is creep. During temperate winters, the upper surface of the regolith is repeatedly subjected to cyclic frost heaving. In the upper layer of soil in winter, ice crystals grow—the crystal particles always grow perpendicular to the soil surface—and this growth pressure is enough to lift up the soil surface. When the frost melts, the soil drops back again. This process is repeated over and over again during the winter. On a slope, this process, in conjunction with the force of gravity, moves the soil particles very slowly downhill.

During warmer months, with each rainfall, the cohesion and friction between individual particles is temporarily decreased to the point where a little downslope movement can take place. The result of this slow downslope movement is seen in tipped fence posts, tombstones, bent trees, and perhaps the most commonly observed result, tipped garden walls.

The most common example of a fall is the rock fall. Rock falls are typically the result of rocks being dislodged from surrounding strata after exposure by the cyclic freezing/thawing of water in joints and cracks. Eventually, the rock loosens and falls. In temperate climates, the results of rock fall are seen during the spring, after the spring rains.
Suggested Reading


Crozier, M. J., *Landslides: Causes, Consequences, and Environment*.

Questions to Consider

1. What portion of the topography is primarily the domain of mass wasting?

2. Assume you are in the market to buy property to construct a home in a region that has a history of landslides. What physical evidence would you look for in a piece of property that would give some indication of the degree of slope stability?
Weathering

Lecture 16

Weathering has to be the most important, or at least one of the most important, processes going on, on Earth’s surface. Now, if I were asked to define weathering in one word, I think I’d use the word “rot.” Weathering is any process whereby rocks rot.

We do not usually associate the word “rot” with rocks, yet that is the simplest way to define weathering. Weathering is any reaction between the rock surface and the atmosphere. The idea of surface has to do with chemistry, in that all reactions involving solids are surface reactions; the center of the particle is not involved. But as the surface is attacked and removed, eventually, the center is exposed and subject to reaction. The idea of atmosphere is that agents—gases—are responsible for the destruction of rocks. The idea of atmosphere also implies that the processes of weathering can go on anywhere the atmosphere can penetrate, including underground caves. Thus, the surface of a rock is any surface that comes into contact with the atmosphere, above or below ground.

A second definition states that weathering is any process by which rocks either disintegrate or decompose. Disintegration implies nothing more than a physical reduction in particle size, giving rise to the terms physical or mechanical weathering. Decomposition implies a chemical change that can be total or partial. The only requirement of chemical weathering is that the products are different from the reactants.

What are the agents of physical weathering? The primary agent of physical weathering is the freezing and thawing of water, the process called frost wedging that we discussed earlier. The 10% expansion as water is converted to ice exerts enormous pressures on any containment. Should that containment be a crack in a rock, the rock will eventually fail after repeated episodes of freezing and thawing. Frost wedging takes place primarily in temperate climates.
Growing plant roots are also effective agents of physical weathering because they grow within cracks and wedge the cracks open as they increase in diameter. In addition, plants are chemically active and thus are agents of chemical weathering. Another effective process is efflorescence. This results in the exfoliation of a rock surface through the growth of soluble crystals precipitated from groundwater just beneath the rock surface. Such a process is most effective in desert regions or in outcrops that face the Sun. As groundwater evaporation continues just below the surface and more salts precipitate, the growth pressure exerted by the minerals causes a crack to form and widen parallel to the rock surface. Eventually, portions of the rock will flake off and fall to become part of the talus below.

Another process, exfoliation, can be seen at work in geological features called batholiths. Batholiths are huge masses of intrusive igneous (or metamorphic) rock created under great pressure by magma solidified deep in the Earth’s crust. The exposure of these masses by erosion results in the development of fractures parallel to the surface of the rock body in a process called unloading, as the rock responds to the decrease in overlying weight. The fractures can then be widened by frost wedging or the growth of plant roots. With time, the outer layers of rock split off in layers that are, in some cases, sizable in thickness.

Once thought to be an effective agent of physical weathering, cyclic expansion and contraction at mineral-to-mineral contacts by daily changes in temperature are no longer thought to be capable of physically disrupting rock. However, a rapid change, such as cold rainwater falling on a rock heated by a fire or a lightning strike, could cause a rock to fracture. Although burrowing animals are not capable of directly attacking rocks, their burrows promote weathering by allowing the penetration of the atmosphere below the surface.

The major processes of chemical weathering are: oxidation, dissolution, and carbonation/hydrolysis. Dissolved oxygen and carbonic acid are the two agents that are responsible for chemical weathering. Oxidation is defined as “any reaction with oxygen.” Of all the natural elements, the one that is most susceptible to oxidation is iron. A chemical reaction commonly used to illustrate the process of oxidation is: $\text{Fe} + \text{O}_2 \rightarrow \text{Fe}_2\text{O}_3$ (iron + oxygen
iron oxide [rust]). Iron-rich minerals, such as the ferromagnesian silicate minerals, are most readily attacked by this process.

An important aspect of oxidation is that for oxygen to be an effective agent of chemical weathering at Earth’s surface, it must be dissolved in water. The oxidation process readily attacks the ferromagnesian minerals, removing the iron from the lattice, which results in the collapse of the remaining mineral structure.

Dissolution means simply “the process of dissolving.” Of all the common rock-forming minerals, the only one that dissolves in water to any extent is calcite, CaCO₃, the major component of limestone. The solvent is not pure water but a dilute solution of carbonic acid created by the reaction between water and carbon dioxide.

Because it is the reaction by which nearly all the major rock-forming silicate minerals decompose, the most important of the three processes of chemical weathering is carbonation/hydrolysis. As the name implies, the process is a combination of a reaction with carbonic acid (carbonation) and water (hydrolysis). Again, as the large molecules are pulled out of the lattice in this reaction, the remaining structure begins to disintegrate. The major end products of the carbonation/hydrolysis reaction are the clay minerals, which in turn are the essential components of soils. All major rock-forming silicate minerals, except for olivine and quartz, decompose to form soluble bicarbonates and silicic acid. The reaction for orthoclase can be represented by the following equation:

\[
K\text{Al}_3\text{Si}_3\text{O}_8 + H^{1+} + \text{HCO}_3^{1-} + H^{1+} + \text{OH}^{1-} \rightarrow \text{KHCO}_3 + \text{H}_4\text{SiO}_4 + \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4.
\]

The rate of chemical reaction is affected by temperature and water, which means that chemical weathering predominates in the tropics.
Composition is also a factor in weathering. Gold, for example, does not react to external influences, whereas silver tarnishes and iron rusts. A geologist named S. S. Golditch formulated Golditch’s Weatherability Series, which parallels Bowen’s Crystallization Series: The minerals that crystallize the fastest are also those that weather the fastest. Basalt, for example, weathers very quickly; granite weathers the slowest.

**Suggested Reading**


**Questions to Consider**

1. Why are the ferromagnesian minerals especially susceptible to the process of oxidation?

2. Theorize as to why mafic minerals and rocks weather at a faster rate than do felsic minerals and rocks.
I think soils have to be, as far as geological materials go, about as important as you can possibly get for human beings, because without soils you would have no rooted land plants, and without rooted land plants you’d have no bottom for the land food chain, and if you don’t have the bottom for the land food chain, you can’t have anybody on top of it.

By definition, soil is that part of the regolith that supports plant life out of doors. Recall that regolith is a mixture of rock fragments and, primarily, clay minerals that accumulates above bedrock. The kind of soil that will develop in any region is determined by the climate. A temperate climate is one in which there are seasonal changes in temperature. This kind of climate can be subdivided based on annual precipitation into humid (20 inches or more per year), semiarid (10 to 20 inches per year), and arid (10 inches or less per year).

The soils that develop in humid, temperate climates are the forest soils; the spodosols form under conifer-dominated cover in regions characterized by cool mean temperatures, and the ultisols form under broadleaf forests and higher mean temperatures. Typically, spodosols and ultisols are acids. Spodosols are slightly more acidic than ultisols.

The soil that forms in semiarid, temperate climates is the mollisol. The mollisol is the soil order that dominates in the grasslands of Earth. Arid soils, termed aridisols, are, for the most part, nothing but regolith, with few of the aspects of soils that can support extensive populations of plants. The tropical soil order, oxisol (or laterite), develops under the ever-hot, ever-wet conditions that exist in the tropics.

The essential components of soil are the clay minerals. The clay minerals are sheet silicates with special properties resulting from the fact that their crystal structures are never electrically neutral. The structures of most clay minerals are negatively charged because of a lack of cations within their
crystal structures. The result of being negatively charged is the attraction and adsorption of cations out of the soil water in sufficient numbers to neutralize the negative charge; this process is referred to as cation adsorption. The unique chemical properties of the clay minerals are the result of their ability to exchange whatever cations are adsorbed to cation adsorption sites on the clay particles for other cations from the surrounding soil water—a process called cation exchange. The process of cation exchange is so important to the soils scientist that there exists a laboratory procedure to quantify the ability of a clay material to exchange cations in terms of the cation exchange capacity (CEC). It is this ability of the clay mineral components to exchange cations that is the basis for the soil’s capacity to support plant life.

Soils that develop in temperate, humid regions receiving more than 20 inches of precipitation annually are typically acidic, because the cation exchange sites are occupied by hydronium ions provided by the dilute solution of carbonic acid that permeates the soil. Because of its dominance, the hydronium ion displaces whatever cations were originally present on the cation exchange sites, thereby hydrogenating the soil. An acid is any compound that will provide a hydrogen ion into solution. Acid is represented by the symbol H. As a chemist, I can write a formula to represent each clay particle: H\(^{1+}\)(clay\(^{-}\)).

Acidic soils are neutralized by treatment with powdered limestone (CaCO\(_3\)), known as agricultural lime. Neutralization takes place as calcium ions placed in solution by the dissolution of the agricultural lime replace the hydrogen ions originally occupying the cation exchange sites of the clay minerals. The formula that now represents the clay particles is Ca\(^{2+}\)(clay\(^{-}\)). Note that the clay mineral is no longer a source of a hydrogen ion and is, therefore, no longer an acid. Once the hydrogen ion is released into solution, it combines with the bicarbonate ion to become undissociated carbonic acid. The soil is now ready to support the kind of plants we want to grow.

How does the plant acquire the calcium ions? Note that the clay minerals cannot simply give the calcium ion away because it will then become electrically charged. The clay mineral particle can only exchange the calcium ions for another cation. For the plants to acquire the calcium ions they need, they secrete carbonic acid from their roots, some of which dissociates to
produce hydronium ions. These are then exchanged for the calcium ions on the clay particles, which are then taken up into the plants. In other words, plants get their nutrients from the clay minerals by cation exchange. However, eventually, all of the calcium ions will have been replaced with hydronium ions, returning the soil to its original acid state, at which point, the soil must be re-treated with another addition of agricultural lime.

Mollisols in semiarid regions are self-neutralizing. They are the great agricultural soils of the world. Rainwater is acidic. Groundwater, heading back to the ocean, is full of soluble bicarbonates, which are alkaline. During the rainy season, acid rainwater moves down through the ground, depositing hydrogen ions. During a drought, groundwater moves up through the soil, bringing with it calcium ions, which displace the hydrogen ions. When the rain returns, the hydrogen ions do not displace the calcium ions because the hydrogen ions, with their +1 charge, do not displace the calcium ions, which have a +2 charge.

Suggested Reading


Questions to Consider

1. In general, soils in humid, temperate regions are described as being “acid.” What does that mean?

2. How do soils go about the task of supporting plant life out of doors?
Climate and the Type of Soils
Lecture 18

The soil scientists say that if a soil is allowed to develop undisturbed, that it develops layers they call horizons. Now, first of all, undisturbed—what does that mean? Well, that means without you or me coming along with a shovel, or a plow, or a D9 dozer. Or it means without Mom coming along with a landslide or some such thing.

Left undisturbed, soils in temperate climates develop a vertical zoneation through the horizon layers. There are five different soil horizons, designated O, A, E, B, and C. The topmost layer, called the O (“organic”) horizon, consists of recognizable plant debris, such as leaves, grass clippings, and twigs. The A horizon, the “zone of alluviation,” is a dark, earthy material consisting of decomposed plant debris, commonly called humus. The E horizon, the “zone of elluviation,” is a leached zone that is composed primarily of quartz sand.

The B horizon is, in many respects, the “heart” of the soil, in that it is the repository of the all-important clay minerals, along with some quartz and iron oxides. Iron oxidizes in a two-step process. First, it oxidizes as iron-oxy-hydroxide—FeO(OH). The mineral name is limonite, which is yellow in color. When limonite dehydrates, it ends up as Fe$_2$O$_3$, which is hematite and is red in color. Where there is pyrite—FeS$_2$—in the soil, the pyrite oxidizes, the sulfur turns into soluble sulfate, and the iron is made present and available to oxygen to go through the process of, first, making limonite, which when dehydrated makes hematite. Yellow limonite, red hematite, and black organic material are the main coloring agents in soils and sedimentary rocks.

The C horizon is referred to as the parent material and is that portion of the regolith undergoing conversion to soil. In terms of our definition for a soil, the C horizon represents the deepest penetration of plant roots, which have a significant role to play in soil formation.
Soils are classified into orders that are characterized by different horizonations. Only five of these will be considered here: the two major soil orders that develop in temperate, humid climates, the spodosol and the ultisol; the mollisol that develops in temperate, semiarid climates; the aridosol that develops in regions receiving less than 10 inches of precipitation annually; and the oxisol that develops in ever-hot, ever-wet tropical climates. Rainwater and groundwater have varying degrees of impact on each of these soil orders.

The spodosols and ultisols are forest soils that develop under conifer and hardwood cover, respectively. Both soils have good development of all the basic horizons. The major characteristic of these soils is that the clay minerals in the B horizon are hydrogenated, rendering the soils acid. But both soils are excellent agricultural soils once the acidity has been neutralized.

The mollisols are neutral-to-alkaline soils that are found in semiarid, temperate regions and have good development of all the basic horizons, except that the O, A, and E horizons are relatively thin. In the B horizon, where these soils are found, the upward percolation of alkaline groundwater during the drought portion of the year neutralizes the clay mineral particles, primarily with calcium ions. With the return of rainwater, the hydrogen ions will not displace the calcium ions, owing to their weaker charge. The presence of calcium in the soils explains the extensive grasslands that are supported by the mollisols. Mollisol grasslands go a long way back in time and enabled the evolution of grazing animals. Every continent has a grassland. The mollisols are commonly referred to as the breadbasket soils in that they grow the grains that feed the greater portion of the world’s population. They are also referred to by the Russian word *chernozem*, meaning “black soil,” in reference to the color imparted by the decaying annual grasses.

For the most part, the aridosols are nothing more than regolith accumulated in desert basins. There is rarely any indication of horizonation and, except for the region referred to as the steppe, there is no continuous plant cover. Because of the extreme dryness of the air, groundwater is drawn upward only to evaporate below the ground surface, giving rise to high concentrations of soluble salts within the soil. In fact, in some cases, a layer of extremely hard
carbonate minerals called caliche or hardpan develops in the upper portion of the soil.

The ultimate result of the deposition of salts is that the aridosol is far too alkaline to allow the growth of familiar food crops. Desert plants are capable of surviving in such an environment by regulating the amount of alkaline or alkaline earth ions taken into their root systems. The aridosol can be made less alkaline by irrigation. The problem with irrigation is that the salts leached out by irrigation into surrounding streams make the stream water unusable with time.

The tropical soils, the oxisols (or laterite), consist primarily of the oxides of aluminum, silicon, and iron that result from the extreme rates and intensity of chemical weathering that take place in the ever-hot, ever-wet tropics. There is no horizonation; most noticeably absent are any O or A horizons. Their presence is precluded by the rapid decomposition of plant remains and the near-instantaneous uptake of the decomposition products by living plants. Although attempts are constantly made to introduce temperate-type agriculture, such efforts fail because of the absence of clay minerals that store nutrients.

**Suggested Reading**


Questions to Consider

1. Why are the mollisols that characterize semiarid, temperate climates the most agriculturally productive of all soils?

2. Why do attempts to grow temperate-climate crops in tropical climates succeed for only two or three growing seasons before they are abandoned?
Now it’s time to start talking about erosion, and I’m going to start off by making a statement that the number one agent of erosion anywhere water can exist is running water or streams. That’s anywhere water can exist—and note, that also means in the desert.

Streams belong to one of two drainage systems, exterior or interior. Exterior system streams are those whose waters eventually reach the ocean, while interior system streams terminate in some inland basin. Exterior streams are by far the more numerous. The hydrologic cycle describes the movement of water on Earth’s surface. The source of water is the ocean. Once removed from the ocean by evaporation, water is taken into the atmosphere and carried inland by the prevailing winds, where it precipitates as rain or snow. Eventually, all water returns to the ocean. Of the total volume of water outside the oceans, nearly 80% resides in glaciers, about 20% is contained in groundwater aquifers, and approximately 0.7% is contained in lakes, with a meager 0.005% contained in all the streams of the world. The seemingly insignificant amount of stream water is responsible for most of the erosional sculpting of the land.

Streams are very specific in the order in which they pick up, transport, and deposit the products of weathering. The solid materials generated by weathering are categorized based on size, with the individual size having no composition implication. From largest to smallest, the particle sizes are boulder, cobble, pebble, granule, sand, silt, and clay.
There are several stream parameters with which we must be familiar to understand how streams perform. The gradient of a stream is the slope of the channel and is measured in the number of feet the channel drops over a horizontal distance of 1 mile. Gradient decreases downstream. The volume of the stream is its cross-sectional area measured in square feet (ft²) at specific locations along its length. The resulting measure is of the wedged width, that is, the distance across the stream and the average depth at that point. Volume increases downstream. The velocity of a stream is measured in feet per second (ft/sec) at specific sites along its length. Velocity increases slightly downstream. The product of volume and velocity, called the discharge, is measured in cubic feet per second (ft³/sec). The amount of energy made available to a stream is proportional to the discharge. Discharge increases downstream in response to erosion and the volume of materials being moved. Discharge will be at a maximum at the time of a flood.

The efficiency of streams as agents of erosion is a product of two types of fluid flow: laminar and turbulent. In laminar flow, the individual molecules of water move downstream along parallel, noninterfering pathways. In turbulent flow, the individual molecules of water move downstream in random, interfering pathways. The available energy is expended in two directions: horizontally downstream and vertically upward. The vertical component picks the particles off the stream bottom, and the horizontal component carries them downstream. Laminar flow does not erode, but turbulent flow does.

To illustrate the importance of turbulence, consider an average stream from headwaters to the mouth. In general, turbulence will be highest in the headwaters of a stream and will decrease toward the mouth. In any stream, the largest particles in the channel are found in the headwaters, where the highest level of turbulence exists during times of flood. The vertical component of turbulence during floods picks the large particles off the stream bottom. Because the downstream component of velocity is relatively small, the particles are moved only a small distance downstream during any one flood event. Downstream, turbulence decreases and bed load particle size decreases, but the total load increases because of the contributions of tributaries. In general, by the time one arrives at the mouth of the stream, the material in the bed load has been reduced to some minimum size, while
the combined bed load and suspended load are at a maximum. At this point, only a relatively small vertical component of turbulence is needed to lift particles, while most of the energy of turbulence is needed to move the load downstream.

The picking up and transportation of particles by a stream is a competition between two forces: gravity and the vertical component of turbulence. Experiments conducted in flumes have shown that the amount of energy represented by the vertical component of turbulence required to break the cohesion between sand-sized and larger particles and the stream bottom is slightly greater than the respective downward force of gravity.

Surprisingly, the same experiments have shown that the amount of energy required to lift silt- and clay-sized particles is equivalent to that required to lift granule- and pebble-sized particles. The silt- and clay-sized particles are so small that they will be contained completely within the laminar layer, which lacks the vertical component of turbulence required to lift them from the bottom. As water velocity and turbulence increase, the thickness of the laminar layer is reduced to the point that eventually, the silt- and clay-sized particles come into the reach of the turbulent portion of the water flow. Once the individual particles are lifted from the bottom, the horizontal component of turbulence moves the particles downstream. The particles will continue to be transported as long as the vertical component of turbulence is equal to or greater than the force of gravity.

When the magnitude of the vertical component of turbulence drops below the force of gravity, the individual particles undergo deposition and return to the stream bottom. During deposition, the particles return to the bottom in order of decreasing size.

The total amount of material that a stream can carry is called the capacity, while the load is the amount of material that the stream is carrying. Load is carried in solution (dissolved load), suspended load, and bed load. Dissolved load consists of the soluble products of weathering. Suspended load usually consists of silt- and clay-sized particles that are carried more or less continuously within the mass of water. Bed load is the material being moved along the channel floor and usually ranges from sand-size particles up to a
size limit referred to as the competency of the stream. Of all the material carried by the stream, dissolved load represents about 25%; suspended load represents about 68%; and bed load about 7%.

Suggested Reading

Easterbrook, D. J., *Surface Processes and Landforms*.

Questions to Consider

1. What experimental observation led to the concept of the laminar layer?

2. Consider the average stream from headwaters to the mouth in terms of the degree of turbulence exhibited by the stream. The decrease in turbulence downstream represents a reallocation of energy between the horizontal and vertical components of turbulence. What evidence can be observed in the bed load that would explain the need for such a reallocation?
Sculpting of the Landscape
Lecture 20

You would think in 250 years we would have gotten our acts together and agreed on how such a basic thing as the sculpting of the landscape takes place. We think we understand streams and all that but, alas, there is no theory that everybody will accept.

One compelling theory on how landscapes are sculpted was set forth by geologist William Davis, who did his work in the early part of the 1900s. Davis was a geomorphologist. Geomorphology is sort of a speciality area in geology, and primarily it is the study of landforms. Although Davis’s work dealt with the evolution of landscapes in humid regions, the basic principles hold for landscapes in semiarid and arid regions, as well. The basis for Davis’s theory is the concept of the base level. Davis’s fundamental concept was that every stream was attempting to carve its channel down to an imaginary surface called a base level. Davis went on to say that any stream could have one ultimate base level and any number of temporary base levels.

The ultimate base level depends on whether the stream belongs to an exterior system, in which the water ultimately flows to the ocean, or an interior system, in which the stream ends in some inland basin. For streams belonging to an exterior system, the ultimate base level is sea level. For a stream belonging to an interior system, the ultimate base level is the elevation of the interior basin into which the stream ultimately flows.

Temporary base levels are features along the course of a stream that have finite lifetimes. An example of a temporary base level would be the level of water in a lake, where in time the sediment transported and deposited into the lake by a stream will eventually fill the lake. In the process, the lake becomes, first, a marsh (a wetland dominated by grasses), followed by a swamp (a wetland dominated by trees), and finally a bog. Once filled and converted to land, the lake as a base level is eliminated. The Great Lakes are not subject to this process because they are not truly lakes but inland seas.
A waterfall is another example of a temporary base level. The goal of a stream flowing over a waterfall is to carve its channel down to the elevation of the lip of the waterfall. All waterfalls are being continuously undermined by weathering and erosion and are retreating upstream, decreasing in height as they go. Even Niagara Falls is eroding upstream at a rate of about 3 feet per year.

According to Davis’s scheme, the appearance of the land depends on the location of the streams of the region with respect to their base levels, with the appearance of the land progressively changing from the stage of youth through the stage of maturity to the stage of old age as the stream channels in the region approach their base levels. With the streams far above their base levels, all the energy allocated to erode carves the channel, via abrasion of the bed load, into the underlying bedrock in the form of a slot canyon. Simultaneously, mass wasting operating on the valley walls causes the valley to assume the characteristic V shape of the youthful stage of landscape evolution.

Within the V-shaped valleys, fast processes of mass wasting, such as rock falls, rock slides, and debris slides, account for the large particle sizes in the stream channel. The stream gradients in V-shaped valleys will be high. The streams will be highly turbulent, with numerous waterfalls and rapids. The stream load will be almost entirely bed load, with little or no dissolved or suspended load.

When all the stream valleys in a region are V shaped and separated from each other by sharp ridges or sharp-edged uplands, the overall appearance of the landscape is rugged and mountainous. As downward erosion continues, a point is reached at which the energy available for erosion is progressively
reallocated, with less energy expended in downward cutting and an increasing proportion of energy allocated to lateral erosion. The valley widens into a valley flat or flood plain. The first sign of reallocation of erosional energy is the initiation of stream sinuosity, called meandering, which brings the youthful stage of landscape development to an end and begins the stage of maturity.

With time, the stream channel becomes increasingly sinuous as lateral erosion increases. The average particle size of the bed load is decreased by continued physical and chemical weathering, generating silt- and clay-sized materials that are taken into suspension, increasing the turbidity of the water. Waterfalls evolve into rapids, which in turn begin to disappear.

Mass wasting reduces the angle of slope of the valley walls to less than the angle of repose and replaces sharp ridge lines with more rounded hilltops. At some point as the stream channels approach their base levels, the valley becomes many times wider than the stream channel, and the landscape enters the stage of old age.

In old age, the sinuosity of meander is extreme; meander loops have been breached during floods to create abandoned meanders or oxbow lakes, so called because they resemble a U-shaped harness called an oxbow. Also evident are wetlands, marshes, and swamps. The overall topography is very subdued, with the uplands separating adjoining streams often not visually apparent. As the stream channels approach their base levels, should the distance between the stream channels and their base levels be abruptly increased via plate tectonics, a process called rejuvenation will be initiated, wherein the stream will return to a more youthful stage and a new cycle will begin. A classic example of this process is seen in the southwest region of the United States. About 10 million years ago, the Colorado River area was uplifted about 10,000 feet, possibly by the accumulation of heat under the mass of granitic rock. As the rock heated and expanded, it lifted the whole area. The main stream and its

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The whole idea of the Grand Canyon and her tributaries is a beautiful, beautiful example of carving and creating the landscape.
tributaries then began carving out the land again, resulting in such areas as the Grand Canyon and Monument Valley.

**Suggested Reading**

Easterbrook, D. J., *Surface Processes and Landforms*.

**Questions to Consider**

1. How do you explain the fact that the level of water in old-age streams, such as the lower reaches of the Mississippi River, is above the level of the surrounding floodplain?

2. What roles do streams and mass wasting play in the sculpting of a landscape?
Stream Erosion in Arid Regions
Lecture 21

There is something different about what’s going on in arid regions as opposed to humid regions. Now, are there different processes going on? No, there aren’t. Uniformitarianism says that there are no different processes.

The big difference between streams in the desert and streams in arid regions is that streams in desert areas are typically interior systems. On emerging from the highlands, some streams terminate in year-round lakes, such as the Great Salt Lake. Other streams terminate in seasonal lakes called playa lakes that hold water only during periods of rain or snowmelt. Most desert streams emerging from highland areas terminate shortly after entering the desert basin.

Nevada is typical of arid regions and is situated in the Basin and Range Province, which contains long, parallel mountain ranges separated by intermontane valleys. The arduous trek of American pioneers across this region is remembered in our nation’s history through such incidents as the starvation and cannibalism of the Donner Party. Streams far above base level in the mountains of what is now Nevada carved the typical V-shaped valleys that Davis described. Rather than flowing into a lake, however, these streams ended at the valley floor, with the water soaking into the ground.

The debris from the streams was simply deposited on the valley floor. A deposit that forms at the mouth of a stream where it enters a larger body of water is called a delta. In the desert, where no larger body of water is present, such a deposit is an alluvial fan. As the highlands eroded and individual alluvial fans grew larger, they eventually merged along the base of the highland to form a deposit called a bajada. It is important to note that as the mass of the highland was reduced by weathering and erosion, the slopes receded parallel to their original slope.

In time, the bajadas from opposite sides of the basin met in the basin center, at which point the entire basin was filled with debris shed from the highlands.
on both sides, creating a bolson. This could be considered the beginning of the end for the stage of maturity in the arid cycle. Eventually, in old age, the highlands were reduced to discontinuous mounds of rock that may be no more massive than a typical house, because the highlands have literally been buried in their own debris. This was how Nevada was formed. As is the case in the humid cycle, re-uplift of the region could result in rejuvenation and a return to a more youthful stage of landscape.

What would a desert region look like if it were the product of an exterior stream system? There are only two major streams worldwide that flow through desert and reach the ocean. One is the Nile River; the other is the Colorado River. Until about 10 million years ago, the entire Southwest was near sea level, and the river we know as the Colorado meandered across an old-age landscape to the sea. The debris created by weathering and erosion was carried off to the Gulf of California. Had the Colorado been an interior system, canyon areas such as the Grand Canyon would not exist.

Because erosion by wind is restricted to sand-, silt-, and clay-sized particles, wind plays a minor role in the evolution of the desert landscape. The rules for wind are exactly the same as for water; namely, sand is the easiest particle size for the wind to move. Silt and clay sizes are very difficult to move but can be moved when they are picked up by sand. In terms of sediment movement, sand is carried near the ground surface as a bed load in a process called saltation. As it moves, the sand loosens fine-grained particles (silt and clay) on the desert floor, which are carried within the mass of air as a suspended load.

The two desert features that are directly the result of wind erosion are desert pavement and ventifacts. In the process of deflation, the wind blows across the surface of regolith, preferentially

The Colorado River carved out the Grand Canyon.
picking up and carrying away sand-sized and smaller particles and leaving behind a layer at the surface consisting of granule-sized and larger particles; this layer is called desert pavement. Because deposits of sand are not common in deserts, what one would encounter during a walk across a desert would be either desert pavement or bedrock. Windblown sand is an effective erosion agent. But many of the features commonly considered to be the result of windblown sand, such as pedestal rocks, are, in fact, the result of the combined efforts of weathering, mass wasting, and running water. Sandblasting produces ventifacts. Typically, a ventifact is a pebble-sized particle or larger that has undergone sand abrasion for a sufficiently long period of time to carve one or more flat surfaces called facets. It is not unusual to find ventifacts with multiple facets, which are most likely due to the particle being reoriented by a flash flood that swept across the valley floor, thereby presenting a new part of the particle to the oncoming wind. Wind is not a major agent of erosion. Even in the desert, the primary agent of erosion is water.

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**Suggested Reading**

Easterbrook, D. J., *Surface Processes and Landforms*.

**Questions to Consider**

1. What is the major difference between streams operating in humid versus arid regions?

2. What is the fundamental difference between the topography of the Basin and Range Province, as seen throughout Nevada, and that associated with the Colorado Plateau?
Glaciers’ ability to scour and sculpt the land is absolutely incredible. … There are about 5 million square miles of glacial ice around the world. Remember, that’s 80% of all the fresh water.

Glaciers are the second most important agent of erosion. Glacial ice forms in regions where it is cold enough for snow and ice to survive year-round. Four of the 5 million square miles of glaciers cover the Antarctica. Glaciers are of two types: continental glaciers and alpine or mountain glaciers. The glaciers covering Antarctica and Greenland are continental glaciers. Alpine or mountain glaciers occupy the high elevations of mountains. The ice in the Arctic is not glacial ice, which forms on land, but sea ice.

Glacial ice forms from snow that recrystallizes to form granular snow, which is, in turn, converted to glacial ice. The accumulated snow is transformed into glacial ice by a combination of sublimation, recrystallization, pressure melting, and refreezing. Sublimation converts the delicate snowflakes into vapor that instantly recrystallizes into a granular ice called firn or névé. The sand-sized crystals then undergo pressure melting at their points of contact. The water flows into the spaces between the grains and instantly refreezes, creating a mass of glacial ice.

Once the ice reaches a thickness of 150 feet, the weight of the overlying ice causes the ice at the bottom to become plastic and begin to move by plastic flow. Above the plastic layer, the ice is still brittle, and its surface is broken with cracks called crevasses. Because alpine glaciers exist in somewhat warmer climes, a layer of water develops at the base of the glacier, producing a wet-based glacier. Because alpine glaciers are wet-based and flow downhill, a typical rate of advance would be a foot or so per day. A continental glacier sits on, essentially, a large horizontal surface. How does it move? Because the snow is constantly falling and creating new ice, the ice collapses under its own weight and moves the glacier. Because continental glaciers form in polar regions, the bottom of the ice sheet is frozen to the
underlying rock, forming so-called dry-based glaciers. Typical rates of movement of continental glaciers would be about 15 feet per year.

Erosion by glacial ice is by two processes: quarrying (or plucking) and abrasion. During quarrying, blocks of rock are physically removed from the underlying bedrock and taken up into the ice. In the case of alpine glaciers, the quarrying is primarily driven by frost wedging. In the case of continental glaciers, the rock eventually succumbs to fatigue, cracks, and is pulled up into the ice. In both continental and alpine glaciers, the rock fragments taken up into the bottom of the ice serve as a gigantic piece of sandpaper or rasp file, eroding the underlying rock by abrasion.

The appearance of the land following alpine glaciation is quite different from that resulting from continental glaciation. Alpine ice forms in the headwaters of V-shaped, youthful mountain stream valleys. The growing ice mass begins to dig a bowl-shaped depression, called a cirque, by the process of quarrying. Alpine glaciers forming in adjacent valleys on both sides of a ridge eventually sculpt knife-edged mountain ridges called aretes. Alpine glaciers that tunnel through ridges give rise to high mountain passes called cols. Several alpine glaciers eroding around a mountain peak create a sharp mountain spire called a horn, for example, the Matterhorn or the Grand Tetons.

Eventually, the ice overflows the cirque and flows down the stream valley, converting the V-shaped youthful stream valley to the U-shaped cross-section of a glaciated valley as, for example, in Yosemite Valley. Because the sculpting by alpine glaciers is superimposed on the already stream-carved topography, the combination is responsible for some of the most spectacular scenery in the world, such as the Alps and the Northern Rockies.

The best example of continental sculpting can be seen from the eastern foothills of the Canadian Rockies to the Atlantic coast. Rather than reducing the relief of the affected region, advancing continental glaciers actually increase the relief of the bedrock surface. The low relief of regions subjected to continental glaciers is largely the result of deposition as the glacier retreats. This type of landscape is seen in Ohio and Indiana and in the Finger Lakes region of upstate New York.
The debris deposited by glaciers is called till, which is both poorly sorted and unstratified. Unstratified means that the debris has no internal layers. Sorting refers to the number of particle sizes contained within a deposit. The poorest sorting is exhibited by a deposit that contains a mixture of all sizes.

The most important glacial till deposit is called a moraine. When a glacier advances to its most distant point and melts, its load is deposited in a ridge along the leading edge of the glacier, called a terminal or end moraine. Should the glacier begin to advance, it will overrun the terminal moraine and reestablish another at the more distant point of advance. As the glacier retreats, it spreads out the debris over the ground in a layer called ground moraine. When a glacier temporarily stops during a retreat, a deposit will form along its edge identical in appearance to the terminal moraine, called a recessional moraine. All glaciers deposit terminal, ground, and recessional moraines.

The debris that accumulates along the edge of a retreating alpine glacier will be deposited at the edge of the ground moraine against the bottom of the valley wall as a lateral moraine. The debris carried on the inner surface of an alpine glacier will eventually be deposited on top of the ground moraine in the middle of the valley, forming a medial moraine.

Not all glacial deposits are poorly sorted. At the terminus of a glacier, turbulent meltwater pours through the terminal moraine, picks up whatever
materials its turbulence allows, and deposits the material as a well-sorted deposit out in front of the glacier. In the case of a continental glacier, the deposit is called an outwash plain. In the case of an alpine glacier, the well-sorted deposit is called a valley train.

**Suggested Reading**

Benn, D., and D. Evans, *Glaciers and Glaciation*.

Easterbrook, D. J., *Surface Processes and Landforms*.

**Questions to Consider**

1. Specifically, why are regions sculpted by alpine glaciation so different in appearance from those sculpted by continental glaciation?

2. What physical evidence in the moraine deposits was used to indicate that the Great Ice Age consisted of several major advances and retreats of the ice sheet?
Of all the fresh water on Earth, it’s tied up in two places: glaciers and groundwater. Now, 80% is in glaciers, but remember now, that’s glacial ice. That’s not going to be available to us for a very, very, very long time. So when it comes to fresh water, groundwater is it.

Our largest readily available source of fresh water is groundwater—that portion of water that falls on Earth’s surface and returns to the ocean underground. It represents approximately 20% of all fresh water on Earth. In the U.S., 40% of all fresh water comes from groundwater resources, with nearly half the states obtaining half their water from groundwater. At the present time, groundwater supplies about 50% of all water used for drinking, 40% of water used for irrigation and crop growth, and 25% of the fresh water demands of industry.

The two parameters of rock that allow the storage and transmission of groundwater are porosity and permeability. Most rocks are not totally solid but rather contain openings. Openings exist between the mineral grains called pores. The amount of space represented by the pores is called porosity. Unless the pores or cracks are interconnected, water will not flow through the rock. The degree to which the pores and cracks are interconnected and, therefore, the ease with which water will flow through the rock is called permeability.

Depending on the combination of porosity and permeability, rocks are classified as aquifers, aquitards, or aquicludes. An aquifer is any rock that possesses sufficient porosity and permeability to yield water with ease. An aquitard is a rock that has sufficient porosity and permeability to yield water but not in significant amounts. An aquiclude is a rock that, because of very low porosity, permeability, or both, produces little or no water. The ideal aquiclude would include unweathered igneous and metamorphic rocks that have few open areas between the interlocking grains. The conditions of temperature and pressure under which igneous and metamorphic rocks form eliminate any porosity and permeability. Another ideal aquiclude
could be unweathered chemical limestones, in which the dense, fine-grained nature of the original rock precludes the formation of significant porosity or permeability.

Rocks possessing high porosity and permeability are ideal aquifers. First among these are sandstones. By virtue of how they form, sandstones almost always have high porosity and permeability. In certain regions, coals are excellent aquifers, because of the cracks (cleat) that characteristically exist in coal. Although not an example of a rock, unconsolidated, coarse-grained sediments, such as sands and gravels, make excellent aquifers.

As rocks that make ideal aquicludes are exposed to weathering, both porosity and permeability can be induced. For example, unloading results in the formation of cracks, leading to fracture porosity in rocks. These rocks become aquitards and may eventually become aquifers. Shales may have very high porosity, but their composition precludes the development of permeability.

As rainwater or melting snow and ice seep into the ground, they percolate downward until the pressure exerted by the overlying rock eliminates all porosity and permeability. In most regions, this will occur at about 2,500 feet. From that point, the rocks begin to fill with water to a level below the surface called the water table. The water table is the contact between the zone of saturation and the zone of aeration. The distance to the water table depends primarily on regional precipitation, with the depth increasing with decreasing precipitation.

In general, the water table follows the lay of the land, except that it is closer to the surface under valley floors. Anywhere that standing or flowing water exists on Earth’s surface, the water table has risen above a topographic low. The surface of water in wetlands, ponds, lakes, or streams is where the water table has cut across a topographic low. Seasonal change in the level of water in such bodies reflects a change in the elevation of the water table with changing amounts of precipitation. During prolonged droughts, such bodies may disappear as the water table drops below the surface of the ground. The water seen flowing in a stream is actually groundwater that has entered the stream channel from below.
There are two types of water tables: regional and perched (or hanging).

- The regional water table is so named because it underlies the entire region. For any region, there is only one regional water table. Most wetlands, lakes, ponds, and streams are the result of the regional water table coming to the surface across a topographic low.

- Perched or hanging water tables occur above the regional water table, where any number can exist. Invariably, perched water tables are the result of layers of impervious shales located between the surface and the regional water table.

Removing large volumes of rock from a region for road construction or mining may interfere with hanging water tables and, ultimately, have a negative impact on the regional water table.

Aquifer systems are classified as either unconfined or confined. Aquifers associated with either regional or perched water tables are called unconfined aquifers. The term unconfined refers to the fact that there is a vertical component of water movement between the aquifers; that is, the water can move from one aquifer to another. Water produced from unconfined aquifers will rise to the water table.

A confined aquifer is not associated with either regional or perched water tables. The requirements for a confined aquifer are usually a highland adjoining a lowland, with an excellent aquifer sandwiched between two excellent aquicludes underlying the lowland and coming to the surface in the highland. Because water entering the aquifer is confined, pressure develops within the aquifer in exactly the same way that pressure develops in a swimming pool being filled with water. Within a confined aquifer, an umbrella-shaped pressure surface extends outward from the surface of the water in the aquifer. By definition, is any well that produces from a confined aquifer. … The advantage of free-flowing is pretty obvious: You don’t have to pump on those.
recharge area, eventually intersecting the aquifer at some distance from the recharge area.

The water from wells drilled into confined aquifers (artesian wells) will rise to the pressure surface. Thus, no pumping is necessary. Many of the aquifers in the Great Plains are confined systems, which allowed settlers there in the early to mid-1800s to transform the region into productive farmland.

### Suggested Reading


### Questions to Consider

1. Why do streams, lakes, and ponds experience seasonal changes in water level?

2. What primarily determines whether a rock will be an aquifer, an aquitard, or an aquiclude?
Lecture 24: The Production of Groundwater

This student one time asked me, “Who discovered that? Who discovered that you could dig a hole in the ground and the thing would fill with water?” Well, I’ll tell you who it wasn’t. It certainly wasn’t the Romans, because—think about it—if they had known that, they wouldn’t have built all those aqueducts.

Little did the Romans know that just for a fraction of the cost of building those aqueducts, they could have dug all the holes in the ground they wanted and had all the water they wanted. Probably the Chinese discovered that holes dug in the ground would fill with water. The Chinese have likely been drilling water wells for 3,000 years or more.

A water well is a dug or drilled hole that fills with water. Production of water from an unconfined aquifer system requires that the well penetrate the water table and intersect the number of aquifers needed to produce the required volume of water.

The average U.S. family consumes about 2,000 gallons of water per week. Although a single aquifer may produce the required volume of water, two or more aquifers usually must be intersected. As the water is pumped from a well drilled into an unconfined aquifer system, the water table surrounding the well is depressed in a cone of depression as the water drains from the rocks. The size of the cone depends on how fast the water is being removed relative to the rate at which it is being replaced from the aquifer system. Once pumping ceases, the water table will begin to rise as water returns into the well.

Overproduction from an unconfined aquifer system will result in the intersection of the cones of depression from adjacent wells and the subsequent lowering of the water table. To reacquire water, wells will need to be deepened to intersect additional aquifers. In time, the acquisition of groundwater for domestic use must be abandoned for water supplied by a municipal system.
Wells producing water from confined aquifers have nothing to do with water tables, either regional or perched. Artesian wells drilled into confined aquifers will produce water up to the pressure surface. Where the pressure surface is above ground, the water will *spout* into the air to reach the pressure surface, producing a free-flowing artesian well. Where the pressure surface is below ground level, the water will again rise to the pressure surface but will not reach ground level.

Overproduction from confined aquifers results in a progressive drop in the pressure surface. In time, free-flowing wells will be eliminated as the pressure surface falls below ground level. The end product of overproduction from confined aquifers is the draining of the aquifer. The results of overproduction can be seen in the Dakota Sandstone aquifer, which extends from the front range of the Rocky Mountains across much of the Great Plains.

A municipal water system is an artificial confined aquifer. In the typical municipal water system, the water is pumped to a holding tank located at the summit or highest point and placed on stilts. The water is then fed through water mains to individual users. A pressure surface extends out from the level of water in the reservoir in exactly the same way the pressure surface extended out from the highland recharge area, eventually intersecting the water mains. The pressure a user experiences at the faucet is determined by the vertical distance between the user and the pressure surface. For water to be provided to new users beyond the limit of the pressure surface, other water reservoirs must be built and connected into the system of water mains to allow all users to be located below one or more pressure surfaces.

A renewable resource is defined as a material that, once mined or harvested, will be replaced by a new unit of material within a reasonable amount of time. A reasonable amount of time is considered the average human lifetime. An example of a renewable resource is timber.

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**If you don’t learn anything else from these lectures on groundwater, just learn that groundwater is *not* a renewable resource. … Once you produce it, it’s gone.**
The view held by many that groundwater is a renewable resource comes from the observation that a gallon of water removed from a well today seems to have been replaced by another gallon the next day. The gallon that flowed into the well overnight was not new but one that had been in the system. When we consider the rate at which water moves through aquifers, it may take hundreds of thousands of years to replace a mined gallon of groundwater with a brand-new gallon. Any time water tables and pressure surfaces drop, it means that water is not being replaced at the rate that it is being mined. Groundwater is a nonrenewable resource.

An excellent example of water being overproduced from an unconfined system is the Ogallala Formation, which is the largest single aquifer system in the United States. The first production of water from the aquifer began in the early 1800s; since that time, the water table has dropped considerably. Even if the removal of water from the Ogallala aquifer stopped today, the aquifer will not refill within the span of human existence in the region.

Suggested Reading


Questions to Consider

1. How do wells drilled into unconfined aquifers differ from those drilled into confined aquifers in terms of the mechanism of water production?

2. How does overproduction affect groundwater availability from unconfined and confined aquifers?
Karst Topography
Lecture 25

If I had to pick one feature that had to be the most impressive feature formed as a result of the activity of groundwater, it would have to be called karst topography. ... And it turns out that karst topography usually is in a valley—although I’ve seen these features developed on hilltops and ridgelines—but usually it is in the valley.

Karst topography is a particular lay of the land named after the Karst Valley in Yugoslavia and is usually found in valleys in humid regions. A characteristic of karst valleys is the absence of through-flowing streams. Any streams are rapidly subsumed underground in swallow holes. Equally characteristic of karst topography are sinkholes, typically arranged in orthogonal patterns.

Underlying the surface is a relatively thick layer (tens to hundreds of feet thick) of pure limestone—that is, 95% calcium carbonate, with the remaining 5% as insoluble residues. The limestone is characterized by cracks that intersect almost at right angles. There are two sets of cracks: In one set, the cracks align parallel to each other; the other set lines up perpendicular to the first set.

The downward percolation of acidic rainwater dissolves the limestone, in particular at the intersections of cracks (called joints). As the limestone is dissolved along the intersection of two joints, it forms cone-shaped holes. The surface becomes depressed, forming a sinkhole. Most sinkholes are solution sinkholes. Karst topography is typically grassy and often used for raising cattle.

Passageway development occurs when the limestone layer, at this point an aquitard, is completely below the water table. The water runs through the
joints, forming thin passageways that turn at right angles. After millions of years, the diameter of the passageways increases to become tunnels that form octagonal patterns below the water table. During this time, the surface of the land and the regional water table are being lowered relative to the limestone layer, which becomes a super-aquifer. Eventually, the result is caves and caverns. When the water table drops below the tops of the passageways, a zone of aeration develops that may ultimately extend throughout the cave system. As the water table continues to drop, it reaches the cave floor. Surface waters may accumulate there in the form of ponds.

With the cave system now completely above the water table, the water percolating through the overlying limestone and heading toward the water
table must cross the cave system. Drops of water collect on the cave roof and eventually fall to the cave floor. With each drop, a tiny deposit of CaCO₃, commonly referred to as dripstone, forms at the point of drop formation and spatter. As this process continues for additional periods of geologic time, the cave becomes adorned with features collectively called speleothems. Conical structures called stalactites build down from the cave roof. Other conical structures called stalagmites build from the floor. Eventually, a stalactite and stalagmite may meet to form a pillar. In some cases, sheets of dripstone descend along a crack to form what spelunkers call bacon rind or bridal veils.

In regions where the cave system is still below the water table, the rock section above the cave roof is being supported by the groundwater in the cave. During long periods of drought, as the regional water table drops below the roof of the cave, the overlying rocks lose their support, and the cave roof collapses to form a collapse sinkhole. An earthquake shock wave, which moves rocks horizontally and vertically, can also cause caves to collapse into sinkholes. A problem with karst topography is the potential for groundwater contamination.

In addition to limestone, karst topography can also be produced with gypsum, though this is much less common than limestone. Finally, karst topography features karst towers, which are formed when weathering removes the top of the cave passageways. Examples can be found in southern China.

**Suggested Reading**


**Questions to Consider**

1. Why do solution sinkholes commonly occur in orthogonal surface patterns?

2. Under what conditions do speleothems form?
Groundwater Contamination
Lecture 26

I’d really like to go back and pick up a little bit more on the contamination of groundwater scene. It’s so important to us, and for what reason? Fifty percent of my drinking water and your drinking water comes from it, you see. So I think anything that we should emphasize to people is to understand what the potential problems are.

The potential sources of groundwater contamination are legion. Although solid waste from mining and agricultural waste are major problems, we will limit our discussion to two of the most prevalent examples of potential groundwater contamination. Garbage is a major problem. Every American generates about 4½ pounds of garbage every day, of which about 40% is waste from paper products, 18% is yard waste, 8% is plastics, 8% is glass, and 7% is food waste. Until 1976, garbage was typically disposed of in open-air solution sinkholes, which had significant potential for contamination.

In 1976, laws were enacted to prohibit the construction of such sinkholes and to require sanitary landfills. The potential for contamination decreased, although it has not been entirely eliminated. Ideally, the landfill is constructed over an aquiclude, for example, shale. The use of combinations of impervious plastic liners with compacted clay seals isolates the refuse from the surrounding regolith and bedrock.

Furthermore, the garbage is compacted to reduce porosity and permeability in the material itself. Perforated piping allows for the detection of effluence, which can be collected and treated for safe disposal. In larger landfills, the gases generated within the decomposing materials can also be collected and used as a fuel to generate electricity. When the landfill reaches capacity, it is again covered with plastic, and vegetation is planted on top. The land can be reclaimed for use as a park or golf course.

Problems arise when landfills are filled to capacity and state or municipal law prohibits the creation of a new landfill. Garbage then has to be trucked
to another locale willing to take it (for a price). One solution to the landfill
problem is to use the material as a source of energy by incineration. According
to estimates, if we were to burn the material we now place in landfills
(called biomass), we could generate approximately 10–15% of the energy
budget of this country. Of course, the toxins generated from incineration
must be removed, but technology exists to accomplish this. A problem with
incineration is that some states prohibit the
process. Recycling is another possible solution,
except that it is expensive; some towns have
stopped recycling garbage for that reason.

Another common example of groundwater
contamination can be found in coastal regions,
where groundwater may provide 100% of the
fresh water. At the point where the fresh water
returns to the ocean, the lower density of the fresh
water causes it to ride out over the encroaching
saltwater, thereby keeping the saltwater at bay.
Increased use of groundwater in coastal regions
results in a rise in the saltwater/fresh water interface, a process known as
saltwater encroachment. Eventually, the saltwater/fresh water interface rises
into the bottoms of wells and the wells must be abandoned. In some areas,
attempts have been made to depress the saltwater/fresh water interface by
constructing large ponds to divert rainwater underground.

Another feature associated with groundwater is geothermal activity.
Throughout the world are countless places where water is heated either by
the geothermal gradient or by underlying magmas that come to the surface.
The geothermal gradient refers to the temperature increase with depth within
the crust of about 25°C to 30°C per mile of depth. In many areas, hot springs
are created by the geothermal gradient as groundwater percolates downward
along fractures, perhaps faults; becomes heated; and returns to the surface.

In other regions there exist hydrothermal features created when groundwater
is heated by near-surface magma bodies. These are rare, existing only in
Yellowstone Park, in the northwestern corner of Wyoming; Iceland; and the
northern island of New Zealand. The hot water created by the magma rises to
the surface, and as pressure is released, the water spouts to the surface in the form of a geyser.

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**Suggested Reading**

Barcelona, M., *Contamination of Groundwater, Prevention, Assessment, Restoration*.

www.groundwater.org

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**Questions to Consider**

1. What kinds of materials constitute the great volume of garbage we now bury in landfills?

2. How does one explain the presence of hot springs in regions that do not have underlying sources of magma?
As a geologist, I would consider rock deformation to be just the epitome of geology because the things we’re going to talk about, folds and faults, this is what creates mountains—and mountains is where it’s at.

Geologic structures are the result of the interplay among stress, strain, and strength. Deformation creates mountains. It can be defined as any process in which rock changes in size and/or shape. Deformation is of three kinds: faults, folds, and joints. Stress is any applied force; strain is a response to stress. Before any material can undergo strain in response to stress, its strength must be exceeded. Strength is the ability to withstand stress without strain. Every material has an inherent strength that must be exceeded by an applied force before anything will happen. Once the stress has exceeded the strength, the material will undergo strain or deformation.

Stress is of two basic types: tension (pull) and compression (push). In tension, the forces operate in opposite directions and directly away from each other. Examples of tension include pulling a drawer open or stretching taffy. In compression, the forces act toward each other in two different arrangements. In non-rotational compression, the forces act toward and directly opposite to each other. The hitting of a nail with a hammer or holding a pen are examples of non-rotational compression. In rotational compression, the forces act toward each other but not directly opposite. Because whatever is being acted upon tries to rotate, we refer to this type of compression as rotational compression. Examples of rotational compression would be twisting the cap off a bottle, turning a doorknob, or spreading butter on bread.

There are three types of strain: elastic, plastic, and brittle. Strain, or deformation, is always accompanied by a change in size, shape, or both. In all cases, once the strength of a material is exceeded, the first response will always be elastic. In elastic strain, the applied energy is absorbed and stored as the material.

Deformation simply is any process whereby something changes in size and/or shape.
undergoes deformation. As long as the force continues to be applied, the energy will continue to be absorbed and stored. Once the applied force is released, the material will return to its original size or shape, and the stored energy will be released in usable form. The importance of elastic strain is the ability of the material to store and release energy.

Examples of an elastic response include the stretching and release of a rubber band. After it is released, the rubber band returns to its original size and shape, with no indication that anything has happened. Another example is the momentary impact of a tennis ball on a tennis racket. Both the ball and the strings on the racket deform, momentarily absorbing and storing the energy applied by the tennis player, then returning to their original shapes and sizes as energy is released when the ball is driven back. Every material has an elastic limit that restricts the amount of energy that can be stored during elastic deformation. Only after the elastic limit has been exceeded can a material respond by plastic or brittle strain.

In plastic deformation, once the elastic limit is exceeded, all the stored energy plus any energy applied subsequent to the exceeding of the elastic limit will be internally consumed as deformation takes place. Plastic deformation is permanent. An example of a material that undergoes plastic deformation is modeling clay.

Materials that undergo brittle strain after the elastic limit has been exceeded will break. Think of the ringing of a bell, which is an elastic response. The energy of the clapper hitting the side of the bell is released in the form of a sound wave that our ears interpret as a tone. In the same way, a plate may be thought of as a flat bell. If it is dropped but doesn’t break, it makes a sound similar to a bell tone. On the other hand, if the plate is dropped with more force, it may break into three or four pieces, each of which gives off its own tone. The melding of the tones is the sound of breaking glass. The plate, or any material, breaks to provide additional surface area from which to release the stored energy; the number of breaks depends on the amount of energy that must be released.

Again, if the plate is dropped without much force, it may only crack to provide the extra surface needed to release energy. But if more force is
applied—if the plate is thrown at a wall, for example—it shatters to provide the surface area needed to release the greater amount of energy. Obviously, brittle deformation is also permanent.

The elastic, plastic, or brittle response of rocks to stress is manifest in the geologic structures of folds, joints, and faults. Rock folds are an example of a plastic response, a permanent deformation. Rock faults and joints are examples of a brittle response. A fault forms where there has been movement and a good deal of energy was released. A joint forms where there has been no appreciable movement and less energy was released.

Can a rock have an elastic response? Yes, evidence exists for this phenomenon in Canada. Two million years ago, a thick sheet of ice covered Canada and part of the northern United States. The continental lithosphere was bowed down under the weight of the ice as the asthenosphere flowed out from beneath the region. When the ice finally melted back to the current location of Greenland, water entered the depression to form Hudson Bay.

Today, the lithosphere under Hudson Bay is slowly rising, indicating that the lithosphere is returning to its original position, as with an elastic response. If this continues, ultimately there will be no indication that the deformation ever took place.

### Suggested Reading


Twiss, R. J., and E. M. Moores, *Structural Geology*.

### Questions to Consider

1. How is the elastic limit of a material related to the three types of strain that may result from the application of stress?

2. Assume a material has been stressed beyond its strength and begins to undergo strain. What will be the order in which the three types of strain will occur, from first to last?
In this lecture, we’re going to talk about kinds of structures. Now, there are three basic kinds: folds, faults, and joints. In this lecture it will be folds. We’ll talk about the plastic deformation in this particular lecture.

Rock structures form as a result of the application of stress beyond the strength of the rock. As we mentioned, the three basic rock structures are folds, faults, and joints. Folds result from compression. When you fold something, you reduce its size. Models also involve a reduction of size, both in dimensions and in material strength. As mentioned earlier, a flume is a model used to study how streams pick up and transport material. The theory of laminar flow was the result of flume experiments.

Geological models are built to gather data and form theories. Anyone can model a fold by simply pushing the opposite sides of a sheet of paper toward each other, which generates a nonrotational compressive force. The trend of the fold is perpendicular to the force. When you do the same thing with a ream of paper, the same thing happens, but some sheets move across each other. This happens in nature, for example, with shale. The grooves, or striations, thus formed are called slickensides and form parallel to the applied force. Special modeling clay, called Kaolinite clay, has been used to test folding and faulting in an apparatus called a clay cake table. A lot of data have been gathered that way, though such modeling has had its critics. Nowadays, modeling is done with computer programs to discover, for example, what generates Earth’s magnetic field or why the magnetic field reverses from time to time.

There are three types of folds: monoclines, anticlines, and synclines, all formed from compression. The simplest of the three types of folds is the monocline: The rocks slope in one direction. Monoclines commonly form around the margins of local or regional uplifts or above zones where rocks have been broken and displaced vertically along faults. The edge of the Colorado Plateau is an example. Anticlines and synclines are almost always
associated with each other. The anticline is an up-warp in Earth’s crust, while a syncline is the adjacent down-warp.

Several basic parameters are used to describe folds, including the amplitude of the fold, the orientation of the axial plane, the strike and dip of the limbs of the fold, the strike of the fold axis, and the plunge of the fold axis. The amplitude of the fold is simply the distance between the top of the anticline to the base of the adjoining syncline. The amplitude is determined by the duration or strength of compressive forces. The axial plane is an imaginary plane, drawn parallel to the fold, that attempts to bisect the fold. The limbs of the fold refer to the rocks that dip away from the axis of the anticline or toward the axis of the adjoining syncline.

Strike and dip are used to describe any planar surface, such as axial planes or limbs. The strike is the direction of the line of intersection of the plane and the horizontal relative to the north geographic pole. Dip is the angle between the plane and the horizontal, measured perpendicular to the strike and identified by direction. The fold axis is the line of intersection between the axial plane and the limbs of the fold. The plunge of a fold is the angle between the axis and the horizontal. Folds come to an end by “plunging.”

Based on the angle and direction of dip of the limbs relative to the axial plane, folds are described as symmetrical, asymmetrical, overturned, and recumbent. A symmetrical fold is one where the axial plane is vertical, and the limbs dip away from the axial plane in opposite directions at the same angle of dip. In general, symmetrical folds are generated by horizontal nonrotational compression, with increased compression resulting in an increase in fold amplitude and a concurrent decrease in the distance between adjacent axial planes.

In asymmetrical folds, the axial plane inclines, and the limbs dip away from the axial plane but at different angles of dip. Most asymmetric folds form by horizontal rotational compression, with continued compression resulting in an increase in asymmetry as the axial plane is tipped in the direction of maximum compressional force.
An overturned fold is one in which the axial plane inclines and the limbs dip in the same direction as the axial plane. Overturned folds are the result of continued deformation of asymmetrical folds. A recumbent fold is one in which the axial plane approaches the horizontal. Recumbent folds form under the most extreme conditions of folding.

Most of the great mountains of the world are referred to as foldbelt mountains because folds are a major component of their overall structures. An example of a foldbelt mountain range is the Appalachian Mountains. We can determine how the Appalachians formed by examining physiographic provinces, that is, regions of common rock types, structures, history, and topography. For the Appalachians, these provinces are labeled, from east to west, as follows: Piedmont, Blue Ridge, Great Valley or Shenandoah, Valley and Ridge, High Plateau, and Low Plateau.

The folds exposed in the Appalachians show a progressive change in style from east to west. The easternmost folding, the Piedmont, is a highly deformed recumbent folding. Westward, the folds reflect a decrease in compressional intensity, with overturned folds in the Blue Ridge Province and highly asymmetric folds in the Valley and Ridge Province. Further west, in the High Plateau, the folds are symmetrical but with high amplitude. By the time we reach the far western Low Plateau, the amplitude is very small; the limbs of the fold have only a 2° to 3° slope—basically, horizontal. This shows that the energy came from east to west. What made the systematic change from east to west? From our knowledge of plate tectonics, we know that the continent-to-continent collision that created the supercontinent of Pangea was what created the Appalachians.

Suggested Reading


Twiss, R. J., and E. M. Moores, *Structural Geology*.
Questions to Consider

1. What would be the order in which the various kinds of folds will develop under continued application of compressional stress?

2. Under what geologic scenario would folds be expected to form?
A fault, by definition, is simply any break in the Earth’s crust along which there has been measurable movement. It really doesn’t say how much it has to move; just as long as you can measure it, it would be a fault. A joint, on the other hand, is a break in the Earth’s crust along which there has been no appreciable or measurable movement.

About 75% of faults form within a zone from Earth’s surface to a depth of about 40 miles—the average thickness of Earth’s crust. Only 20% of faults fall in the zone from 40 miles to 200 miles below the surface, and 5% from 200 miles to 450 miles below the surface. Below that, the rocks become totally plastic, and folds form rather than faults. Faults are of four basic types: normal, thrust (with an angle less than 45° relative to the horizontal) or reverse (with an angle greater than 45° relative to the horizontal), strike-slip, and transform.

The rock masses on opposite sides of normal or thrust faults are referred to as the hanging wall and the footwall, terms that were coined by miners who encountered faults while following beds of coal or mineral lodes. The footwall is the rock mass below a fault plane. The hanging wall is the rock mass above the fault plane.

Strike and dip are also used to describe the orientation of the fault plane. The strike of a fault plane is the direction of the line of intersection between the fault plane and the horizontal relative to the north geographic pole. The dip is the angle between the fault plane and the horizontal, plus the direction at which the fault plane slopes away perpendicular to the strike.

The displacement of a fault is the actual distance of movement along the fault plane. The vertical component of movement is called the throw. The horizontal component of movement is called the heave. If the throw is less than the heave, the result is a low-angle fault. If the reverse is true, the result is a steep or high-angle fault.
Normal faults form under tensional forces, with the hanging wall moving down relative to the footwall. The major sites of normal faulting are the divergent plate margins. The edges of continents are examples. Normal faults also form in regions that have been subjected to uplift in response to tensional forces. For example, a massive crustal block rising 45 million years ago resulted in the formation of the Colorado Plateau and the Basin and Range Province.

Apparently, the rocks of the Colorado Plateau were thick enough to resist deformation. As a result, they show little or no deformation, except for monoclinal folds and normal faulting along the plateau margin. Because the western portion of the crustal block, centered over Nevada, was thinner, tensional forces created many north-south–trending normal faults. Within this region, called the Basin and Range Province, normal faulting occurred in two scenarios. In the first, successive faults all dip in the same direction, resulting in a rotation of the block between faults and giving rise to a mountain range along one edge and a basin on the other. In the second scenario, faults alternate in dip direction, resulting in an up-thrown block called a horst that forms a mountain range and down-thrown block called a graben that forms a basin.

Most thrust or reverse faults form in response to nonrotational compressive forces and are characterized by the hanging wall having moved up relative to the footwall. Again, the difference between thrust and reverse faults is the angle of the fault plane, with thrust faults having an angle of less than 45° and reverse faults greater than 45°. A large-scale site of a thrust fault is a zone of subduction where one continental plate thrusts against another, for example, the west coast of South America. Here, the footwall has plunged beneath the hanging wall. Because the angle is greater than 45°, the result is a reverse fault. The zone of subduction associated with the Andes Mountains is a reverse fault.

Where the zone of subduction is further offshore, the footwall dives beneath the hanging wall and the angle is shallower than 45°, resulting in a thrust fault. When andesitic magma comes to the surface, an island arc is formed. The Japanese Islands are an example of this.
Strike-slip faults form from rotational compression, with the fault plane oriented vertically and parallel to the direction of applied force. The displacement of strike-slip faults is horizontal, with little or no vertical movement. Because the fault plane is vertical, the terms hanging wall, footwall, heave, and throw are not applicable. Strike-slip faults are described as either right-lateral or left-lateral, depending on the orientation of the forces and the relative movement of the rocks on opposite sides of the fault from the viewer. The best-known example of a right-lateral strike-slip fault in the United States is the San Andreas Fault.

Oceanic ridges are cut across by thousands of transform faults that allow the lithospheric plates to move on Earth’s spherical surface. At first sight, transform faults appear to be strike-slip in character, and indeed, the central portion of the fault shifts in a strike-slip motion. However, the fault also possesses two ends, along which the movement of the oceanic crust on opposite sides of the fault is in the same direction, albeit at different rates. At some point when the rates of movement on opposite sides of the fracture become equal, the fault terminates.

Joints are breaks in Earth’s crust along which there has been little or no measurable movement. Of all geologic structures, joints are by far the most common, being found in all exposed rocks. Perhaps the most common occurrence is in the layers of sedimentary rocks. Joints can be of three types: shear, tension, and columnar. Shear joints form by the application of compressive forces and occur in sets that intersect at almost right angles. The direction of maximum compressive stress bisects the acute angle between sets of shear joints. Tension joints also form from compressive forces. They form parallel to the direction of maximum compressive stress. They seem to be less abundant than shear joints.

Columnar jointing is a special type of fracture set that forms in igneous rock bodies. Hexagonal in cross-section, columnar joints are fractures that result as the basaltic magma cools and shrinks, forming a structure called a devil’s postpile. The Palisades on the Hudson River’s west bank provides an example; there, the formation is composed of a thick sill, a layer of solidified basaltic magma.
Suggested Reading


Twiss, R. J., and E. M. Moores, *Structural Geology*.

Questions to Consider

1. How can joints be used to determine the direction of maximum compressive stress?

2. How would one go about determining whether a strike-slip fault was right- or left-lateral?
Earthquakes

Earthquakes and volcanic activity have to be the most exciting phases of geology, at least in my opinion. And the interesting thing about these two phenomena is that if you sort of go back in time, there’s always been a relationship between the two that has been known for a very, very, very long time.

For centuries, earth scientists have known where the major earthquakes occurred. They also knew they occurred in the same locales as the most violent volcanoes—the Ring of Fire in the Pacific Ocean basin, the Mediterranean-Himalayan zone, and the Indonesian zone. It was believed that one phenomenon was the cause of the other. With the advent of the theory of plate tectonics, we know that it is not a question of cause and effect; both volcanoes and earthquakes result from the activity of convergent plate or divergent plate margins, with convergent plate margins producing the most violent eruptions.

The reason why [earthquakes and volcanoes are] associated with each other is because they’re both associated with the same thing: zones of subduction. You see, we never knew that until plate tectonics came onto the scene.

The volcanism that occurs along zones of subduction is extremely violent, whereas the volcanism at oceanic ridges—for example, Iceland—is in the nonexplosive Hawaiian phase. The difference lies in the difference between magmas. Andesitic magma coming to the surface in the zone of subduction is full of gas and is always explosive. Basaltic magma, erupting at an oceanic ridge, on the other hand, brings very little gas to the surface and erupts with low intensity.

To explain why earthquakes associated with convergent plate margins are of much higher magnitude than those associated with divergent plate margins,
we must review our discussion of stress and strain. Under compression, rocks are very strong, whereas under tension, rocks are weak.

The many columns that characterize ancient Greek architecture indicate that the Greeks did not understand how to overcome the inherent weakness of rocks under tension. The ancient Romans invented the arch, the secret of which is the keystone at the top. Because the keystone acts as a wedge, the contact between the keystone and the adjacent component of the arch is under nonrotational compression, which is transferred throughout the structure. The arch works because rock is strongest under nonrotational compression.

The amount of energy stored before reaching the elastic limit is determined by the inherent strength of the rock. Because rocks are very strong under compression, the amount of energy stored during the elastic phase of deformation and released during brittle failure will be potentially large. Conversely, rocks are inherently weak under tension, meaning that little energy is stored during the elastic phase of deformation and released during brittle failure. Convergent plate margins at zones of subduction are subject to enormous compressive forces. Thus, earthquakes associated with these areas are of potentially high magnitude. Earthquakes associated with divergent margins at rift zones, rift valleys, and oceanic ridges are the result of tensional forces and are always of low magnitude.

The energy released during faulting is in the form of shock waves, referred to specifically as seismic shock waves. In general, shock waves are of two types: shear waves and compression waves. Shear waves can be transmitted
only through solids; consider that only solids can be “sheared.” The particles in a solid material through which the shock wave is propagated are moved perpendicular to the direction of propagation.

Compression waves can propagate through solids, liquids, or gases. As compression waves propagate, they move the materials back and forth in the direction of propagation. The best model to illustrate a compression wave is the toy spring called a Slinky. Our ears respond to compression waves that our brains interpret as sound.

Two important points are used to locate the origin of earthquake energy: focus and epicenter. The focus of an earthquake is the point at which the energy is released. The epicenter of an earthquake is the point on Earth’s surface immediately above the focus. For earthquakes occurring at Earth’s surface, the focus and epicenter are the same point.

Because faulting is a brittle response, most earthquake foci are located at Earth’s surface, where the rocks are most brittle. The number of earthquake foci decrease in frequency with depth. The foci of earthquakes are categorized as shallow, intermediate, and deep. Shallow-focus earthquakes occur from Earth’s surface to a depth of about 40 miles. Seventy-five percent of all earthquakes are shallow focus. Intermediate-focus earthquakes occur from a depth of 40 miles to about 200 miles. The frequency of intermediate-focus earthquakes drops to about 20%. Deep-focus earthquakes occur down to depths of about 400 miles. Earthquakes do not occur below this depth because the rocks become totally plastic.

Earthquake shock waves are categorized as body waves and surface waves. Body waves originate at the focus and are propagated through Earth’s interior. Body waves are both shear and compression in type, with both types of wave following the exact same path. The shear body waves are designated s-waves. The compression body waves are designated p-waves. Body waves are very low amplitude and very high velocity. The materials through which they pass experience a very small amount of movement. The body waves pass through Earth at a velocity of 24,000 mph. Because the epicenter is the point closest to the point of energy release, the epicenter is the point on Earth’s surface where the energy is at a maximum.
Surface waves originate and spread out from the epicenter. In contrast to body waves, the amplitudes of surface waves can be high enough to be seen as they propagate across Earth’s surface but travel at much lower velocities. Surface waves are of two types: Love waves and Rayleigh waves. Love waves are shear waves and consist of the horizontal portion of shear, moving Earth’s surface back and forth horizontally and perpendicular to the direction of propagation. Rayleigh waves are a combination of the vertical component of shear plus the to-and-fro motion of compression, resulting in a rolling motion as they move across Earth’s surface. Surface waves are responsible for most of the damage resulting from an earthquake, with Love waves being more destructive than Rayleigh waves.

**Suggested Reading**

Hough, S. E., *Earthquake Science: What We Know (and Don’t Know) about Earthquakes.*

**Questions to Consider**

1. What is the source of the energy released in the form of an earthquake shock wave?

2. Why are the earthquakes associated with convergent plate margins always of greater magnitude than those associated with divergent plate margins?
We’re going to talk about damage due to earthquakes now. … First of all, there are two words that we use to describe earthquakes: One is intensity and the other is magnitude. Now, these are totally different. Intensity refers to the amount of damage that an earthquake causes. Magnitude involves the actual amount of Earth movement.

The severity of an earthquake can be reported in terms of either intensity or magnitude. The intensity of an earthquake refers to the observed results of the quaking and the amount of resulting damage. An earthquake’s magnitude involves determining the amount of Earth movement and the amount of energy released based on actual measurements of Earth movement.

The first comprehensive study of earthquake intensity was performed by two seismologists, Rossi and Mercalli. The result of their studies were scales of damage, in which each step is a verbal description of what one would expect to experience or see. Because both scales were similar, their results were combined in what is referred to as the Mercalli/Rossi scale or the modified Mercalli scale. Using this scale, an earthquake of magnitude 1 will be detectable only by sensitive scientific instruments. Major but repairable damage will occur at a magnitude of 6. A magnitude of 8 would not leave many buildings standing. At a magnitude of 9, the shock wave is visible. In all of known history, there have been only four or five earthquakes of a magnitude of 9. Another type of scale, the Richter scale, invented by Charles Richter, assigns a magnitude from 1.0 to 10.0, in which each next higher step in the scale represents 10 times the amount of Earth movement and 30 times the amount of energy released than the preceding step.

A great deal of research has gone into devising ways to build structures to resist earthquake damage. Realizing that there is no structure that is earthquake proof, ways have been tested to minimize damage. The type of building materials can affect the amount of damage.
• Buildings constructed of flexible materials, such as metal, have a better chance of survival.

• Wood is effective but is subject to destruction by fire.

• Steel and glass buildings, while flexible, are not practical because of the potential damage of the glass, which could rain down on the street.

• Masonry is too brittle.

A compromise is the construction of masonry components around a metal framework that serves to distribute energy throughout the building, rather than allowing it to concentrate in one place.

Observations have shown that structures whose foundations are anchored in bedrock have a higher tendency to survive an earthquake than those whose foundations are in unconsolidated materials. During the 1989 Loma Prieta earthquake that struck San Francisco, one of the highly damaged areas of the city was the Marina District, where condominiums had been built on top of sediment deposited into the bay following the great earthquake and fire of 1906. Engineering studies have shown that such loose material, though compacted, has a tendency to momentarily turn to a gelatinous consistency as the shock wave passes.

In California, by law, buildings must be bolted to their foundations. Larger buildings in California have shock absorbers. Electrical and gas appliances, such as water heaters, must be strapped and bolted to a wall, because fire is the primary cause of damage during an earthquake (from leaking gas

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mains and so on). Many lessons were learned from San Francisco’s great earthquake of 1906. In that disaster, approximately 80% of the city was destroyed by the combination of fire and earthquake. Firefighters were unable to control fires throughout the city because their water mains were severed by the same earth movement that had severed the city’s gas mains and fed the flames.

One of the most destructive earthquake-generated phenomena is the giant sea wave called a tsunami. Meaning “harbor wave” in Japanese, tsunamis are commonly referred to as tidal waves, although they have nothing to do with the tides. Most tsunamis are created by the release of earthquake energy from vertical fault movements within or along the margin of an ocean basin. Tsunamis cross the open sea with amplitudes rarely exceeding a foot but with speeds averaging 500 miles per hour. On reaching the shoreline, the increase in amplitude creates waves that can reach 100 feet high and drive onto land at speeds of more than 100 miles per hour, causing enormous destruction and death. The worst tsunami to hit the Japanese Islands occurred in 1896, when a wall of water estimated to be nearly 100 feet high crashed onto the eastern coastline of Honshu. Some tsunamis are generated by violent volcanic eruptions. The eruption of Krakatau in 1883, for example, generated a tsunami that washed over low-lying islands and swept more than 36,000 people to their deaths.

To warn inhabitants within and around the Pacific Ocean basin, the Seismic Sea Wave Warning System (SSWWS) was established in 1946. Earthquakes anywhere within or adjacent to the Pacific basin are monitored in Honolulu, Hawaii, with warnings broadcast throughout the Pacific.

The interesting thing is if you go to California, they’re probably the best state, probably in the world, in terms of designing things to withstand earthquakes.

Suggested Reading

Bryant, E., *Tsunami: The Underrated Hazard*. 
Hough, S. E., *Earthquake Science: What We Know (and Don’t Know) about Earthquakes*.

**Questions to Consider**

1. Fire causes more earthquake damage than any other single factor. Why?

2. As a potential homebuilder in an earthquake-prone region, what features could you incorporate into the design of your home to minimize earthquake damage?
Seismology
Lecture 32

Seismology is the study of earthquakes. ... Let me describe, first of all, the difference between two instruments. There’s a thing called a seismometer, and then there’s a thing called a seismograph.

An instrument whose name ends in -graph gives a permanent record of whatever was measured in the form of a -gram, while an instrument whose name ends in -meter measures but does not provide a recording of any kind. A seismograph provides a seismogram, while a speedometer provides no record. Seismometers existed long before the invention of the seismograph. The first seismometer was invented by the Chinese sometime in the 2nd century. Seismometers were the tools of the trade for nearly 1,500 years.

Sometime in the mid-1700s, the first seismograph was invented. The basic design was improved on in 1858 by an Italian physicist named Cavalleri, who used two pendulum-based instruments to record the maximum amplitude of both horizontal and vertical Earth motions. Cavalleri’s instrument consisted basically of a ring stand from which the pendulums were suspended, one on a string and the other on a spring. A pen extending from the pendulum drew a line on a piece of paper. The passage of the Love and Rayleigh waves would move the ring stand, while the pendulums, because of their inertia, would remain motionless. The instrument with the pendulum suspended on a string recorded the passage of a Love wave by drawing a line on a piece of paper placed on the base of the ring stand. The instrument with the pendulum suspended on a spring recorded the passage of a Rayleigh wave by drawing a line on a piece of paper attached to the upright of the ring stand. Combined, these two devices measured the amplitude and direction of the shock waves. The major shortcoming of these seismographs was the fact that they could not record any time-related component of an earthquake.

The problem of recording time-related events was solved in the late 1800s by an English engineer named John Milne, who replaced the flat recording surface with a rotating cylinder to which the recording paper was attached.
To record the horizontal motions of Love waves, Milne designed an instrument with a pendulum suspended horizontally. The vertical movement of Rayleigh waves was recorded with a vertical-pendulum instrument comparable to Cavalleri’s. As the cylinder was rotated and translated (moved sideways) along its axis by a clock mechanism, the recording pen scribed a timed, spiraling line on a piece of paper wrapped around the cylinder. When removed from the cylinder and laid flat, the resultant seismogram recorded seismic history over a period of time.

The modern seismic station consists of two horizontal-pendulum instruments oriented at right angles to each other and one vertical-pendulum instrument. The two horizontal instruments allow the recording of Love waves approaching from any direction. The vertical motion of the Rayleigh waves is recorded by the vertical-pendulum instrument. All seismograms are accurately timed by the recording of a signal sent out from synchronized cesium clocks, one of which is located at the Bureau of Standards at Fort Collins, Colorado. The fact that all seismographs worldwide are tuned to the same clock allows seismograms from around the world to be compared.

The two bits of information a seismologist wants to glean from every seismogram are the location of the epicenter and focus and the magnitude of the earthquake at the epicenter. The distance from a seismic station to the epicenter is determined by using the different arrival times of the p- and s-waves and the data from a time-travel plot available at the recording station. (The body waves arrive faster than the surface waves, and the p-wave [compression wave] is faster than the s-wave [shear wave].) The geographic location of the epicenter is determined by using the distance data from a minimum of three seismic stations plotted as a circle centered at the respective stations. By using the distance data as the radius of a hemisphere centered on the respective stations, the point where the three hemispheres intersect is the location of the earthquake focus.

I’m going to tell you right here and now, you cannot predict an earthquake—they’re like volcanic eruptions.
The magnitude of the earthquake at the epicenter can be determined from the data recorded at a single seismic station. The amplitude of the surface waves will be at a maximum at the epicenter and decrease away from the epicenter in a predictable fashion. Determining the amplitude of the surface waves at a particular seismic station and knowing how far away the earthquake occurred enables scientists to calculate the amplitude of the surface waves at the epicenter. The amplitude of the surface waves at the epicenter can then be used to calculate the Richter scale reading (giving the magnitude). The actual determination employs the use of a nomograph.

Like so many geologic events, including volcanic eruptions and slope failures, earthquakes cannot be predicted with the level of precision that would be of use to those potentially involved.

Suggested Reading

Bryant, E., *Tsunami: The Underrated Hazard*.

Hough, S. E., *Earthquake Science: What We Know (and Don’t Know) about Earthquakes*.

Questions to Consider

1. Why are two mutually perpendicular/horizontal-pendulum instruments required to record all incoming seismic waves?

2. What allows the data from a single seismic station and a simple nomograph to be used to estimate the Richter scale reading at a distant earthquake’s epicenter?
The Formation of Mountains
Lecture 33

The topic is mountains. As a teacher, I think of all the lectures we’ve had in this series, this is the one that probably is most frustrating for me.

Although no absolute definition exists, to most geologists, the term “mountain” can be applied to any topographic feature that rises more than 1,000 feet above the surrounding terrain. There are four types of mountains: volcanic, domal, block-fault, and foldbelt.

Volcanic mountains, as we have seen, are associated with three geologic scenarios: divergent plate margins, convergent plate margins, and hot spots. Mountains associated with divergent plate margins range from the thousands of cinder cones associated with rift zones, to Mount Kilimanjaro located in the East African Rift Valley, to the oceanic ridges, which are, in fact, the most extensive mountain ranges on Earth, with a combined length of about 40,000 miles. The cones of the oceanic volcanoes of the oceanic ridges are very broad based, with gently sloping sides (shield volcanoes). The oceanic ridge in the Atlantic, for example, is roughly 2 miles high from its base but 1,000–1,500 miles wide. Given that the Atlantic itself is only about 3,000 miles across, the oceanic ridge occupies one-third to one-half of the ocean floor. Scenically, the most impressive volcanic mountains are the island-arc and continental-arc volcanic mountain chains associated with the convergent plate margins, as we have already discussed. An example of an oceanic ridge rising over a hot spot above the ocean surface is Iceland. Part of the rift valley associated with the oceanic ridge can be seen running through the center of Iceland.

Although the epeirogenic (vertical) forces that create them are perhaps the most difficult to explain, domal mountains are the simplest both geologically and structurally of all the various kinds of mountains. The vertical forces responsible for domal mountains originate beneath the continental crust far from any plate boundary. The best explanation for epeirogenic forces is heat that accumulates under the continental crust, causing the rocks to expand.
The subsequent decrease in density and increase in buoyancy causes the hot rocks to rise and the overlying crust to dome. The resultant doming can be of either a local or regional type. An example of regional doming is the uplift of the continental crust in the Colorado Plateau.

The rocks underlying the Basin and Range portion of the Colorado uplift (situated in Nevada) are thinner than under the Colorado Plateau and, subsequently, weaker. Although the rocks of the Colorado Plateau were little affected by the tensional forces that developed, the rocks of the Basin and Range were broken by many parallel north-south-trending normal faults. The result of the normal faulting was the creation of block-fault mountains throughout the region. Block faulting occurs under two scenarios. In one case, the faults are parallel and dip in the same direction, resulting in a rotation of the block between the faults and forming a mountain ridge along one edge of the block and a down-thrown basin along the other. In the second scenario, the parallel faults alternate in dip direction, resulting in an up-
thrown mountain range bordered by fault scarps on both sides, a relatively flat summit, and a down-thrown block forming the adjoining basins.

An excellent example of local doming is the area on the South Dakota/Wyoming border known as the Black Hills. This is a north-south-trending dome about 50 miles wide and 100–150 miles long that rises to just over 7,000 feet above sea level. We do not know if heat caused this relatively small area to dome, but in the process of uplifting, the sedimentary rock that once covered the area was stripped away, exposing a core of granitic rocks. During the Archean period, 1.5 billion years ago, the rocks at the core of the Black Hills were formed through hydrothermal metamorphism and were injected with gold. The Black Hills were sacred to the Sioux Nation but were overrun by white prospectors in the late 1800s. All gold produced from the Black Hills today is restricted to rocks that go back to the Archean age.

Most foldbelt mountains are located near the edges of continents, with the core (a complex mixture of igneous and metamorphic rock) located seaward and the folded sedimentary basin landward. Much of our current understanding of the origin of foldbelt mountains arose from studies that began in the mid-1800s by an American paleontologist, James Hall, who was investigating the section of sedimentary rocks associated with what is now called the Valley and Ridge Province of the Appalachian Physiographic Provinces. Hall observed that while most sedimentary rocks were of shallow marine origin, the sedimentary rocks associated with the Appalachians were very thick.

Geologists were agreed that the marine sedimentary rocks formed from the sediments that accumulated on the continental shelf with an average depth of only about 600 feet. Hall’s main problem was to explain how tens of thousands of feet of sediments could accumulate in a part of the ocean that was, at most, only 600 feet deep. Hall’s conclusion was that the surface of the continental shelf continuously down-warped under the weight of the sediments, forming a giant syncline. A contemporary, James Dana, called the structure a geosyncline.

With the advent of the theory of plate tectonics, we now know that a wedge of sediment called a geocline begins to accumulate along the margin of
newly formed continents and continues to grow seaward for the lifetime of the ocean. The result is an ever-thickening sediment wedge, while a shallow marine environment is maintained over the continental shelf. A continent-continent collision compresses the geocline, folding it to ultimately become a range of foldbelt mountains. All the great mountains of the world are foldbelt mountains—the Alps, the Himalayas, and the Appalachians, for example. It is the force of a collision at the zone of subduction that makes the folds that become foldbelt mountains.

**Suggested Reading**


**Questions to Consider**

1. Why are most of Earth’s major mountain ranges located along the margins of continents?

2. What is the most logical source of energy for epeirogenic forces?
I want to conclude our discussion of mountain building with the introduction of something we call orogenic styles, ways in which the mountains are created. Remember, now, what an orogeny is: An orogeny is a mountain-building episode.

The term orogeny refers to the processes by which foldbelt mountains form, all of which involve massive, horizontal compression. (Epeirogeny is the process of vertical compression.) Foldbelt mountains form under three basic convergent scenarios: ocean-continent collisions, ocean-island arc-continent collisions, and continent-continent collisions. Foldbelt mountains have two parallel components, a complex core made up of a mixture of igneous and metamorphic rocks and a zone of folded and faulted sedimentary rocks.

The ocean-continent collision begins with the formation of a geocline along the margin of a continent adjoining an opening ocean. The coastlines of the supercontinent of Pangea would have been the sites of geoclines, accumulating sediment from the interior of the vast supercontinent. When Pangea broke up about 200 million years ago, the new continents of South and North America began moving westward, forming zones of subduction along their western margins as the oceanic lithosphere plunged below the continental lithosphere. Some of the stress along the zone of subduction was relieved by the formation of thrust faults that brought mixtures of igneous rocks, metamorphic rocks, and meta-sediments to the ocean surface along the zone of subduction as an accretionary wedge. The mixture of rock types within the accretionary wedge is called a melange.

The descending plate was subjected to increasing temperatures and pressure and was converted into metamorphic rock. At great depths, magmas began to form, as seawater and water provided from the dehydration of hydrous minerals initiated the melting of existing rocks. Continued formation of thrust faults eventually lifted the accretionary wedge to form a coastal mountain range. As deformation continued, andesitic magmas began erupting to the
surface (in stratovolcanoes), creating a continental-arc mountain range. Simultaneously, massive volumes of granitic magma were intruded into the edge of the continent.

While these events were shaping the edge of the new continent, the sediments that had previously accumulated in the geocline were being deformed by compressive forces into folds, as we discussed earlier. The axes of the folds paralleled the continental margin, with asymmetric folds forming nearest the continental margin and becoming more symmetrical inland. With time, the folded rocks nearest the continental margin began to resist further folding and broke along thrust faults that drove rocks inland. This sequence of events resulted in the Andes Mountains.

The early events of the ocean-island arc-continent collision are the same as those described for the ocean-continent collision. The difference in this scenario is that the zone of subduction forms further offshore. Once again, an accretionary wedge forms seaward of the island arc. As andesitic magmas continue to erupt to the surface, adding to the volcanic mountain chain, granitic magmas begin to intrude into the cores of the islands, progressively thickening the mass of the islands and resulting in the creation of an island-arc chain of volcanic islands, such as the Aleutian Islands.

As this process continues, granitic magma begins to rise to the surface, lifting the chain of islands, emplacing itself in the mass of volcanic rocks, freezing, and forming batholiths. This creates the complex core of volcanic islands found, for example, in the Japanese Islands. A back-arc basin forms between the island arc and the continent that accumulates sediments from both the island and the land side, adding to the geoclinal sediments already present. In some cases, rifting within the back-arc basin results in the formation of a marginal sea, such as the Sea of Japan. As compressive forces continue, the sediments within the back-arc basin or marginal sea are folded, faulted, and thrust up onto the continental margin in the form of stacked-thrust sheets of sedimentary rocks. Through this process, the Japanese Islands will eventually be forced landward. The sediments in the basin will be folded and thrust up on the edge of the Asian continent and come to resemble the Andes Mountains in South America.
Some of the truly impressive mountains of the world are examples of continent-continent collisions. To illustrate the continent-continent collision, we return to the breakup of Pangea, when a small fragment that was to become India headed northward. India had its own geocline, out in front, and was heading toward Asia. The ocean bottom was being subducted off the coast of Asia. On the Asian continent, an accretionary wedge rose high above the ocean. Between the volcanic-arc complex and the accretionary wedge was a basin, known as a fore-arc basin, which was accumulating sediment. When India’s geocline ran into the accretionary wedge of Asia, India’s geocline was thrust southward and folded into a foldbelt mountain range. The fore-arc basin was thrust northward on top of Asia, resulting in another foldbelt mountain range. The continental lithosphere of India was low-density rock, which uplifted as the Himalayas were formed. In fact, the Himalayas are still rising because of the buoyancy of that portion of the lithosphere. All this happened about 45 million years ago.

Another example of a continent-continent collision occurred about 350 million years ago when the continents of Laurentia (North America plus Greenland) and Gondwana (primarily Africa) collided, contributing to the formation of the supercontinent of Pangea, with a central, highly deformed core and fold belt mountains of sedimentary rocks on the west and east sides. The picture would have been similar to the Himalayas. When Pangea began to break up about 200 million years ago, the break occurred along the central core of the mountain range, with one-half of its fold belt mountains going westward with the newly formed North American continent and the other half with its fold belt mountains going eastward with the newly formed continent of Africa. Perhaps 100 million years later, any surface expression of those mountains would have eroded away, very close to sea level.

The Himalayas formed when India’s geocline ran into the accretionary wedge of Asia, creating a foldbelt mountain range.
However, about 60 million years ago, the entire eastern margin of North America, from the Mississippi to the outer edge of the continental shelf, was uplifted in a broad arch about 6,000 feet. Streams were rejuvenated, and a new topography resulted in the Appalachians. The basic rock structures of the Appalachians remained as they were when they were created at the time the continents of Gondwana and Laurentia collided. This crystalline core is visible in the Piedmont. The other half of the Appalachians—broken off when Pangea split up—became the Atlas Mountains in Africa.

Future mountain building will occur if Africa runs into Europe and, after that, if Australia collides with China. But those possibilities are in the very distant future. The bottom of the Mediterranean Sea is being consumed by a zone of subduction, which means that Africa is moving toward Europe. If the continents collide, the resulting mountain range will be equal in grandeur to the Himalayas. In the same way, the Indonesian zone of subduction is drawing Australia closer to China; the two may collide in the far distant future.

How long will any kind of a collision take to occur between Australia and the mainland of China? Well, it’s going to be a very, very long time, even geologically.

Suggested Reading


Questions to Consider

1. In what ways do orogenic and epeirogenic mountain-building forces differ?

2. In what ways do mountains created by continent-continent collisions differ from those formed by ocean-continent or ocean-island arc-continent collisions?
I’ve decided to devote the last two lectures of the course to a study of economic geology, the use of natural materials for the benefit of society. And the two materials I’ve chosen to talk about are coal and petroleum. And I chose those because those two materials provide 90% of all the energy budget of this country.

Coal comes from preserved wood. Good preservers of wood are swamps, where the oxygen content and microbial activity are very low. Microbial activity is lowered at pH levels of less than 3. Peat is wood that has been preserved in a swamp. When peat is buried, it becomes coal. Coal became a major source of energy when Thomas Newcomen invented the steam engine in 1705. It was James Watts who made the engine work. The first fuel was wood, which proved impractical. Thus, coal became the primary fuel and remained so until the early 1900s, when petroleum took over.

Two important aspects of coal are rank and quality. Rank is about carbon. Any organic material comprises carbon and volatiles. The carbon content of coal can be ranked.

- Wood has about 45% carbon.
- Peat has about 55% carbon.
- Lignite (also called brown coal) has about 65% carbon.
- Subbituminous coal has about 75% carbon.
- Bituminous coal has more than 85% carbon.
- Anthracite has more than 95% carbon.
Energy is stored in carbon and can be measured in BTUs (British thermal units) per pound of dry weight. Wood has 4,500 BTUs per pound, while anthracite has 15,000 BTUs per pound. In the eastern United States, the coal is primarily bituminous. In the western United States, the coal is mostly lignite or subbituminous. Anthracite is relatively scarce anywhere in the world.

Coal quality is measured in terms of ash and sulfur. The source of sulfur, one of the six elements required for life (along with carbon, oxygen, hydrogen, nitrogen, and phosphorous), is the tree itself. Ash is silicon and aluminum that the tree rejects and stores in dead wood cells. (Note that the only living wood in a tree is the layer right below the bark. The rest of the interior of the tree is dead wood.) High-quality coal has less than 10% ash and less than 1% sulfur. Medium-quality coal has 30% ash and 3% sulfur. High-quality coal comes from the southern Appalachian Basin and medium-quality from the northern Appalachian Basin. All coals in the western United States are high quality, though lower in rank.

Today, so-called steam coal is used to generate steam to drive turbine engines and make electricity. Coal would be a great fuel if it were not for the sulfur in it. Until 1970, any kind of coal could be burned, but of course, its sulfur content reacting with water in the atmosphere resulted in acid rain. In 1970, the Environmental Protection Agency clean air laws were enacted, which prescribed a compliance coal that has less than 1.2% sulfur. All western coals are compliance coals. Most of the coals from the eastern United States are noncompliance coals.

The production of compliance coals from noncompliance coals can be accomplished in two ways: cleaning and blending. Cleaning: In coals where the total sulfur is in excess of 1%, most of the additional sulfur is in the form of pyrite. Because pyrite is denser than the coal itself, total sulfur can be reduced by crushing the coal into a fine powder and subjecting it to float/sink separation, which removes that fraction of the coal rendered denser by the presence of pyrite and leaves the remaining coal lower in total sulfur. Blending involves mixing high-quality compliance coal with noncompliance coal to produce a mix with less than 1.2% sulfur.
Two devices can be introduced into power-plant design to minimize the amount of SO\textsubscript{x} gases vented to the atmosphere: scrubbers and getters.

- A scrubber is literally a washing machine that scrubs the gases emerging from the firebox with an alkaline solution that precipitates the SO\textsubscript{x} gases as an inert sulfate.

- A getter is a chemical trap for the SO\textsubscript{x}. The coal is powdered, and with limestone powder, it is blasted into the firebox. As the coal burns, the sulfur generates SO\textsubscript{x} gases. The limestone decomposes into carbon dioxide and calcium oxide; these elements “get” the SO\textsubscript{x} gases, creating calcium sulphate, which is benign. The sulfur content of the fuel is monitored, and a computer calculates how much calcium oxide is needed. (Note that the fuel can be any material with an organic content greater than 25%, including low-quality coals or gob, a product of coal cleaning.)

A problem in the East has been acid mine drainage. Whenever you mine coal, the coal of the associated rocks has this pyrite in it. Whenever pyrite oxidizes and is put in the solution, it generates sulfuric acid. So if you come into the modern type of mining operation in the East today, you’ll find out that acid mine drainage is not a problem anymore. They know how to reclaim the land and put it back to active use without it being decimated by all this acid production. Keep in mind, the acid source today in the East—in all of the Appalachian area and all the entire East—doesn’t come from active mines: it comes from old abandoned deep mines.

There’s a bad feeling in a lot of people’s minds about coal and the mining of coal, and I understand that. But I think we have to realize in the future we’re going to need energy … .
Suggested Reading

Thomas, L., *Coal Geology*.

Questions to Consider

1. How do the eastern and western coals of the United States compare in rank and quality?

2. What is the source of the ash and sulfur found in coal?
In this lecture, we’re going to talk about petroleum. Petroleum represents 70% of the total energy budget of this country, and this is especially why I think everybody ought to know something about it.

Petroleum comes from small marine plants raining to the bottom of the ocean, where they are preserved and buried in reservoirs, that is, rocks of high porosity and permeability, such as sandstone and limestone. A cap rock—the best is shale—sits over the reservoir, keeping the oil and gas inside. Keep in mind that the oil in this system is emulsified with water. For commercial production, the oil must be concentrated into a smaller volume. The structure that performs this function is a trap, such as an anticlinal trap. The oil migrates to the axial region of the anticline, where a well can be drilled.

Seventy percent of the U.S. energy budget is oil-based. Most of the known oil reserves are in the Middle East. The United States owns about 5% of the rest of the world’s oil reserves. The United States consumes about 30% of all the oil produced in the world and imports about 51% of all the oil it uses. When the United States supported Israel during the 1973 war with its Arab neighbors, the members of the Organization of the Petroleum Exporting Countries (OPEC), which is dominated by the countries of the Middle East, imposed an oil embargo on our country. A crisis was precipitated in the United States, eventually causing Americans to lower their demand for oil. With the reduction in demand, the embargo was lifted. The obvious problem at that time was the large size and gas inefficiency of American cars. When Japan provided an answer by exporting more efficient cars to the United States, the American car industry followed suit and began to manufacture more efficient cars. But memories are short, and American cars have become larger.

In 1952, at a meeting of the American Association of Petroleum Geologists, M. King Hubbert warned about the overproduction of nonrenewable resources. Hubbert predicted that American oil wells would peak out (both in
production and discovery) in the 1960s. In fact, domestic production peaked in 1968. Hubbert also predicted that worldwide production would peak somewhere around the turn of the 21st century. Although highly unpopular and rejected at the time, Hubbert’s predictions are now proving to be true. It has been estimated that worldwide production will peak in about 2010. Hubbert also predicted that there would not be enough oil left anywhere in the world to even bother to look for it by 2100.

What can we do in the United States? According to Charles Mankin, former director of the Sarkeys Energy Center at the University of Oklahoma, Americans can reduce imports by eliminating the need for gas, not diesel. Then, the United States would have enough oil to be self-sufficient.

One way to do this would be to start producing ethanol, as has been done in Brazil. In Brazil, ethanol is made from sugar cane. In the United States, ethanol could be made from corn. Cars can run on ethanol. Cars can also run on liquefied natural gas. This began to be made a few years ago, but the trend did not last.

The future appears to be in hydrogen. The hydrogen fuel cell is currently being developed. Its first use was in the Apollo Project to the Moon. Although one hydrogen cell does not have much power, hydrogen cells can be made in any size. To make a hydrogen cell, hydrogen gas and oxygen are brought together. They run into a catalyst, which strips the electrons off the hydrogen anions to make ions. A film allows the hydrogen ions to pass through to the other side of the cell, but the electrons cannot get through. The electrons follow a wire (creating an electric charge) to reach the other side of the cell and react with oxygen to form water. Jonathan Rifkin, author of *The Hydrogen Economy*, advised
using renewable sources of electricity (for example, solar and wind sources) to make hydrogen cells.

**Suggested Reading**


**Questions to Consider**

1. According to recent estimates, will the finding of new petroleum deposits significantly prolong the availability of petroleum as a major world energy source?

2. What appears to be the best potential way for the world to wean itself of its need for oil?
Timeline

B.C.

13.7 billion years ago..............Big Bang—origin of the universe.

4.5 billion years ago...............Creation of planet Earth from protoplanet Earth.

3.9–4.2 billion years ago........Oldest crustal rocks.

3.6 billion years ago...............First bona fide evidence of life (blue-green algae).

2.5 billion years ago...............Modern rate of plate tectonics thought to begin.

1.0 billion years ago..............Formation of Rodinia, the supercontinent that preceded Pangea.

800–700 million years ago......First large soft-bodied animals.

550 million years ago...............First shelled animals.

300 million years ago...............Creation of supercontinent of Pangea.

200 million years ago...............Breakup of Pangea—creation of modern continents.

60 million years ago...............Extinction of dinosaurs.

2 million years ago...............Onset of Northern Hemisphere continental glaciation.
A.D.

1785. James Hutton publishes his *Theory of Earth*.

1830. Charles Lyell publishes the first real geology text, *Principles of Geology*.

1857. James Hall theorizes geosyncline.

1859. Charles Darwin publishes *Origin of Species*.


1902. E. Rutherford and F. Soddy establish radioactive dating.

1915. Alfred Wegener proposes supercontinent of Pangea and its breakup to form the modern continents.


1963. Vine and Matthews document the concept of the sea floor spreading with their discovery of magnetic zonation of the oceanic crust.

Mid-1960s. Originally recognized in the 1920s by a German seismologist, Beno Gutenberg, his discovery
of the asthenosphere was viewed with great skepticism until the 1960s.

Mid-1960s..............................Establishment of the theory of plate tectonics.
**Glossary**

**aa**: The Hawaiian term for basaltic lava characterized by a rough, jagged surface.

**abrasion**: The process whereby rock surfaces are worn away by the frictional contact of rock particles transported by wind, running water, waves, glacial ice, or gravity.

**abyssal plain**: The perfectly flat, deepest portion of the ocean bottom beyond the continental rise.

**Acadian orogeny**: The orogenic event that affected the northern Appalachians during the Devonian period.

**accretionary wedge**: A mixture of materials stripped from the descending lithospheric plate that is accreted to the edge of the overlying plate.

**acid mine drainage**: The acidic iron- and sulfate-rich water that is commonly associated with the mining of materials containing pyrite.

**acid soil**: The soil typical of humid, temperate climates, in which the cation exchange positions have been hydrogenated by percolating acidic rainwater.

**active volcano**: Any volcano that shows some indication that the associated magma is molten.

**agricultural lime**: Powdered limestone that is used to neutralize acidic soils.

**Alleghenian orogeny**: The final orogeny that created the structures seen throughout the present-day Appalachians and that completed the formation of Pangea.
**alluvial fan**: The gently sloping, fan-shaped deposit that accumulates where a mountain stream flows out onto an adjoining basin, particularly in arid and semiarid regions.

**alpine glacier**: A glacier confined to a mountain valley.

**amino acids**: Complex organic molecules that are the basis for the development of life.

**amplitude**: The distance from the crest of a wave to the bottom of the adjoining trough. In the case of folds, the distance between the crest of the anticline to the bottom of the adjacent syncline.

**angle of repose**: The angle above which loose material will begin to move downslope.

**anion**: An atom or group of atoms that possesses a negative charge because of an excess number of electrons.

**anticline**: A convex upward fold in which the oldest rocks are located in the center.

**aphelion**: The point in the orbit of a solar system object where it is farthest from the Sun.

**aquiclude**: An impermeable rock or unconsolidated deposit that is incapable of allowing the passage of water.

**aquifer**: A rock or an unconsolidated deposit with sufficient porosity and permeability to conduct significant volumes of water to a well or spring.

**aquitarde**: A semipermeable rock or unconsolidated deposit that does not readily conduct water to a well or spring.

**arete**: A knife-edged mountain ridge created by alpine glaciation.

**aridosol**: Alkaline or saline soils that develop under arid conditions.
**arkose**: A sandstone of continental origin containing at least 25% feldspar.

**artesian well**: Any well producing water from a confined aquifer.

**ash**: Pyroclastic materials with diameters of less than 2.0 mm generated during volcanic eruptions.

**asteroids**: Any of a number of relatively small celestial bodies that orbit the Sun, mostly between the orbits of Mars and Jupiter.

**asthenosphere**: Part of the upper mantle immediately below the lithosphere that is characterized by a plastic response to stress.

**asymmetric fold**: A fold whose limbs dip in opposite directions at different angles.

**atom**: The neutral system of negatively charged electrons moving around a dense, positively charged nucleus.

**atomic mass**: The sum of the number of protons and neutrons in the nucleus of an atom.

**atomic number**: The number of protons in the nucleus of an atom.

**axial plane**: An imaginary plane that attempts to divide the cross-section of a fold into two equal halves.

**back-arc basin**: A basin, such as the Sea of Japan, that forms between a chain of island-arc volcanoes and the mainland, resulting from the rifting of the ocean floor.

**bajada**: A series of overlapping alluvial fans along the base of a mountain range.

**Barringer Crater**: The most recent impact crater on Earth, located in northeastern Arizona.
**basalt**: A fine-grained, dark-colored, extrusive igneous rock composed primarily of calcic plagioclase and pyroxenes.

**base level**: The surface down to which a stream is attempting to carve its channel.

**Basin and Range Province**: A geologic province centered over Nevada that is characterized by north-south–trending block-fault mountains.

**batholith**: A massive, intrusive igneous body with a surface exposure of greater than 40 square miles.

**bauxite**: The primary ore of aluminum, essentially hydrated alumina, \( \text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O} \).

**bed load**: That portion of a stream’s load being carried along the bottom of the stream channel.

**Big Bang**: The theoretical explosion that initiated the formation and expansion of the Universe.

**biochemical sedimentary rock**: A sedimentary rock composed of materials generated by organisms.

**black hole**: An object that has collapsed under its own gravitation to such a small radius that its gravitational force traps photons of light.

**block-fault mountain**: Linear mountain ranges formed under tensional forces bounded on both sides by normal faults.

**body wave**: The seismic waves that travel through Earth.

**bolson**: An alluvium-covered basin into which drainage from adjacent mountains flows.

**bomb**: An aerodynamically shaped pyroclastic rock greater than 64 mm in diameter formed by the midair solidification of molten lava.
**Bowen’s crystallization series**: An order of crystallization of silicate minerals from the cooling of molten magma or lava.

**breccia**: A sedimentary rock composed primarily of angular, granule-sized or larger rock fragments.

**brittle strain**: The response of a material when, once the elastic limit has been exceeded, the material breaks.

**caldera**: A large basin-shaped volcanic depression that is produced by the collapse of the overlying cone into an empty or partially empty magma chamber.

**caliche**: A mixture of sand, gravel, or desert debris cemented with porous calcium carbonate.

**capacity**: The total amount of load that a stream can carry.

**carbonaceous chondrite**: A meteorite containing chondrules having a high abundance of carbon and other volatile elements.

**carbonation**: Any reaction involving carbonic acid.

**carbonation/hydrolysis**: The major process whereby most rock-forming silicate minerals undergo chemical weathering that involves a reaction with carbonic acid (carbonation) and water (hydrolysis).

**cation**: A positively charged ion.

**cation adsorption**: The process whereby clay mineral particles neutralize their negative charges.

**cation exchange**: The process whereby positive ions in cation-adsorption sites can be replaced by other cations present in the soil water.

**cave and cavern**: Underground passageways created by the groundwater dissolution of limestone.
cementation: A process whereby loose sediments are converted into sedimentary rocks by minerals precipitating from groundwater solution into the pore spaces between the grains.

chemical atomic weight: The weighted average mass of the isotopes making up an element.

chemical sedimentary rock: A sedimentary rock consisting of non-clastic materials that were not generated by organisms.

chemical weathering: Any process whereby a mineral or rock is partially or totally decomposed.

chernozem: A Russian word meaning “black soil,” in reference to the black color of mollisols.

chert: A sedimentary rock consisting of crypto-crystalline quartz.

chondrite: A stony meteorite containing chrondrules.

chrondrule: A spherical inclusion in certain meteorites, usually composed of silicates.

cinder cone: A cone of loose cinders that accumulates around a volcanic fissure or vent.

cinders: Uncemented fragmental volcanic ejecta ranging from 3 mm to 4 mm in diameter.

cirque: A bowl-shaped mountain depression that forms at the headwaters of an alpine glacier.

clastic: Fragments of rock that have been moved from their point of origin.

clay minerals: A group of hydrous aluminum silicates formed from the carbonation/hydration of most of the major rock-forming silicate minerals. They are the major component of soil.
climate: The conditions of temperature and precipitation that exist for a long period of time in any region.

closed universe: According to theory, a universe that will eventually collapse back to the original primeval atom or singularity.

cohesion and friction: The two forces that resist the movement of loose materials on slopes.

col: A high mountain pass formed by the back-to-back intersection of two cirques.

collapse sinkhole: A sinkhole that forms when the roof of a cavern collapses either under its own weight or following the removal of weight-supporting groundwater.

columnar joint: Prismatic columns, commonly hexagonal cross-sections, that are found in basaltic rocks.

comet: A celestial body thought to be composed primarily of water ice that orbits the Sun in huge, highly elliptical patterns.

compaction: A process of lithification whereby clay-rich sediments are converted to rock by the physical exclusion of water. Shales and mudstones form by compaction.

compression: A force that acts toward a body and tends to reduce its volume and dimensions.

compression wave: A shock wave in which the particles of the propagating medium move back and forth in the direction of propagation.

cone of depression: The conical depression of the water table around a pumped water well.

confined aquifer: An aquifer sandwiched between two aquicludes and within which the water is under pressure.
**conglomerate**: A sedimentary rock composed primarily of rounded, granule-sized and larger particles.

**contact metamorphism**: The processes of change that take place in a host rock because of the heat at contact with an intruding magma.

**continent-continent collision**: A major mountain-building episode resulting from the collision of two continents. The current collision of India and Asia is an example.

**continental-arc volcano**: The chain of volcanoes that forms on the edge of the continental plate overlying a zone of subduction.

**continental crust**: The granitic rocks that underlie the continents and range up to 45 miles thick under mountain ranges.

**continental glacier**: A glacier of considerable thickness that covers a large part of a continent, obscuring the topography of the underlying surface over an area of at least 20,000 square miles.

**continental shelf**: The upper surface of the geocline surface that extends from the shoreline to the continental slope. The shallow portion of the ocean, averaging about 600 feet at the outer edge.

**convection cell**: The pattern of heat-driven asthenospheric rocks in which the central heated portion rises and the cooling outer portion sinks.

**convergent plate margin**: A boundary where two lithospheric plates are moving toward each other.

**core**: The innermost portion of Earth, thought to be composed of a mixture of iron and nickel. The outer portion of the core is molten, while the center is possibly solid or a highly viscous liquid.

**cosmic dust**: The remains of former stars, consisting of bits and pieces of metals, minerals, rocks, and ices, that fill the cosmos.
covalent bond: The chemical bond in which atoms join by a sharing of their outermost electrons. The strongest of all chemical bonds.

crater: The circular to elliptical structure that occupies the summit of a volcano. The bowl-shaped depression formed by meteorite impact.

creep: The slow, continuous movement of regolith downslope under the force of gravity.

cross beds: Individual beds inclined at an angle to the main bed of a sedimentary rock.

crust: The outermost portion of Earth that consists of the oceanic and continental crusts.

dark matter: The unseen matter that occupies the space within galaxies.

deadman: Structural components of walls designed to prevent the toppling of the wall by creep.

decollment: Near-horizontal thrust faults that form where upper folded and faulted layers of sedimentary rock move over underlying rocks.

decomposition: Any weathering process whereby minerals and rocks are partially or totally changed in composition.

deep-focus earthquake: An earthquake whose focus is located from about 200 miles to 450 miles below Earth’s surface.

deep-sea trench: A long, narrow depression on the ocean floor that forms along convergent plate margins.

desert pavement: The layer of granule-sized and larger particles covering the desert floor, produced by the preferential removal of sand-sized and smaller particles.

diatom: A single-celled plant that secretes a siliceous frustule.
dip: The angle that a structural plane, such as a fault or a bed, makes with the horizontal.

disintegration: The process by which rocks are physically reduced in particle size.

displacement: The actual amount of movement along a fault surface.

dissolution: The process by which a solid dissolves in a solvent.

dissolved load: That stream load that is carried in solution.

divergence: Refers to the movement of lithospheric plates away from each other.

divergent plate margin: The margin between diverging lithospheric plates at rift zones, rift valleys, linear oceans, and oceanic ridges.

domal mountain: Mountains created by the localized, vertical uplift of Earth’s crust.

dormant volcano: A volcano that has not shown signs of activity in historic time, has been active in the past, and is expected to be active in the future.

double-chain silicate structure: The silicate structure in which two parallel chains of silicon tetrahedra are joined along their lengths.

drag fold: A minor fold, usually in incompetent beds, that forms on opposite sides of a fault by the movement of rocks.

dripstone: The common name given to the materials that form from the precipitation of calcite or other materials from water solution.

dry-based glacier: A glacier, usually in polar regions, that is frozen to the underlying bedrock.

dust: The smallest particle size visible to the unaided human eye.
**dynamo-thermal metamorphism**: A type of regional metamorphism involving high pressures, shearing stress, and heat.

**earthquake intensity**: The amount of damage incurred by an earthquake.

**earthquake magnitude**: The amount of movement involved in an earthquake. Magnitude is measured by the Richter scale.

**ecliptic**: The plane of Earth’s orbit around the Sun.

**elastic limit**: The point beyond which a material can no longer absorb and store energy.

**elastic strain**: The type of strain in which the applied force is absorbed, stored during deformation, and released as the material returns to its original shape.

**electron**: A negatively charged fundamental particle.

**energy level**: Discrete level surrounding the nucleus of an atom within which the electrons reside.

**epicenter**: The point on Earth’s surface immediately above the focus of an earthquake.

**epiorogenic force**: Vertically directed mountain-building force.

**erosion**: Any process whereby the products of weathering are picked up and carried away.

**evaporite sedimentary rock**: A sedimentary rock formed from materials that are so water soluble that the water must be evaporated before precipitation will commence.

**exfoliation**: Any process whereby concentric layers are removed from the surface of a rock.
**exterior drainage**: Drainage systems where the water eventually reaches the ocean.

**extinct volcano**: A volcano that is not active and is not likely to become active in the future.

**fall**: One of the three types of mass wasting requiring the least amount of involvement of water; in a fall, rocks are subjected to maximum Go Force and little or no Stay Force.

**fault**: A break in Earth’s crust along which there has been movement.

**ferromagnesian silicate mineral**: Those silicate minerals containing appreciable amounts of iron and magnesium.

**fire fountain**: An eruptive feature in which basaltic magmas are blown into the air up to a few thousand feet and break into cinders that fall around the vent to form a cinder cone.

**flat universe**: The scenario in which the expansion may stop, but the Universe will never collapse.

**flint**: A type of chert used by paleo-people to fashion tools.

**flood basalt**: Horizontal to sub-horizontal flows of basaltic lava that issue from many fractures over a wide area.

**floodplain**: That portion of a stream valley adjacent to the stream that is constructed of sediments overlying the erosional valley flat.

**flow**: A type of mass wasting that involves major quantities of water that intermix with loose debris to form a material that has the properties of a liquid.

**flyweight star**: A star less than 0.5 solar masses.

**focus**: The point at which the energy of an earthquake is released.
fold: A bend in strata, usually in response to compressional forces.

fold axis: The line of intersection of a fold and the axial plane.

foldbelt mountain: A mountain range within which a significant portion consists of folded sedimentary rocks.

footwall: The mass of rock beneath a fault plane.

fossil: The remains or the impression of the remains of a once-living organism.

fracture: A break in a rock due to mechanical failure. The breaking of a mineral other than along cleavage plains.

framework silicate structure: The silicate structure characterized by a three-dimensional arrangement of tetrahedra, in which each oxygen is shared by an adjoining tetrahedron.

free-flowing artesian well: An artesian well that produces water above the surface of the ground.

frost heaving: The process whereby particles of soil are lifted by the growth of an underlying ice crystal.

frost wedging: A physical weathering process whereby rocks are split apart by the cyclic freezing and thawing of water in fractures.

fumarole: A volcanic vent that emits hot gases.

galaxy: A huge group of stars, planets, and other bodies in the Universe.

geoclone: The wedge of sediment that accumulates at the margin of a continental trailing edge.

geosyncline: A regional downwarping of the continental margin.

geyser: A volcanic feature that cyclically emits hot water and steam.
**Gondwana**: The Late Paleozoic continent of the Southern Hemisphere consisting of the present-day continents of South America, Africa, Antarctica, Australia, and India.

**graben**: The downthrown block associated with block-fault mountains.

**gradient**: The slope of a stream channel.

**granite**: A coarse-grained igneous rock consisting primarily of orthoclase, quartz, and plagioclase feldspar with minor amounts of biotite and amphiboles.

**granodiorite**: A coarse-grained igneous rock similar in composition to granite except for containing less orthoclase. With granite, makes up the continental crust.

**graywacke**: A dark-gray sandstone consisting of poorly sorted, angular quartz and feldspar with a variety of rock fragments in a clayey matrix.

**Go Force**: A term used in this discussion for the downslope component of gravity.

**ground moraine**: Till deposited during the retreat of a glacier.

**hanging wall**: The mass of rock above a fault plane.

**hardness**: The ability of a mineral to resist scratching by another mineral.

**Hawaiian phase**: The phase of eruption intensity described as nothing but the quiet evolution of lava. Molten rock on Earth’s surface or its solidified counterpart.

**heavyweight star**: A star having greater than 8 solar masses.

**hematite**: The major mineral of iron, Fe₂O₃.

**horizon**: A layer that develops in undisturbed soils.
**horn**: A sharp mountain peak sculpted by the combined efforts of several surrounding cirques.

**horst**: The upthrown block associated with block-fault mountains.

**hot spot**: A source of basaltic magma at the top of the asthenosphere; hot spots are associated with mantle plumes and can last for several millions of years.

**hot spring**: A spring emitting water heated either by the geothermal gradient or by an underlying magma.

**hydrogen bond**: The bonding that occurs when a hydrogen atom comes between two small, highly electronegative atoms, such as N, O, and F.

**hydrologic cycle**: The circular pattern by which water originates from the oceans, passes through the atmosphere to the land, and eventually returns to the oceans.

**hydrolysis**: Any chemical reaction involving water.

**hydrothermal feature**: Surface emissions of heated water or steam.

**hydrothermal metamorphism**: The metamorphic process whereby host rocks are altered by the reaction with water or gases derived from magma.

**Iapetus Ocean**: The ocean created by the breakup of the supercontinent of Rodinia.

**igneous rock**: Any rock formed from the cooling and solidification of molten rock.

**inorganic**: Refers to compounds in which carbon is not a major component.

**interior drainage**: Streams that originate and terminate within the continent.
**intermediate-focus earthquake**: An earthquake that occurs in a zone from about 40 miles to about 250 miles below Earth’s surface.

**ion**: An atom or group of atoms that has become positively or negatively charged.

**ionic bonding**: The electrostatic attraction between oppositely charged ions.

**iron meteorite**: Meteorites consisting of iron with varying amounts of nickel.

**island-arc volcano**: A volcano associated with a zone of subduction that builds from the ocean floor between the deep-sea trench and the continental margin.

**isolated tetrahedral silicate structure**: A silicate structure in which the silicon tetrahedra are joined by other metal ions.

**isotope**: Atoms with the same atomic number but different atomic masses.

**joint**: A break in the crust along which there has been little or no movement.

**Jovian planet**: Any of the four large gassy planets that orbit the Sun.

**karst topography**: Irregular topography developed by the surface and groundwater dissolution of underlying soluble rock, usually limestone.

**lahar**: A mudflow associated with a volcanic eruption.

**laminar flow**: The type of fluid flow in which the individual molecules are visualized as moving along parallel, uninterfering paths.

**laminar layer**: A thin layer of water theorized to exist where the water meets the stream channel and within which the water moves by laminar flow.

**lateral moraine**: A low, ridge-like moraine carried on or deposited near the side of an alpine glacier.
**lava**: Molten rock on Earth’s surface or its solidified counterpart.

**lava lake**: A lake of molten lava, usually basaltic, that accumulates in a summit crater or on the flanks of a shield volcano.

**left-lateral strike-slip fault**: A strike-slip fault where an observer standing on one block must turn to the left to find the same index locality on the opposite block.

**lepton**: A fundamental particle of which the electron is the stable form.

**levee**: A natural or artificial embankment along the bank of a stream that serves to confine the stream flow to the channel.

**lightweight star**: A star between 0.5 and 4 solar masses.

**limb**: The part of a fold between the axes of the anticline and the adjacent syncline.

**limestone**: A sedimentary rock consisting primarily of the mineral calcite, CaCO₃.

**limonite**: A generic term for hydrated iron oxides, FeO(OH).

**linear ocean**: A flooded rift valley; an intermediate stage between a rift valley and an opening ocean.

**lithification**: Any process that converts loose sediment into a sedimentary rock.

**lithosphere**: The combination of the crust and the outer, brittle portion of the mantle.

**load**: The amount of material actually being carried by a stream.

**Love wave**: The surface seismic wave in which the movement of the ground is horizontal and perpendicular to the direction of propagation.
**luster**: The appearance of a mineral under reflected light.

**magma**: Molten rock below Earth’s surface.

**magnetic reversal**: The change in the polarity of Earth’s magnetic field.

**magnetite**: The magnetic iron mineral Fe₃O₄.

**main sequence**: The period of a star’s lifetime during which it is converting hydrogen to helium in its core.

**mantle**: That portion of Earth between the top of the core and the bottom of the crust.

**marginal sea**: The semi-enclosed sea between an island arc and the mainland. An example is the Sea of Japan.

**maturity**: The stage in Davis’s cycle in which deposition exceeds active erosion, the streams are of low gradient and meandering, and wide floodplains are being created between subdued hills.

**meander**: The sinuous pattern characteristic of streams that have progressed to the stage of maturity.

**medial moraine**: A moraine carried on or in the middle of an alpine glacier that results from the coalescence of two inner lateral moraines below the juncture of two alpine glaciers. Upon retreat of the glacier, the moraine is deposited in the middle of the valley.

**melange**: A mass of folded, faulted, and metamorphosed rock that forms at convergent plate margins as part of the accretionary wedge.

**Mercalli/Rossi scale**: A scale of relative earthquake damage.

**metallic bond**: A type of chemical bond in which the valence electrons are not confined to individual atoms but, rather, flow freely through the entire crystal structure.
**metamorphism**: The combined chemical, mineralogical, and structural changes that take place within a rock mass as a result of the application of heat, pressure, and chemically active fluids.

**metasomatism**: A hydrothermal metamorphic process in which the original minerals of a rock are partially or totally replaced with a new assemblage of minerals.

**meteor**: The streak of light created as a meteoroid plunges through Earth’s atmosphere.

**meteorite**: A meteoroid that has survived the passage through Earth’s atmosphere and has impacted Earth.

**meteoroid**: A small interplanetary body.

**middleweight star**: A star between 4 and 8 solar masses.

**mineral cleavage**: The breaking of a mineral along planes of weakness within its crystal structure.

**mollisol**: The soil order that develops in semiarid, temperate climates.

**monocline**: A localized steepening in an otherwise uniform dip.

**moraine**: A mound, ridge, or other landform consisting of till deposited directly by a glacier.

**mud cracks**: Shrinkage cracks that develop in fine-grained, unconsolidated deposits as a result of drying or freezing.

**mudstone**: A sedimentary rock similar in composition to a shale but without the fine lamination characteristic of shale.

**Nebular hypothesis**: The theory set forth in 1755 by Immanuel Kant proposing that our solar system formed from a cloud of interstellar cosmic dust and gas.
**neutron**: The subatomic particle located in the nucleus of an atom with no charge and a mass of 1 amu; it consists of two down quarks and one up quark (ddu).

**neutron star**: A very dense stellar remnant whose interior consists entirely of neutrons.

**nomograph**: A graph or chart reducing a mathematical formula so that its value can be read for any value assigned to the variables involved.

**non-clastic**: Refers to material or rocks formed from substances once in solution.

**non-ferromagnesian silicate mineral**: Silicate minerals whose compositions do not include appreciable amounts of iron or magnesium, primarily the feldspars, quartz, and muscovite.

**non-renewable resource**: A material that, once harvested, will not be replaced by a newly created unit of the material within a reasonably short period of time, usually taken as a human lifetime.

**non-rotational compression**: Compression in which the forces act toward and directly opposite each other.

**non-silicate mineral**: Minerals whose anion is other than the silicate anion.

**normal fault**: A fault formed under tensional forces in which the hanging wall has moved down relative to the footwall.

**nuée ardente**: A highly heated mass of gas-charged lava ejected more or less horizontally from a vent or summit of a volcano onto the outer slope, where it flows swiftly downslope as an avalanche.

**ocean-continent collision**: The convergence of an oceanic and continental plate at a zone of subduction.
**ocean-island arc-continent collision:** A convergent plate movement whereby an oceanic plate converges on a plate occupied by a chain of island-arc volcanoes and a continent.

**oceanic crust:** That portion of the crust underlying the ocean basins, consisting of basaltic lava.

**oceanic ridge:** A volcanic mountain range arising from the abyssal sea floor at the divergent plate margins; the site of sea floor spreading as new oceanic lithosphere is being created at its summit.

**octet rule:** The rule states that atoms that are able to acquire eight electrons in the outermost energy level become chemically inert.

**old age:** The third and final stage of Davis’s landscape evolution theory, in which the stream channel is very near the base level, the relief of the landscape is very low, the stream gradients are very low, meandering is extreme, and abundant abandoned meanders or oxbow lakes are present.

**Oort cloud:** The theoretical cloud of comets that surrounds the solar system at a distance of approximately two light years.

**open universe:** The scenario in which the Universe will continue to expand forever.

**organic:** Refers to materials in which carbon is a major component.

**orogenic forces:** The horizontal, compressive forces that are generated at convergent plate margins.

**outwash plain:** The well-sorted, stratified deposit of sand, gravels, and cobbles eroded and transported from the terminal moraine of a continental glacier by meltwater streams.

**overturned fold:** A fold where both limbs dip in the same direction.
oxbow lake: A water-filled abandoned meander that is characteristic of stream valleys in Davis’s landscape evolution stage of old age.

oxidation: Any reaction with oxygen.

oxisol: The soil order that forms in ever-hot, ever-wet tropical climates, consisting of a mixture of iron, aluminum, and silicon oxides.

pahoehoe: The Hawaiian term for a type of basaltic lava characterized by a smooth, ropey surface.

Pangea: The supercontinent proposed by Alfred Wegener that broke up about 200 million years ago to create the modern continents.

pedalfer: Acidic soils that form in humid, temperate climates under forest cover. In the United States, the term pedalfer has been superceded with the spodosol and ultisol soil orders.

pedocal: Neutral to alkaline soils that form under semiarid, temperate climates. In the United States, the term pedocal has been superceded by the mollisol order.

pedology: The scientific study of soils.

Pelean phase: A violent phase of volcanic eruption involving large volumes of pyroclastic material as well as a nuée ardente.

perched water table: The water table associated with a mass of groundwater isolated above the main body of groundwater by an impermeable layer of rock. Also referred to as a hanging water table.

peridotite: A coarse-grained, ultra-mafic igneous rock, consisting primarily of olivine, that makes up the upper portion of the mantle.

perihelion: The point in the orbit of any Sun-orbiting body where it most closely approaches the Sun.
**permeability**: The ability of a rock or unconsolidated material to transmit a fluid.

**petrology**: A general term for all the available methods to study the natural history of rocks.

**physical property**: Any property of a mineral that can be determined with the senses.

**physical weathering**: Any process whereby rocks are physically reduced in size.

**piedmont glacier**: An alpine glacier that has advanced beyond the base of a mountain onto the adjacent valley floor.

**pillow lava**: Basaltic lava that has cooled and solidified underwater.

**planet**: The celestial body that forms from a proto-planet by the melting and density separation of the mass into layers surrounding a dense core.

**planetesimal**: Small bodies orbiting around the Sun that coalesced to form the proto-planets, from which the planets evolved.

**plastic flow**: Flowage within a solid body.

**plastic strain**: The response to stress whereby a material consumes the applied energy and deforms permanently.

**plate**: The pieces of the lithosphere involved in plate tectonics.

**playa lake**: A shallow lake found in arid regions that holds water during the wet season but disappears during the dry season.

**Plinean phase**: A violent phase of volcanic eruption in which pyroclastic material is blown tens of thousands of feet into the air.
plunge: The angle between the fold axis and the horizontal; the process by which folds come to an end.

porosity: The percentage of a rock or unconsolidated material represented by void space.

pressure melting: The melting of a solid due to the favoring of the liquid phase over the solid phase under pressure.

pressure surface: The surface associated with a confined aquifer to which water will rise when released from the aquifer.

primeval atom: The small sphere proposed by Georges Lemaître to contain all the matter in the Universe before the Big Bang.

proton: The subatomic particle in the nucleus of an atom with a single positive charge and a mass of 1 amu; it consists of two up quarks and one down quark (uud).

proton-proton chain: The reaction within a star whereby four hydrogen nuclei combine to create one helium nucleus.

proto-planet: In the planetesimal hypothesis, the intermediate stage between the planetesimal and a planet.

pyrite: A mineral with the composition FeS₂. Commonly called “fool’s gold.”

quark: A fundamental particle, of which there are six types; two of these, the up (u) quark and the down (d) quark, join to create protons and neutrons.

quarrying: The process of glacial erosion whereby rock fragments are loosened, detached, and removed from the bedrock.

radiolaria: Marine protozoans that secrete shells of silica.
**Rayleigh wave**: The surface seismic wave that is a combination of the compression wave motion and the vertical component of the shear motion.

**recessional moraine**: An accumulation of till deposited along the front edge of a glacier during a significantly long standstill in the retreat of the glacier.

**recharge area**: The site or area where water enters an aquifer system.

**recumbent fold**: A fold where the limbs approach the horizontal.

**red giant star**: A star that has finished its core hydrogen-burning stage and has begun hydrogen shell burning, resulting in the cooling and expansion of its outer layers.

**regional water table**: The water table underlying a region.

**regolith**: The accumulated solid products of weathering above bedrock.

**rejuvenation**: The process of renewed erosion by a stream in response to an increase in the distance between the stream channel and the base level.

**relief**: The average distance between the hilltops and valley floors in a region.

**renewable resource**: A material that, once harvested, will be replaced by a new unit within a reasonably short period of time, taken to be an average human lifetime.

**Richter scale**: The scale created by Charles Richter in 1934 that evaluates the actual earth movement and amount of energy released during an earthquake.

**rift valley**: A valley created by the rifting of a continent along a developing divergent plate margin.

**rift zone**: The zone of fractures that appears on land as the first sign of the development of a divergent plate margin.
right-lateral strike-slip fault: A strike-slip fault where an observer standing on one block would be required to turn to the right to find the same index locality on the other side of the fault.

Ring of Fire: The arc of volcanism along the eastern, northern, and western margins of the Pacific Ocean basin.

ripple marks: A series of parallel or sub-parallel, small-scale ridges and valleys that form as currents of wind or water move across the surface of a sand deposit.

rock fall: The free-fall mass-wasting process whereby a newly detached rock fragment falls from a steep slope.

rock fragments: Fragments of rock created by physical weathering.

rock transport: The lateral movement of masses of rock in response to the forces involved in the formation of foldbelt mountains.

rotational compression: Compression in which the forces act toward but not opposite to each other.

sabkha: A hot, dry desert environment within which significant thicknesses of salts accumulate by the evaporation of water. Usually a broad, nearly horizontal surface located along an ocean margin where water is introduced by the tides.

sandstone: A sedimentary rock consisting primarily of sand-sized particles.

sanitary landfill: A site where municipal waste is deposited, compacted, and buried in such a fashion to minimize potential environmental contamination.

sedimentary quartzite: A sandstone consisting nearly entirely of quartz grains cemented with silica.

sedimentary rock: A rock formed from the products of weathering.
Seismic Sea Wave Warning System: The system installed around the Pacific Ocean basin to warn low-lying areas of impending tsunamis.

seismic wave: A shock wave associated with an earthquake.

seismogram: The record from a seismograph.

seismograph: An instrument that detects an earthquake and provides a record of the generated seismic waves.

seismometer: An instrument that detects an earthquake but does not provide a record.

septic system: A system for the disposal of domestic sewage in lieu of a municipal disposal system.

shale: A fine-grained, thinly laminated sedimentary rock consisting primarily of clay minerals. The most abundant of all sedimentary rocks.

shallow-focus earthquake: An earthquake that occurs from the surface to depths of about 40 miles.

shear joint: A fracture generated by shear forces along which there has been no or little movement.

shear wave: A shock wave in which the material transmitting the wave moves perpendicular to the direction of propagation.

sheet silicate structure: The silicate structure in which the silicon tetrahedra are joined into sheets that are stacked one over the other and joined together by cations.

shield: That portion of the continental crust that has been relatively stable over a long period of time.
**shield volcano:** The type of volcano that forms by repeated flows of basaltic lava. Commonly, shield volcanoes form in association with oceanic hot spots, although some do form on land.

**silicate anion:** The major building block of the silicate minerals, consisting of four oxygen atoms and a single silicon atom with an overall $-4$ charge, $(\text{SiO}_4)^{4-}$.

**silicate mineral:** A mineral whose major component is the silicate anion.

**silicon tetrahedron:** The three-dimensional arrangement of the silicate anion.

**single-chain silicate structure:** The silicate structure consisting of parallel single chains of silicon tetrahedra joined together by cations.

**singularity:** The theoretical dimensionless point consisting totally of energy that preceded the Big Bang.

**slickenside:** A polished, smoothly striated surface resulting from the mutual abrasion of rocks on opposite sides of a fault.

**slides:** A group of mass-wasting processes intermediate between flows, which require significant amounts of water, and falls, which require the least amount of water.

**solar mass:** The mass of the Sun.

**solar wind:** The stream of charged subatomic particles flowing outward from the Sun.

**solution sinkhole:** The type of sinkhole that forms by the dissolution of rock at the intersection of shear joints.

**SONAR:** The echo-sounding device used to determine water depth.

**sorting:** The process whereby particles are separated by size.
**specific gravity**: The ratio of the weight of an object to the weight of an equal volume of water.

**speleothem**: Any formation of travertine, commonly called dripstone, that forms within a limestone cave or cavern.

**spodosol**: The humid, temperate-climate soil order that forms under conifer cover.

**Stay Force**: In the context of this discussion, the force that resists the downslope movement of loose materials.

**stony-iron meteorite**: The rarest of all meteorites.

**stony meteorite**: The most abundant of all meteorites, making up 93% of all meteorite falls.

**strain**: The response to stress.

**stratification**: A structure produced by the deposition of sediments in tabular units, such as beds or layers.

**strato-volcano**: The type of volcano associated with zones of subduction, consisting of alternating layers of pyroclastic material and andesitic lavas.

**streak**: The color of a powdered mineral.

**stream volume**: The cross-sectional area of a stream channel measured at the surface of the water.

**strength**: The ability to withstand stress without strain.

**stress**: Any applied force.

**strike**: The direction of the line of intersection of a plane with the horizontal.
**strike-slip fault**: A type of fault in which there is horizontal offset along a vertical fault plane with little or no vertical offset.

**Strombolian phase**: The phase of volcanic activity characterized by frequent explosive eruptions.

**subduction**: The process whereby one lithospheric plate moves beneath another.

**supernova**: A violent stellar explosion.

**surface wave**: The seismic waves that move out in all directions from the epicenter of an earthquake, consisting of Love and Rayleigh waves.

**suspended load**: The fine-grained portion of the stream load, primarily silt- and clay-sized, that is transported for considerable periods of time within the mass of water.

**suture zone**: The zone where continents weld together following a continent-continent collision.

**symmetrical fold**: A fold where the limbs dip away from the axial plane in opposite directions at the same angle of dip.

**syncline**: A concave upward fold in which the youngest rocks are in the core of the fold.

**Taconic orogeny**: A major orogenic event that affected the northern Appalachian region during Ordovician time.

**temporary base level**: Any base level, other than sea level, that can serve as a base level for a limited period of time.

**tension**: The type of stress in which the forces act directly away from each other.
tension joint: A fracture within a rock that has formed under tensional forces, along which there has been little or no movement.

terminal moraine: The deposit of till that marks the furthest extent of a glacier’s advance.

Terrestrial Planets: The innermost four planets of the solar system.

texture: The general appearance of a rock in terms of the size, shape, and arrangements of the constituents.

thrust fault: A fault where the hanging wall has moved up relative to the footwall, and the angle between the fault plane and the horizontal is 45° or less.

transform fault: A special type of strike-slip movement that develops perpendicular to the trend of the oceanic ridge and allows the plates to move on a spherical surface.

triple alpha reaction: The nuclear reaction in which three helium nuclei combine to form a carbon nucleus.

tsunami: A sea wave of enormous energy generated by a submarine earthquake or volcanic eruption.

tuff: A general term for any rock composed of pyroclastic material.

turbulent flow: The type of fluid flow that involves both horizontal and vertical movement of the fluid.

ultimate base level: The level below which a stream cannot carve its channel. For exterior streams, the ultimate base level is sea level. For interior streams, it is the elevation of the basin in which the stream terminates.

ultisol: The humid, temperate-climate soil order that develops under hardwood forest cover.
**unconfined aquifer**: The type of aquifer associated with regional or perched watertables.

**unloading**: The process by which fractures form in rocks parallel to the surface as a result of the removal of the overlying rock by erosion.

**U-shaped valley**: The diagnostic cross-sectional shape of a valley carved by a glacier.

**valley flat**: The bedrock surface carved by a meandering stream.

**valley train**: The stratified, well-sorted material deposited by meltwater streams down-valley from the terminus of an alpine glacier.

**van der Waals bonding**: A weak intermolecular attractive force; the weakest of all chemical bonds.

**ventifact**: Any object carved by windblown sand.

**viscosity**: A property of all liquids; the resistance to flow.

**Volcanian phase**: The phase of volcanic eruption defined as infrequent but severe explosions.

**V-shaped valley**: The characteristic cross-section of a stream in Davis’s state of youth.

**water table**: The contact between the zone of aeration and the zone of saturation.

**weathering**: Any process whereby rocks either disintegrate or decompose.

**welded tuff**: A tuff formed by pyroclastic materials that were partially molten at the time of deposition.
**wet-based glacier**: Glaciers in which a layer of water generated by pressure melting separates the ice from the underlying bedrock. Most alpine glaciers are wet-based.

**white dwarf star**: The compact remnant of a low-massed star, in which the core is becoming dominated by helium.

**Wilson cycle**: A theory proposing that plate tectonics represents a cyclic process in which a supercontinent breaks up, forming new continents, that then move away from each other for about 250 million years; at that point, they change direction and return to form another supercontinent 250 million years later.

**x-ray diffraction**: An instrumental analytical technique that allows the identification of solid crystalline materials.

**yellow boy**: The deposit of limonite, FeO(OH), that accompanies the contamination of streams by acid mine drainage.

**youth**: The initial stage in Davis’s theory of landscape evolution, in which the distance between the stream channels and their base levels is at a maximum.

**zone of aeration**: The zone above the water table, within which the pores are devoid of water except during times of precipitation.

**zone of saturation**: The zone below the water table, within which the pores are filled with water down to the deepest penetration of groundwater.

**zone of subduction**: The zone where the oceanic lithospheric plate is being driven beneath the overlying continental plate.
Biographical Notes

M. K. Hubbert (1903–1989). Hubbert was born in San Saba, TX, in 1903. He attended Weatherford Junior College from 1921 to 1923 and received his B.S. and M.S. from the University of Chicago. He taught geophysics at Columbia University and received a Ph.D. in 1937. During World War II, he was a senior analyst at the Board of Economic Warfare in Washington, DC. Following the war, he joined Shell Oil Company, where he was director of the research laboratory. He retired from Shell Oil in 1964 and joined the U.S. Geological Survey, where he was a senior geophysicist. Hubbert was best known for his studies of petroleum and for his predictions of the peaks of domestic and world production, both of which have been proven to be quite accurate.

James Hutton (1726–1797). Hutton was born in Edinburgh, Scotland, and educated at the University of Edinburgh, where he studied medicine for three years. He completed his medical studies in Paris and received his doctorate in medicine at Leiden in 1749. With no medical positions available, he abandoned medicine and devoted himself to the study of agriculture on a plot of land that he inherited from his father. He traveled widely to learn the practical aspects of farming. It was during these journeys that he began to study Earth’s surface and surface processes. In 1785, he published a paper entitled “Theory of the Earth, or an Investigation of the Laws Observable in the Composition, Dissolution and Restoration of Land upon the Globe.” In this paper, which he presented to the newly established Royal Society of Edinburgh, he expressed views that were totally alien to most of the earth scientists of the day. He stated that the rocks seen at Earth’s surface were formed from the wastes of older rocks that were carried by streams to the ocean, where they were deposited on the ocean bottom and converted to new rocks by great pressures. These rocks were then uplifted to Earth’s surface where, upon exposure to the atmosphere, they began to decay to form the wastes of which future rocks would be made. During the later part of his life, he devoted his time to writing a text entitled Theory of the Earth, which was published in two volumes in 1795. It was largely Hutton’s views in this publication that built the foundation for the modern science of geology.
Alfred Wegener (1880–1930). Wegener earned a Ph.D. in astronomy from the University of Berlin in 1904. Following graduation, his interests centered on geophysics, meteorology, and climatology. During this time, he championed the use of balloons to track air currents. Following an expedition to Greenland to study the circulation of Arctic air masses, he accepted a position of tutor at the University of Marburg. While at Marburg, Wegener came across a paper describing the identical assemblages of plant and animal fossils on opposite sides of the Atlantic. He also noticed what many other observers of maps had seen, namely, the distinct similarity of the Atlantic coastal outlines of South America and Africa, an observation that no doubt planted the seeds of continental drift in Wegener’s mind. Wegener was drafted into the German army in 1914. After being wounded in battle, he was released from combat duty and served out the remainder of the war in the army weather-forecasting service. Following his military service, Wegener continued to collect evidence to demonstrate that South America and Africa were once joined into a larger continent. In 1915, he published the first edition of *The Origin of Continents and Oceans*, in which he outlined his theory of continental drift. Reaction to his ideas was almost universally hostile, certainly among the Northern Hemisphere geologists who dominated the science of geology at the time. Only geologists living in the Southern Hemisphere were attracted to his theory. It would be more than a half century before he would be shown to be essentially correct in most aspects of his theory of a supercontinent that broke up to create the modern continental masses. Unfortunately, the theory of plate tectonics would come long after his death.

J. Tuzo Wilson (1908–1993). The son of a Scottish engineer, Wilson graduated with degrees in geology and geophysics from the University of Toronto (B.A. and Sc.D.) and Princeton University (Ph.D.). During the late 1930s, he worked for the Geological Survey of Canada, where he became one of the first geologists to use aerial photography to study Earth’s surface. As a result of these photographic surveys, Wilson and five colleagues were able to prepare the first tectonic map of Canada. Following his service with the Canadian Army Engineers during World War II, Wilson was appointed professor of geophysics at the University of Toronto. During his 20-year tenure, he made significant contributions that eventually led to the formulation of the theory of plate tectonics. Wilson was first to explain the
formation of hot spot volcanoes associated with mantle plumes, the existence of transform faults, the opening and closing of the ocean basins, and the concept now known as the Wilson cycle, which proposes the cyclic creation, breaking up, and reformation of supercontinents.
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of coal, coal exploration, and mining technology and successfully bridges the gap between the academic and practical aspects of coal geology.


**Website:**

Groundwater is a major source of water and will be increasingly important in years to come. This website of The Groundwater Foundation provides a wide variety of topics for anyone wishing to expand their understanding of groundwater. www.groundwater.org.
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