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How the Earth Works

Course Guidebook

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Washington University in St. Louis

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Michael E. Wysession is Professor of Geophysics at Washington University in St. Louis. He earned his Sc.B. in Geophysics from Brown University and his Ph.D. from Northwestern University.

Professor Wysession has established himself as a world leader in the areas of seismology and geophysical education. He has developed several means of using the seismic waves from earthquakes to "see" into the earth and create three-dimensional pictures of Earth's interior. These images help us to understand what Earth is made of and how it evolves over time. An important focus of Professor Wysession's research has been the complex boundary region between the solid rock of Earth's mantle and the liquid iron of Earth's core. Another focus has been the identification of large regions of water-saturated rock in the deep mantle. Some of these investigations have been carried out using seismic information from arrays of seismometers that Professor Wysession has deployed across America. The results show that our planet is in constant internal motion, carrying heat from the deep interior up to the surface like a continual conveyor belt. Professor Wysession is also a leader in geoscience education. He is the lead author of Prentice Hall's ninth-grade physical science book, *Physical Science: Concepts in Action*. He also has supervised, in the role of primary writer, several other secondary-education textbooks, such as Prentice Hall's ninth-grade text *Earth Science* and sixth-grade texts *Earth's Interior*, *Earth's Changing Surface*, and *Earth's Waters*. Professor Wysession regularly gives workshops that help train secondary-education science teachers to teach earth and physical science.

At a more advanced level, Professor Wysession is the coauthor of *An Introduction to Seismology, Earthquakes, and Earth Structure*, a leading graduate-level textbook used in geophysics classes around the world. He also constructed the first computer-generated animation of how seismic waves propagate within the earth from an earthquake, creating a 20-minute film that is used in many high school and college classrooms. Professor Wysession has also written about the deep Earth in several general-audience publications, such as *Scientific American*, *American Scientist*, and *Earth Magazine*.

Professor Wysession's commitment to science and education began early. After he received his bachelor's in Geophysics, he taught high school math and science at Staten Island Academy in New York before going on to graduate school. After receiving his Ph.D., he joined the faculty at Washington University in St. Louis, where he has played a major role in the revisions of both the undergraduate and graduate-level geoscience curricula. He was asked to be the first Residential Faculty Fellow in Washington University's new residential college system, through which he lived with his family in a freshman dormitory for three years.

Professor Wysession has served as the editor of several journals of the American Geophysical Union, and his community service work has included several positions of responsibility within the Incorporated Research Institutions for Seismology (IRIS), which works to ensure strong continued funding for geophysical science at the national level. Professor Wysession is chair of IRIS's Education and Outreach program, overseeing the improvement of geophysical education on a variety of levels.

Professor Wysession's research and educational efforts have been recognized through several fellowships and awards. He received a Science and Engineering Fellowship from the David and Lucille Packard Foundation and a National Science Foundation Presidential Faculty Fellowship, awarded by President Clinton; both were awarded to only 20 American scientists across all disciplines. Professor Wysession also was awarded fellowships from the Kemper and Lily Foundations to enhance his teaching. He has received the Innovation Award of the St. Louis Science Academy and the Distinguished Faculty Award of Washington University. In 2005, Professor Wysession had a Distinguished Lectureship with IRIS and the Seismological Society of America, entertaining and educating audiences across the country about earthquakes and seismology.

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Scope:

Because the daily lives of most people nowadays can be so busy and hectic, it is appealing to think that at least the ground beneath our feet is steady, constant, and unchanging. Nothing could be further from the truth. We live on a vibrant, dynamic planet that is constantly in motion, inside and out. If you could view Earth's history sped up, like a movie on fast-forward, our planet would look more like the swirling eddies of a whirlpool than a ball of rock. Continents would whiz about the surface, and rocks would continuously be cycling from the surface to the deep interior and back again. Because the surface changes so much over time, you would no more be likely to recognize the planet of our past than you would the planet of our future. Recent discoveries in the earth sciences (geology, geophysics, geochemistry, and geobiology) are now revealing what our planet Earth is made of, what its history has been, and, more importantly, "how it works."

The movie analogy is really not a bad one. Our current scientific investigations give us a "snapshot" of our planet as it is today. From this single image, we attempt to reconstruct its past and predict its future. It is a difficult task, like trying to reconstruct the plot of a movie like Humphrey Bogart's *The Big Sleep* from just one still. The detective movie's plot, with all of its twists and turns, is hard enough to follow with repeated viewings, but to jump in the middle and figure things out would be daunting, if not impossible; this, however, is what geologists do. They are like detectives themselves, examining the geological clues at hand in order to not only reconstruct Earth's history but also to make predictions about its future.

While it is true that our world is in flux and we may be, as Etta James sang, "Standin' on Shaky Ground," there really are some constants in our world. As far as we can tell, there are definite laws to the universe. The fundamental forces that control the motions of objects and the flow of energy seem constant and unchanging. In fact, given these laws, once the Big Bang occurred, 13.7 billion years ago, the eventual formation of stars and planets was inevitable. The machinery of our universe was set in motion; gravity, electromagnetism, and the strong and weak nuclear forces made sure that there were lots of planets orbiting lots of stars in lots of galaxies. We have a particular interest, however, in one specific planet: Earth. Though there are likely to be many billions of planets in just our galaxy alone, it turns out that very few might be like our own. The conditions required to maintain liquid water on a planet's surface for 4 billion years (the time needed for single-celled life to evolve into something that can dribble a basketball or write a love sonnet) are remarkably unusual, and I will explore this idea in more detail later on in the course.

One very important part of the study of how the earth works is the interdisciplinary nature of it. Earth science is not for the faint of heart—this is not "rocks for jocks." In a modern-day university earth science department lecture, you are as likely to hear about the biological DNA of rock-chewing bacteria, the physics of the magnetic field of Jupiter, or the chemistry of ozone reactions in the atmosphere as you are likely to hear about more traditional topics of "geology." This is because the divisions between the different sciences are entirely artificial. Nature does not know about biology, physics, and chemistry; there is only Nature, and all of the sciences are involved in it. This is nowhere more true than in the study of a planet and how it works.

In very general terms, however, Earth's story is a simple one. Earth was intensely hot when it first formed and has cooled ever since. In fact, by about 50 million years after the origin of the solar system (which we now think was about 4.567 billion years ago), Earth may have been entirely molten. Since that time, Earth has steadily cooled down, losing its heat into space. This is what all planets do, and the particular size, location, and composition of Earth (including, very importantly, the amount of heat internally generated through radioactivity) has determined *how* Earth has cooled down. For our planet, the flow of heat from the interior to the surface takes the form of plate tectonics, which involves the vigorous convection of Earth's rocky mantle layer and the horizontal motion of broken pieces (plates) of Earth's outermost layer. As the plates move, they drag the continents about the surface, and the history of these continental collisions has been largely responsible for the geology we find about us. Even today, dramatic occurrences like earthquakes, volcanoes, the opening of oceans, and the upward thrust of mountains result from the inexorable motions of plate tectonics, releasing unfathomable amounts of energy.

Any good story has to have conflict, however, and it turns out that plate tectonics has a nemesis: the sun. As fast as mountains go up and lands are formed, sun-driven erosion tears them down. Sunlight drives the cyclic flow of water through the oceans and atmosphere, and the scouring of water and ice destroys rock and carries it to the oceans. Rivers are the highways of this destruction, carrying hundreds of millions of tons of former mountains toward the oceans each year. The surfaces of the continents are therefore like a battleground torn and ravaged by the two armies of Earth's interior and the sun, each relentlessly expending their arsenals of energy upon it. At various times in Earth's history one or the other may appear to be the victor, but it is the struggle between the two, unassumingly known as the rock cycle, that has shaped the lands we live on.

There is one more frequent characteristic of a great movie: a surprise twist of the plot in the end. *We*—humans—are that surprise. It is not possible for us to examine Earth objectively as if we were something *other* than the planet we live on. We are an integral part of Earth, constantly sharing our atoms with it (there are atoms in your body that were in dinosaurs, volcanoes, Julius Caesar, and that have flowed out the mouth of the Nile River many, many times). In fact, we might be considered as Earth's experiment in consciousness. Life has always played an important role in shaping Earth's surface—on the land, in the oceans, and in the atmosphere—but we have now reached a critical moment where humans have become the dominant agent of geologic change on Earth. We are altering Earth's land, water, and air faster than any other geologic process. It is therefore vitally important that we understand, in the context of *How the Earth Works*, the nature of our geologic powers if we are to have any hope of being able to control them.

Lecture One

Geology's Impact on History

Scope: Earth is a remarkable planet, and we know of no other like it. Earth is geologically alive—constantly in motion and ever-changing. Powerful forces within the planet open oceans and create mountains. As fast as mountains go up, however, the sun-driven forces of erosion tear them down. The surface of Earth is a battleground between the dueling forces of plate tectonics and erosion. There are many important characters in this story, including gravity, entropy, the conservation of energy, water, and the evolution of life—and, of course, the story has gone on for a long time and is only about half done. In this first lecture, we will set the stage for an investigation of our most remarkable planet, and outline the factors that control its fate.

Outline

I. These 48 lectures will show you how the earth works and give you an intuitive understanding into how Earth's processes of physics, chemistry, biology, and geology all work together in intricate, complex, subtle, violent, and often beautiful ways.

- **A.** We live on a planet that is constantly in motion and constantly changing.
- **B.** The interconnectedness of the different Earth-science systems is a fascinating part of Earth's story.
- **C.** The workings of planets involve great spans of time and distance.
- **D.** Human beings are not passive observers of Earth but central characters connected to all the other parts of the planet.

II. Earth is both biologically and geologically alive. Forces at work cause its interior and exterior to constantly change and evolve.

- **A.** Earth's movements are usually slow compared to human time scales; still, there are plenty of catastrophes to keep things lively.
- **B.** Within Earth, rock is constantly flowing on the order of centimeters a year, giving the illusion that Earth is static and unchanging.

C. However, sped up like a movie on fast-forward, Earth's history would look more like the swirling eddies of a whirlpool than a ball of rock.

  1. Continents would whiz about Earth's surface.

  2. Rocks would continuously cycle from the surface into the deep interior of Earth and back up again.

  3. The planet of our past would be no more recognizable than the planet of our future.

D. We try to understand things that happened billions of years ago with incomplete evidence. It is like trying to reconstruct the plot of a complex movie from just one photo still.

E. We have some help: There are fundamental laws of physics that control the motions of objects and the flow of energy.

  1. We can trace the history of our planet to its beginning—and then even further back to the Big Bang, 13.7 billion years ago.

  2. Given these laws of physical forces, the eventual formation of stars, planets, and maybe life itself was arguably inevitable.

  3. Once the machinery of our universe was set in motion, gravity, electromagnetism, and the strong and weak nuclear forces ensured there were many planets orbiting many stars in many galaxies.

  4. However, very few planets may be like our own because the conditions required to maintain liquid water on a planet's surface for 4 billion years are remarkably unusual.

F. This is not a geology course in the narrow sense of being only about rocks and fossils.

  1. Most of us doing research about Earth are from other areas of science such as geophysics, geochemistry, and geobiology.

  2. Divisions between different sciences are entirely artificial; this is particularly true in the study of a planet and how it works.

III. Plate tectonics is the unifying theory of geology that provides the framework for understanding how our planet evolves and changes over time.

A. Earth's outermost layer, the lithosphere, is made up of about a dozen large pieces (and many smaller ones) of Earth's surface called plates. As the plates move, they drag the continents about the surface embedded within them.

B. The ocean seafloor forms from molten magma, making long chains of underwater volcanoes. Ocean plates form and move away from these mid-ocean ridges, growing older and colder with time.

C. Eventually, these ocean plates grow heavy and sink down into the mantle at ocean trenches along the edges of plates (subduction zones).

D. Plates move about horizontally at Earth's surface, and where continents collide, mountains form dramatically.

E. Much of what we call geology is the result of where these plates have been over time and the history of their collisions.

1. Saudi Arabia has a quarter of the world's oil because of the particular history of motions of the Arabian and Eurasian plates.

2. Earthquakes and volcanoes are usually the direct result of plate tectonics; they involve unbelievable amounts of energy, often with terrible consequences for humanity.

IV. The nemesis of plate tectonics is the sun, which drives processes that erode the surfaces of continents. The constant struggle between plate tectonics and erosion has shaped the lands we live on.

A. The energy that shapes the surface of the land comes from the sun and Earth's interior.

1. In the sun, energy is released from the atomic process of nuclear fusion in which hydrogen atoms fuse to form helium atoms; a small amount of mass is destroyed in the process and is converted to radiation that reaches Earth as sunlight.

2. Within Earth's interior, the radioactive decay of elements splits atoms and destroys mass which, in the process, is also converted into radiation.

3. Uranium, thorium, and potassium produce the heat responsible for Earth being geologically vibrant and active.

B. Sunlight drives the water cycle, which drives the rock cycle at Earth's surface.

1. Water evaporates up off the ocean, gets carried to the land, falls on Earth's surface as both rain and ice, and moves across Earth as a powerful mechanism of erosion.

2. Sediments, carried by water into the oceans, eventually become new rock through the processes of the rock cycle.

C. Other important characters in the story include gravity, entropy, the conservation of energy, and water.

V. Humans are an inextricable part of Earth's story.

A. Humans have become the dominant agent of geologic change, shaping and reshaping Earth's land, water, and air faster than any other geologic process.

B. Climate changes have continuously shaped the course of human history.

VI. Earth science is an incredibly new field. Many ideas discussed here are currently being debated within the geoscience community.

Recommended Reading:

Bjornerud, *Reading the Rocks: The Autobiography of the Earth*.

Calvino, *Cosmicomics.*

Savoy, Moores, and Moores, eds. *Bedrock: Writers on the Wonders of Geology*.

Questions to Consider:

1. What geologic processes must have occurred for fossil ammonites (relatives to the nautilus that dominated oceans hundreds of millions of years ago) to now be found in rocks at the highest mountains on Earth?

2. What would our planet look like if it contained no radioactive isotopes within it? What would it look like if radioactivity were producing twice as much heat within Earth's interior?

Lecture Two

Geologic History—Dating the Earth

Scope: The writer John McPhee once described the following analogy: If the length of your arm represented Earth's history, a light brush of a nail file across the tip of your fingernail would erase all of human history. Earth is enormously old, but determining its exact age took centuries of work. Scientists during the 1800s were obsessed with the task and made many failed attempts. Geologists had used laws of stratigraphy to determine the relative ages of rocks and had established a detailed qualitative geologic time scale largely based upon the sequential appearances and extinctions of life forms in the fossil record. It was not until the discovery of radioactivity, however, that absolute ages could be ascribed to Earth's rocks and fossils. Radioactivity not only provides the heat that keeps our planet geologically alive, but it also provides the means to determine its history. Interestingly, the oldest rocks on Earth did not originate here, they are meteorites that formed at the very beginnings of our solar system.

Outline

I. Time is the foundation of geology.

- **A.** The whole process of Earth's creation and evolution occurs on timescales that are unimaginably long to us.
- **B.** Going backward in time, we can see the effect of adding a power of 10 in years at each step.
    1. 10 years ago (10^1)—Where did you live and work?
    2. 100 years (10^2)—First cars in production; you were not alive yet.
    3. 1000 years (10^3)—The Middle Ages; sun and planets orbit Earth.
    4. 10,000 years (10^4)—The dawn of civilizations.
    5. 100,000 years (10^5)—The rise of *Homo sapiens*; Neanderthals around.
    6. 1,000,000 years (10^6)—Early hominids like Australopithecus.
    7. 10,000,000 years (10^7)—The age of mammals; no bipedal hominids.
    8. 100,000,000 years (10^8)—The age of dinosaurs.

9. 1,000,000,000 years (10^9)—Only single-celled organisms exist.
10. 4,567,000,000 years—The beginning of Earth.

C. Humans have existed as a species for almost 200,000 years, which is 0.004% of the age of Earth.

II. Humans have long been fascinated with time and the question of the age of Earth.

A. Time has formed a central part of philosophies and religions from their very inception. There have been many differences in the perceptions of how time operates.

1. Eastern philosophies and religions have long thought of time as being cyclical, repeating after a time of catastrophe.
2. The Judeo-Christian/Islamic tradition views time as linear, having a discrete beginning and ending.
3. These contrasting views can be seen in the great historical debate of the 18th century between the uniformitarians—who believed in the cyclical, repetitive, and practically endless nature of Earth's geology—and the Catastrophists, who believed that the earth was very young and had entirely formed in a catastrophic event.

B. Scientists and theologians have used many methods to try to determine the age of our planet.

1. Early societies used religious texts to try to determine Earth's age, with numbers ranging from thousands to billions of years.
2. Scientists in the 18th and 19th centuries used sedimentation rates, ocean salinity, and models of cooling materials to determine Earth's age; most of these estimates were far less than the real age.
3. Detailed estimates of Earth's age by a leading physicist of the 19th century, William Thomson (Lord Kelvin), in the range of 20 to 100 million years, were wrong because radioactivity had not yet been discovered; these estimates inadvertently set back studies in geology and evolutionary biology because they portrayed an Earth too young for geological and biological processes to operate.

C. An accurate determination of Earth's age had to wait until the discovery of radioactivity.

III. In the years before radioactivity could determine the ages of rocks, geologists had to use a variety of techniques to determine the relative ages of rocks.

A. The laws of horizontality and superposition were used to determine sequences of geologic events.

1. It was assumed, mostly correctly, that layers of sedimentary rocks were laid down horizontally and in sequence with the oldest layers at the bottom.

2. Any faults or dikes that cut across these layers or other geological structures must be younger than the features they cut across.

3. The Grand Canyon provides a classic example of the relative ages of rock layers.

B. Erosional surfaces within rock layers, called unconformities, represented missing gaps of time.

C. Sequences of rock layers could be identified across great distances and could be assumed to have the same ages.

D. The discovery that many extinct animals had very limited times of existence provided an important means of identifying the relative age of a rock layer even without the presence of the sequence of layers above and below it.

E. These laws, taken together, allowed 19^{th}-century geologists to construct a detailed geologic time record that related past geologic events with the biologic fossil record. Many of the names of geologic periods were taken from the places that key fossils or rocks were found.

1. The eras were subdivided into periods, and recent periods were further subdivided into epochs, based upon further details in the rock record.

2. The rock record was divided into three eras (Paleozoic, Mesozoic, Cenozoic) based upon the kinds and complexity of life forms identified; the Cenozoic (era) included the present time.

3. Because fossils older than the Cambrian period of the Paleozoic era were not found, all time older than that was lumped together as the Precambrian eon.

F. Radioactivity, the same process responsible for providing the heat that keeps our planet geologically alive for so many years, provides a clock for determining the absolute ages of rocks.

G. The oldest objects on Earth are not from Earth.

Recommended Reading:

Bryson, *A Short History of Nearly Everything.*

Gould, *Time's Arrow, Time's Cycle.*

Questions to Consider:

1. Under what circumstance might the laws of superposition be incorrect in interpreting the relative ages of rock layers? Where might you go to see this?
2. The divisions in time within the geologic time scale get finer and more detailed the closer you get to the present. What are two different reasons for this?

Lecture Three

Earth's Structure—Journey to Earth's Center

Scope: Geologists work under a severe handicap: Light does not travel through rock. We know more about the structure of galaxies that are billions of light years away and seen through telescopes, than we do about the interior of our own planet. Advanced techniques of analyzing seismic waves from earthquakes, however, are now allowing us to map out the three-dimensional structure inside Earth. Temperature and pressure both increase rapidly with depth, but they have dueling effects on the form and behavior of rock. The dominating structures within Earth's mantle occur beneath subduction zones, where sheets of ocean seafloor can be seen sinking all the way to the bottom of the mantle. Some of the return flow of rock up to the surface can be seen in the form of large mantle plumes, the biggest two of which are found beneath the Pacific Ocean and the southern African Plate. Beneath the mantle, the outer core consists of a swirling ocean of liquid iron that creates a constantly shifting magnetic field that often reverses direction on a random basis. At Earth's center, the intense pressure causes a small snowball of "frozen" iron that seems, paradoxically, to be spinning faster than the rest of the planet. The entire planet's interior is in motion, though for the mantle, it is at very slow rates—about as fast as your hair grows.

Outline

I. During this lecture, you will get a sense of what the inside of our Earth is like and what processes are used to construct 3-D pictures of Earth's deep interior.

II. All planets are layered, and Earth is no different. The layers take three general forms: a core, a mantle, and a crust.

- **A.** The crust and top part of the mantle form a layer called the lithosphere. This is known as a plate, and forms the basis of plate tectonics.
- **B.** Underlying the lithosphere is a thin layer called the asthenosphere. Unlike the rigid lithosphere, the asthenosphere is softer and weaker (though still solid rock!).

C. People have tried for a long time to determine what is inside our planet.

   1. In 1681, Thomas Burnet described Earth as having three layers in his book *Telluris Theoria Sacra* or *The Sacred Theory of the Earth*.

   2. In Burnet's model, the mantle was a layer of water that rose to the surface, breaking apart the continents and providing the water for the biblical flood.

   3. Burnet also thought, correctly, that Earth formed from a homogenous ball of rock that became layered over time.

III. Plate tectonics is the foundation of geology.

A. A plate has two forms: continental crust and ocean crust. Ocean crust is very young and continental crust is very old, in terms of geological time.

B. We know that plates move on the order of centimeters a year because of data collected from extremely sensitive GPS sensors. Over geologic time, the continents move many thousands of kilometers.

C. Most of the interiors of the plates are fairly rigid and unchanging. Earthquakes and volcanoes primarily occur at the boundaries of plates.

D. Earthquakes and seismology are the focus of my own research. Earthquakes provide our only means of seeing deep into our planet, like using a CAT scan to take remote pictures of the inside of a human body.

E. Seismic tomography is similar to medical tomography. We have seismometers all around the globe that are used to look at the paths of seismic waves through Earth and generate tomograms.

IV. The inside of Earth is unusual. What would you actually see if you entered Earth?

A. The top of the crust of a continent is composed of a lot of different types of rock, both sedimentary and volcanic.

B. The continents are layered and highly structured. A great deal is known about this structure because seismic tomographic imaging is used to map out the locations of oil, natural gas, coal, and minerals.

C. At the mantle, we enter into rock that is denser, heavier, and hotter.

1. One hundred kilometers down, the temperature is more than 1400°C.
2. At the center of the planet, the temperature is more than 5500°C.

D. There are no open spaces inside Earth because the pressure is too intense. The pressure at the core is 3.64 million times the pressure at Earth's surface.

V. What has seismic tomography shown us in terms of what Earth is doing?

A. There are regions within the mantle that are moving up and down.

1. Seismic waves speed up or slow down depending upon the temperature of rock.
2. Waves travel quickly through cold rock and slowly through hot rock.
3. Seismologists represent these speeds with red and blue colors and use the data to construct 3-D pictures of the inside of Earth; the red regions are places where the seismic waves are traveling slowly (hot rock) and the blue regions are places where the seismic waves are traveling quickly (cold rock).
4. These data are not only snapshots in time, but give us a sense of Earth's motions.

B. The entire planet is churning, convecting, and flowing. Sped up in geologic time, it would look like an eddy of swirling rock and metal.

C. Seismic tomography removes the effects of radial layering and reveals the variations within layers.

D. Tomography has allowed seismologists to track the motion of the Farallon slab as it sinks toward the core beneath North America.

E. There are regions of hot rock within the mantle that are buoyant and may be feeding hot spot volcanoes at the surface (e.g., Hawaii).

VI. The compositions of crystals and minerals are instrumental in figuring out what is inside the planet.

A. Crystals at surface pressures are not stable at deeper levels. The intense pressures cause minerals to entirely change their color and texture (e.g., graphite into diamond).

B. Using bits of rock sandwiched between diamond tips (diamond anvil cells), we can re-create the conditions of the inside of the earth.
   1. The cell is squeezed to intense pressures and then heated with a laser.
   2. Comparing the results of this laboratory experiment with information from seismic tomography produces a good picture of what is at the center of the earth.

C. The mantle is composed almost entirely of silicate rocks, and the core is almost entirely iron and nickel.

D. The outer part of the core convects and churns so actively that it generates a geodynamo. This activity creates the magnetic field at Earth's surface.

E. The inner core is solid iron. Recent seismological work suggests that the inner core might be rotating relative to the rest of the earth—rotating faster than the mantle and lapping it every 100 to 400 years.

F. The magnetic field randomly reverses with time and also gives us a layer called the magnetosphere that protects us from solar wind and allows life to exist on the surface of land.

Recommended Reading:

Oldroyd, *Thinking about the Earth: A History of Ideas in Geology*.

Vogel, *Naked Earth*.

Questions to Consider:

1. Though the asthenosphere may be partially molten, how do we know that it cannot be totally liquid?
2. Tarzan creator Edgar Rice Burroughs created a whole world called Pellucidar that existed on the inside of the mantle in a hollow core (his character Tarzan actually goes down there in *Tarzan at the Earth's Core*). Why is such a situation impossible?

Lecture Four

Earth's Heat—Conduction and Convection

Scope: It is a law of the universe (the second law of thermodynamics) that heat flows from hot regions to cold regions, not the other way around; this law determines the life history of all planets. Earth is about 6000°C at its center and a little more than 0°C at its surface, so heat is constantly flowing out toward Earth's surface and then out into space at a rate of 44.2 trillion watts—almost triple the global rate of human energy use. The source of Earth's heat is primarily the radioactive decay of isotopes of uranium, thorium, and potassium. Earth would be a frozen, geologically dead cinder floating in space if it were not for radioactivity. This flow of heat occurs in three ways: conduction, convection, and radiation. Earth loses its heat to space through radiation, but radiation plays only a small role inside the planet. Because heat conducts through rock so slowly, most of Earth's heat is carried internally by means of convection, with some important results. Convection in the liquid iron outer core creates our planet's magnetic field. Convection in the rocky mantle is the driving force for plate tectonics, which is the mechanism by which the continents move horizontally about Earth's surface.

Outline

I. Heat is the lifeblood of planets. It is what flows throughout Earth (largely from the interior out) and what drives all the motions. If we are going to understand how the earth works, we need to understand the flow of heat.

II. Gravity is an overwhelming force that drives the motions of Earth, but it is only one of four forces. All of geology can be explained with these four forces, and they all play important roles.

- **A.** Gravity is the weakest of the four, but it acts over the largest distances and over all matter.
- **B.** One of the most important forces is electromagnetism. Electrons have a negative charge, and protons have a positive charge; opposite charges attract, and like charges repel—this bonding gives structure to matter.

C. The strong nuclear force holds all particles together (including the nucleus of an atom). If it were not for the strong nuclear force, you would never have any atoms larger than hydrogen.

D. The weak nuclear force, 10 trillion times smaller than the strong nuclear force, determines the radioactive decay for certain elements. The decay of unstable isotopes gives off energy that is vital in keeping our planet alive and heated.

III. Thermodynamics, the flow of heat, determines the motions that will eventually power plate tectonics and lead to mountains and oceans.

A. The measure of the oscillation of the atoms of objects in motion is their temperature.

1. If you give an object more heat, you raise its temperature.
2. Temperature is a measure of the motion of atoms
3. Heat is the transfer of energy from one object to another.
4. Throughout Earth, energy is constantly flowing and is always conserved (neither created nor destroyed).

B. Energy takes many different forms: kinetic energy, potential energy, electrical energy, chemical energy, and nuclear energy. Energy is constantly changing from one form to another, but the energy is always conserved in any of these transfers.

C. When you heat any object, the atoms within it vibrate more energetically and the object expands in a process called thermal expansion. When the object expands, it becomes more buoyant, and gravity provides the pressure that will cause it to rise.

D. For most planets (including Earth), the heating of the mantle comes from two sources: the radioactive decay of certain elements and the primordial heat coming out of the planet's core.

E. Planets only cool one way: having their surface in contact with the chill of space.

F. Much of the high temperatures within Earth are due to the more frequent collisions of atoms that result from the high pressures.

G. Another important factor for Earth is the second law of thermodynamics, which determines that heat will always flow from a hotter region to a colder region.

1. Time flows in the direction of entropy (disorder); things go from an ordered state (with the heat packed into one place) to a disordered state (with the heat dissipated).

2. This process drives the heat from the inside of the earth out through the surface and into space.
3. Heat is leaving the surface of Earth at a rate of about 44.2 terawatts (TW) or 44.2 trillion watts—the equivalent of about 700 billion 60-watt light bulbs.

H. Radioactivity is important as well. Our planet would be chilled and immobile (like the moon) if it were not for the heat constantly being created internally. Four isotopes—uranium-238, uranium-235, thorium-232, and potassium-40—constantly generate heat within our planet and keep it geologically active.

IV. Heat flows from one place to another in three ways: radiation, conduction, and convection.

A. Radiation is the natural emission of electromagnetic waves.

1. The wavelength of radiation is a function of temperature; if objects are hotter, they emit a higher frequency of radiation.
2. Because light does not pass through rock, radiation does not play a big role for getting heat from the inside of the earth out into space.

B. Conduction is the transfer of heat by atomic motions and happens in two ways.

1. Within rock, thermal conduction occurs when excited atoms bump into each other, propagating heat; this is a very slow process.
2. Within metals, electrical conduction occurs when electrons move around freely and carry energy rapidly. In Earth's core, electrical conduction works wonderfully because the core is made of metal; our mantle and crust are made of rock, so conduction is not efficient.

C. Convection occurs when, instead of energy flowing through the rock, you move the rock and take the energy with it.

V. How does heat get from the center of Earth's core out to the surface?

A. Within the inner core, the heat will flow almost entirely by electrical conduction.

B. Once it gets to the outer core, it will move quickly from the liquid iron bottom of the outer core to the top of the outer core because it will be both convecting and electrically conducting.

C. The heat conducts incredibly slowly through the rock at the base of the mantle, creating an unusual area called the core-mantle boundary region.
D. Once in the mantle, the heat convects from the base to the top. This process, mantle convection, is the driving force for plate tectonics.
E. The heat conducts slowly across the top of the hot rock near the surface, creating another thermal boundary layer (the lithosphere) like the core-mantle boundary region. As a result, the temperature increases tremendously across the lithosphere.
F. Once it gets to the surface, heat radiates out into space, largely in the infrared spectrum.

Recommended Reading:

Calvino, *Cosmicomics.*

Davies, *Dynamic Earth*.

Stacey, *Physics of the Earth.*

Questions to Consider:

1. What would happen to the temperatures within Earth if you suddenly released the pressures on the materials there? (Hint: Think about what the gas law states.)
2. How is convection within the mantle similar to a boiling pot of soup? How is it different?

Lecture Five
The Basics of Plate Tectonics

Scope: Earth has the right conditions for the convection of its mantle to take the form of plate tectonics, where the top 100 kilometers or so of the lithosphere is divided into a couple dozen distinct pieces called plates. The process by which these plates move about Earth's surface is called plate tectonics, and it is the principal unifying theory in geology that explains the existence of continents, oceans, mountains, earthquakes, volcanoes, the distribution of mineral resources, the changing climate, and many other things. The theory of plate tectonics evolved from earlier ideas such as Wegener's hypothesis of continental drift. Earth's plate tectonics, and therefore mantle convection, is driven by two factors: internal heating from radioactivity and surface cooling. The actual pattern of plate tectonics, including the history of the movements of continents, is driven by the sinking of cold and dense ocean seafloor back into the mantle. Ocean lithosphere is created at mid-ocean ridges and is consumed back into the mantle at subduction zones.

Outline

I. The theory of plate tectonics—the idea that the earth's surface is divided into plates that move about and bang into each other, creating all the geology we see—is the framework for understanding the geology of Earth's surface.

- **A.** The development of the theory of plate tectonics represents a classic example of a paradigm shift—disparate geological data suddenly made sense within the framework of plate tectonics.
- **B.** The theory of plate tectonics drew from many earlier ideas about the movements of the continents.
  - **1.** People like Francis Bacon had commented upon the fit of continents around the Atlantic Ocean.
  - **2.** Benjamin Franklin, in 1782, proposed something similar to plate tectonics: that the earth is acting like a fluid, breaking the plates up and moving them about.
  - **3.** In 1908, Frank Taylor proposed the idea that the continents had previously moved.

4. The influential hypothesis of continental drift, including the idea that the continents had previously been part of a supercontinent called Pangaea, was published by Alfred Wegener in 1915 but was never fully accepted by the geological community.
5. The theory of plate tectonics was finally formalized in 1967 by scientists Jason Morgan and Dan McKenzie, independently, though many other scientists were involved in the discoveries that led up to it.

II. The lithosphere is divided into about a dozen major plates, with another dozen smaller plates. The exact number is not significant, because there is no clear distinction between small plates and microplate fragments within internally deforming regions of larger plates.

A. Most plates contain both continental and oceanic crust. Major ones are the North American, South American, African, Eurasian, Indo-Australian, and Antarctic plates.

B. Many plates consist of smaller plates that move independently of each other.

1. The African Plate consists of the Somalian and Nubian plates that are rifting apart at the rift valleys of eastern Africa.
2. The Indo-Australian Plate consists of three separate plates: the Indian, Australian, and Capricorn plates.

III. The boundaries between plates can be divergent, convergent, or conservative.

A. Divergent plate boundaries occur when plates move apart from each other.

1. Divergent boundaries on continents take the form of continental rifts like the African rift valleys.
2. Divergent boundaries in the oceans form ridges and rises, like the Mid-Atlantic Ridge and East-Pacific Rise.

B. Convergent boundaries occur when plates smash together.

1. A convergent boundary between oceanic and continental crust forms a subduction zone, where the plate containing the ocean crust sinks beneath the plate containing the continental crust.
2. A convergent boundary between two pieces of oceanic crust forms a subduction zone, where the older ocean crust usually sinks beneath the younger oceanic crust.

3. A convergent boundary between two continents results in the formation of a mountain range because the continental rock is too buoyant to be able to sink into the mantle.

C. Conservative boundaries occur whenever two plates slide past each other. These boundaries are called transform faults (e.g., the San Andreas Fault); transform faults that occur within oceans are usually part of the mid-ocean ridge system.

IV. The process of plate tectonics is the surface expression of mantle-wide convection.

A. Seismic tomography, computer convection modeling, and laboratory corn syrup experiments show that the style of convection that you get within Earth (or any other planet) is dependent upon very particular characteristics: temperature differences in the mantle, the viscosity of the material, the size of the planet, the density of the rock, the magnitude of gravity, and how much the rock expands when heated.

B. Mantle convection is primarily driven by the sinking of cold sheets of ocean lithosphere that have been cooled through contact with ocean water.

C. Mantle rock is heated both by internal heating from radioactive decay and from the conduction of heat out of the core, though the relative importance of these two mechanisms for plate tectonics is not known.

Recommended Reading:

Kuhn, *The Structure of Scientific Revolutions*.

Sullivan, *Continents in Motion*.

Questions to Consider:

1. The geologic evidence in support of plate tectonics is overwhelming and looks so obvious to us now, in retrospect. Why might it have taken such a long time for scientists to see the obvious conclusion that Earth’s surface is made of horizontally moving plates?
2. Can you think of other examples where solids behave like liquids over long periods of time?

Lecture Six

Making Matter—The Big Bang and Big Bangs

Scope: To make a planet like Earth requires a wide variety of building materials, and the elements that form Earth's varied layers have a very unusual history. Nearly all of the matter of our current universe formed in the earliest days of its existence—within a few seconds after the Big Bang. Most of this matter, which formed from the pure energy of the Big Bang, took the form of hydrogen and helium atoms within about 300,000 years. So where did all of the other elements like carbon, oxygen, and iron come from? Elements larger than hydrogen and helium formed during the last supernova stage of dying stars. Within a few hundred million years after the Big Bang, the hydrogen and helium had pulled together under the force of gravity to form stars, which shine because hydrogen atoms are fusing together to make helium atoms, releasing radiation energy in the process. When the hydrogen runs out, the stars go through a rapid sequence of fusion stages called a supernova that produces heavier elements and then ejects them into space. This means that most of Earth, including your body, is made of the exploded ashes of a dead star.

Outline

I. The matter of our planet was primarily made through two very different mechanisms: the Big Bang and the supernovae of dying stars.

A. The hydrogen and helium of this universe were created at the start of the Big Bang, about 13.7 billion years ago.

B. Nearly all atoms larger than hydrogen and helium are created in the last stages of the life cycle of large stars as they pass through the supernova stage.

II. Our universe came into creation in an unimaginably cataclysmic process called the Big Bang, which began about 13.7 billion years ago.

A. Before the Big Bang our universe, including the spatial dimensions that comprise it, did not exist.

B. The moment the Big Bang occurred, the universe immediately began to expand at speeds on the order of the speed of light. The energy and matter expanded outward, pulling the universe with it.

C Soon after the Big Bang, energy began converting into matter according to Einstein's well-known equation $E = mc^2$.

D. The evidence for the Big Bang theory comes primarily through its ability to explain three major lines of evidence: the distribution and motions of galaxies, the cosmic microwave background radiation, and the composition of the universe.

1. The Doppler shift of light from stars shows that the universe is expanding; the distribution of locations of galaxy clusters as well as their relative velocities show that they are not moving from a single point, but that the entire fabric of space is expanding.
2. Energy in the microwave spectrum (corresponding to a temperature of about 2.7 degrees Kelvin [K]) exists everywhere in the universe; this matches the predicted spectrum of the remnant reverberation of the Big Bang after stretching the universe out to its current size.
3. The composition of the universe, seen in the make-up of stars and interstellar dust, is about 75% hydrogen and 25% helium, with all other elements comprising insignificant masses; this matches theoretical predictions for the Big Bang process.

III. The predicted timeline of the Big Bang involves initial changes occurring rapidly with later changes occurring more slowly.

A. At the start of the Big Bang, all four of the fundamental forces were unified as a single force. The universe likely consisted of many more spatial dimensions than the three we have.

B. By 10^{-43} seconds after the Big Bang the single unified force began to split apart.

C. By 10^{-34} seconds, the universe entered into a period of inflationary expansion, moving faster than the speed of light. This means that the majority of our universe is forever invisible to us, as the light from stars in these parts can never catch up to us.

D. By 10^{-32} seconds, the first subatomic particles were forming. The universe was 30 centimeters in diameter and had a temperature of 3×10^{26} K.

E. By 10^{-11} seconds, the four forces had finally separated with the split of the electromagnetic and weak nuclear forces.

F. By 10^{-5} seconds, protons and neutrons had formed, though it was still too hot for stable atoms to form. The universe was 0.002 light-years in size (100 times the earth-sun distance) and had a temperature of 10^{13} K.

G. By one second, electrons had formed and were annihilating positrons. The universe was three light-years in size with a temperature of 10^{10} K.

H. By three minutes, hydrogen atoms were forming, though it was still too hot for stable atoms to form. The universe was 50 light-years in size with a temperature of 1 billion degrees Kelvin.

I. By 10,000 years, matter began to dominate over radiation. The universe was two million light-years in size with a temperature of 30,000 K.

J. By 1 billion years, protogalaxies and the first stars were forming. The universe was 10 billion light-years in size with a temperature of only 10 K.

K. By 5 billion years, full galactic disks were forming. The universe was 20 billion light-years in size with a temperature of 5 K.

L. Currently, 13.7 billion years after the Big Bang, the universe is 40 billion light-years in size with a temperature of 2.7 K (−270.42°C).

M. The fate of the universe depends upon the amount of mass it contains.

1. If there is too much mass, the universe will stop expanding and eventually collapse; if there is too little mass, the universe will continue to expand forever.

2. It currently seems as if the rate of expansion of the universe is actually increasing.

IV. The force of gravity is responsible for the formation of galaxies. Galaxies contain between tens of millions and a trillion stars. Stars are more plentiful and tend to be much larger near the centers of galaxies.

V. Stars are born when there is enough hydrogen that the intense pressure causes hydrogen atoms to fuse together to form helium, emitting light in the process. This process is called nuclear fusion.

A. Most of a star's existence involves the fusion of hydrogen in the star's core to form helium.

1. Near the end of a star's life, hydrogen fusion occurs in the outer layer of the star, and the star swells in size to become a red giant or supergiant.

        2. In the final stages of a star, when the hydrogen runs low, the helium begins fusing to start a series of fusion reactions that creates elements larger than helium.

    B. Stars follow a life cycle that is variable depending upon the size of the star.

        1. Low-mass stars, at the end of their lifetimes, go through a sequence of becoming red giants, planetary nebulae, and then white or black dwarves; small stars can last for many billions of years.

        2. High-mass stars go through a final sequence of being a red supergiant, a supernova, and either a neutron star or black hole; very large stars can burn out in only thousands of years.

    C. This process of creating higher elements is called nucleosynthesis. It does not make all elements in the same ratios.

VI. The fact that our solar system contains planets means that our sun must be a second-generation star. A previous star had to die for the planet Earth to be formed from its remains.

Recommended Reading:

Hawking, *A Brief History of Time.*

Tyson, *Death by Black Hole: And Other Cosmic Quandaries.*

Questions to Consider:

1. What would happen to the life cycle of stars if the force of gravity were larger than it is (with the other forces remaining unchanged)? What would the implication of this be for the time needed for the evolution of complex life?
2. What was our universe like before the Big Bang? Is this conceivable?

Lecture Seven

Creating Earth—Recipe for a Planet

Scope: Our whole solar system—including the sun, planets, asteroids, meteoroids, and comets—formed at the same time: 4.567 billion years ago. It began as a huge, sparse distribution of dust and gas that pulled together under its own gravitational attraction. As this planetary nebula coalesced, it began to rotate due to the conservation of angular momentum, looking like a huge, rotating fried egg in space. The center of the solar system, containing 99.85% of the mass involved, pulled together to form the sun. The rest began to clump together to form millions of baby planets called planetesimals. These planetesimals combined through countless violent collisions until the planets, dwarf planets, moons, and asteroids were formed; this process took only tens of millions of years. The early Earth was very hot, heated by gravitational compression, the collision of impacting planetesimals, the sinking of the iron core, and the radioactive decay of short-lived radioactive isotopes. Earth reached it hottest moment when a Mars-sized object struck it, ejecting debris that would eventually come together to form our moon. At this point, about 40 million years ago, most, if not all, of Earth was molten; Earth has cooled steadily since then.

Outline

I. All societies and cultures have had creation myths, often very colorful and creative, that have explained how Earth was formed. Our current story, provided through sciences like geophysics, is no less amazing and fantastic.

A. Our Earth and the rest of the planets revolve around a sun as part of a solar system that also contains asteroids, meteoroids, comets, and small debris—all orbiting the sun.

B. Figuring out this story is like detective work. Geologists, by looking at the clues in our solar system, have been able to figure out how our solar system, including Earth, came about.

C. Any model that explains the solar system has to be able to explain the observations we see around us and has to be able to predict new observations as they come up. The best model for this is the idea that our solar system formed from a protoplanetary disc.

D. The clues we have to go by are:

1. The total mass of the planets is small, about one one-hundredth of that of Sun.
2. The planets closest to the sun are more metal-rich, with some rock and almost no gas and ice; as you go further from the sun, the planets become more rocky, and then become mostly gas and ice.
3. Craters are very abundant on some planets.
4. All planets travel about the sun in nearly the same plane (the solar ecliptic) and in the same direction; most planets rotate in the same direction.
5. Planetary orbits do not intersect.

II. The hypothesis that Earth, along with the rest of the solar system, formed simultaneously from a protoplanetary disk (also called accretionary disk) best explains the available geological and astrophysical evidence.

A. This disk formed relatively quickly from thin, diaphanous interstellar clouds of hydrogen and helium as well as the elemental remains of a previous supernova.

B. This very broad and diffuse cloud of gas, dust, and ice particles was pulled together by the gravitational attraction of its own mass.

C. As the cloud began to contract it began to spin faster according to the conservation of angular momentum, as with the formation of the galaxy; soon it took the form of a central bulge with a surrounding disk along the equator of its rotation.

D. The sun formed at the center of the disk, involving almost 99% of the mass of the solar system.

1. The center of the protoplanetary disk compacted so that the temperature at the core reached about 10 billion degrees Kelvin.
2. This compression of the center caused a gigantic explosion, called the T-Tauri phase, which cleared much dust and gas from the inner solar system and removed Earth's earliest atmosphere.
3. When pressures and temperatures in the core got high enough, the sun began fusing hydrogen into helium and became a star.

E. The planets and other objects in the solar system formed from the outer parts of the disk.

1. The protoplanetary disk was initially very smooth but began to get locally lumpy.
2. Electrostatic forces began to cause the dust and ice to clump together to form protoplanetary dust balls.
3. When these dust balls became larger than about one kilometer in diameter, gravity rapidly began to pull them into larger masses. At one point there were millions of these planetesimals.
4. The planetesimals continuously collided with each other and swept up nearby gas and dust, growing larger until the eight major planets and their major moons had formed.
5. This period of major collisions (the late heavy bombardment period) lasted for about a half-billion years and is responsible for the major impact basins seen on Mercury and the moon.

III. Earth has had two major phases in its history: a brief period of heating up and a long period of cooling down that will continue until the sun becomes a red giant.

A. Earth heated up to the state of being entirely or nearly entirely molten due to several different factors.

1. Compression of the growing Earth caused increasingly high pressures that in turn caused high temperatures.
2. The impacts of planetesimals and smaller meteoroids heated Earth through the conversion of gravitational potential energy into kinetic energy and then into thermal energy (heat).
3. The gravitational collapse of the mass of the planet, as well as the sinking out of iron to form the core, caused an additional conversion of gravitational potential energy into heat.
4. The high levels of short-lived radioactive isotopes, produced during the supernova phase, provided large amounts of heat.
5. The impact of a Mars-sized planetesimal ejected enough material into orbit around Earth to eventually form the moon and also provided the remaining heat needed to melt most, if not all, of the mantle.

B. Very quickly Earth was cooling off faster than it was heating up, and Earth has continued to cool ever since.

1. A solid lithosphere began to form, with pieces of continental crust embedded within it.

2. There is a debate as to whether all of today's continents existed at that time and have just been recycled, or whether the amount of continental crust has continuously grown since then.

Recommended Reading:

Calvino, *Cosmicomics.*

Ferris, *The Whole Shebang: A State-of-the-Universe Report*.

Questions to Consider:

1. If Jupiter had grown to about 80 times its current size, it would have become a star on its own. What would Earth have been like in that case?
2. Why would the separation of iron out of the initially homogeneous Earth to form Earth's core have occurred in a quick, runaway process?

Lecture Eight

The Rock Cycle—Matter in Motion

Scope: Though rocks may seem constant and unchanging when viewed from our very brief life spans, they are actually caught up in a continuous cycle of changing forms known as the rock cycle. The rock cycle can be thought of as beginning with igneous rocks because they form directly from magma; the other two kinds of rocks, sedimentary and metamorphic rocks, form from previous rocks. Sedimentary rocks form from the cementation of pieces of previous rock that have been eroded, transported, and deposited in a new location. Metamorphic rock forms when previous rock is subjected to high temperatures and/or pressures and changes its form, texture, and mineral composition. Due to the complex competing forces of Earth's internal heat-driven and surface sun-driven geologic processes, rocks may move in many different ways through the rock cycle.

Outline

I. We can explore the various stages of the rock cycle by trying to solve the following challenge: How do we get a carbon atom from a piece of paper back into another tree?

- **A.** We could bury the paper next to the roots of the tree, where it will dissolve over time and allow the carbon atom to be absorbed through the roots, akin to weathering.
- **B.** We could burn the piece of paper, creating carbon soot that could be absorbed in the roots and carbon dioxide gas that could be absorbed by the leaves of the tree.
- **C.** We could eat the piece of paper, combining the carbon atom with the oxygen in our bodies to create carbon dioxide. We could exhale this carbon dioxide into the air, where it could be absorbed by the tree.
- **D.** We could flush the piece of paper down the drain, where it would make its way to the ocean. Once there, there are multiple paths the carbon atom could take:
  - **1.** It could leave the ocean surface in the form of carbon dioxide and travel through the air back to the tree.

2. It could be eaten and eventually buried as organic calcium carbonate ooze in a process called deposition.
3. Once buried, the carbon atom could get squeezed and compressed to make sedimentary rock through the process of lithification.

E. There are several ways for the atom to get back to the tree.

1. Lowering the sea level could expose the rock to weathering and rain, which would dissolve the calcium carbonate and release the carbon dioxide back into the atmosphere (or back into the ocean).
2. The rock could get trapped within a plate collision and pushed down, where the increase in temperature and pressure could change the rock into marble—a process called metamorphism; the marble could erode and release carbon dioxide gas into the atmosphere or back into the ocean.

F. The carbon atom at the bottom of the seafloor could be subducted into the mantle. At about 100 kilometers down, water will leave and carry carbon dioxide into the mantle above it, lowering the melting point of the rock and forming magma.

1. The magma could erupt at the surface as a volcano and the carbon dioxide gas could travel through the atmosphere back to the tree.
2. The magma could crystallize underground and create a new igneous rock which can be eroded at the surface or buried and metamorphosed again.

G. The subducted lithosphere could take the carbon deep into the mantle, where the intense pressure would squeeze it into a diamond. The slab of ocean seafloor eventually sinks to the base of the mantle, where it will eventually heat up and expand.

1. The rock could become buoyant and melt as it reaches the surface, becoming carbon dioxide and returning to the atmosphere.
2. The rock could be buried for hundreds of millions of years until mined by humans.

H. There are many different paths in this process, and each one is unique according to its particular geological environment.

I. Humans play a vital role in the rock cycle, in the same way they affected the future of this hypothetical carbon atom.

II. Geology used to be an inorganic field, but now we realize that so much of the geology of the surface of Earth happens with life involved—the concept of inorganic chemistry has been largely abandoned.

A. Chemical reactions that alter rocks on Earth's surface are intimately involved with single-celled organisms that are involved with the process of erosion.

B. People have long been aware of their connection to the land. They trade atoms with the environment continuously.

C. Biology has shown us that we are not single organisms separate from others but are walking colonies of organisms (e.g., bacteria throughout our digestive tract).

III. Rocks retain the clues of their history for a long time. Using a random particular rock, a geologist can piece together its story.

A. This particular rock has three different layers: a white layer sandwiched between two dark layers.

B. The rock is flattened, so the whiter rock sticks out of the sides while the darker rock is worn away.

C. The dark rock is a highly metamorphosed rock (schist) that probably began as mud and was squeezed to make shale, which was squeezed to metamorphose into slate. This rock probably ended up in the core of a mountain.

D. The white rock is quartz, which cracked into this rock in a molten state sometime after the initial schist formed. The quartz crystallized and solidified; when the top of the mountain wore away, the rock became exposed to the surface.

E. The nicely rounded shape means that this rock has traveled down a stream. Because quartz is harder than schist, the schist wore away; given enough time, the rock would crumble and only the quartz would remain.

F. As geologists, we are just beginning to explore the remarkable ways that rocks form and understand their long and tortured pasts as they travel through and around this tremendously complex rock cycle.

Recommended Reading:

Emiliani, *Planet Earth: Cosmology, Geology, and the Evolution of Life and Environment*.

Officer and Page, *Tales of the Earth*.

Questions to Consider:

1. What role does water play in the rock cycle?
2. How would the rock cycle on continents be different if there was no life there?

Lecture Nine

Minerals—The Building Blocks of Rocks

Scope: Rocks are made of minerals—every child learns this in school. To appreciate the miracle that minerals can exist, however, requires a deeper appreciation of the physics of atomic particles. There is a very delicate balance between the electromagnetic and strong nuclear forces that both allows atoms to stably exist and lets atoms bond together in stable ways. It is the bonds between atoms that hold them in regular, locked configurations and allow minerals, and therefore rocks, to be stable. Bonds can be ionic, covalent or metallic, and this affects a mineral's behavior. There are almost 4000 minerals occurring in nature, but most of Earth can be described with about a dozen. Silicon and oxygen are the two most abundant elements in Earth's mantle and crust, and most rocks and minerals (called silicates) contain them. For a mineral to exist, the sum of the electric charges of the atomic ions must equal zero, and the ion sizes must be compatible. If the sizes do not match, the atoms—which are constantly oscillating—fly apart from each other. Changing temperature or pressure changes the relative ion sizes, causing one mineral to transform into another (e.g., graphite transforming into diamond).

Outline

I. The properties used to describe minerals are a result of their atomic structure.

- **A.** Crystals of minerals form naturally due to the fundamental laws of the universe.
- **B.** The process of forming matter is a result of the electromagnetic force. Opposite charges attract, proton-rich nuclei repel, and atoms stay together to form matter.
  - **1.** Electrons arrange themselves into separate regions called orbitals.
  - **2.** Electrons are not stable unless their outer orbitals are complete; they will either gain or lose electrons so that the outer orbital has a full complement of electrons.

C. A mineral is a naturally occurring, solid, inorganically formed material with a definite chemical composition and an ordered atomic arrangement. To make a mineral, two conditions must be met:
   1. The electrical charge of the mineral must add up to zero.
   2. The atoms must combine in a stable manner.

II. There are four ways that atoms bond: ionic, covalent, metallic, and intermolecular. These are all important for the formation of minerals.

A. Ionic bonds are the most common and involve negative and positive ions held together by electromagnetic force. The classic example of an ionic bond is the way sodium and chlorine atoms, two incredibly corrosive materials, combine to form ordinary table salt.

B. Covalent bonds are more efficient in terms of holding atoms together. They occur when atoms share electrons (e.g., the carbon atoms in diamonds or the bonds between silicon and oxygen).

C. Metallic bonds occur when the outermost electrons are free to move between all atoms. Metallic bonds tend to be weaker than ionic or covalent bonds, and make many metals soft and pliable (e.g., copper wire).

D. Intermolecular bonds, also called van der Waals bonds, result from the electrically polar nature of molecules and tend to be the weakest (e.g., the ability of carbon sheets in graphite to slide off so easily).

III. Only certain combinations of elements can result in the formation of stable minerals, depending upon the electrical charge and sizes of the ions.

A. For small variations in composition, mineral structures will stay the same, with slight variations to accommodate new elements. If the variations are large, the mineral structure will fall apart and change to a new structure.

B. If a combination of ions has a charge that does not add up to zero, it will attract additional ions until it does.

C. Because silicon and oxygen are the primary elements within Earth's mantle and crust, most rocks are silicate rocks. Silicate rocks are built around tetrahedra of one atom of silicon with four atoms of oxygen.

1. The tetrahedra are tightly internally bonded with covalent bonds, but usually form ionic bonds with other ions.
2. The silicate tetrahedra can also bond with each other in the form of chains, sheets, or 3-D structures.
3. The way that the silica tetrahedra bond with each other and with other ions determines the crystal structure, density, strength and other properties of the material.

IV. The Earth is made of a fairly small number of elements.

A. The Earth primarily consists of four separate elements: iron (35%), oxygen (30%), silicon (15%), and magnesium (13%). Other elements include nickel (2.5%), sulfur (2%), calcium and aluminum (each 1%), and everything else (about 0.5%).

B. There are 92 naturally occurring elements, but only eight of them account for 99.5% of Earth's mass. These resulted from the process of nucleosynthesis in the last dying moments of the stars that created them.

C. The percentage composition of elements within Earth's crust varies according to the mass, the volume, or the number of atoms. By the number of atoms, oxygen is about 63% of Earth's crust; by weight, oxygen is about 47% of Earth's crust; and by volume, oxygen is 91.7% of Earth's crust.

D. Earth's mantle is mostly made of silicon and oxygen and magnesium, with small amounts of iron and other elements. As a result, the mantle is almost entirely made of the minerals olivine and pyroxene and their higher-pressure phases.

E. Given an empty space, most minerals will grow slowly into a symmetrical crystal that is an indication of their internal atomic structure. Because minerals usually form within the enclosed spaces of forming or pre-existing rocks, they usually take the form of irregularly-shaped mineral grains.

Recommended Reading:

Brown and Mussett, *The Inaccessible Earth*.

Vonnegut, *Cat's Cradle*.

Questions to Consider:

1. All glass is almost entirely pure silica (silicon-oxygen tetrahedra) that has frozen rapidly into a random structure. Why is glass not considered a mineral?
2. Pure silica is transparent and colorless, like quartz. How do glass manufacturers create glass of different colors?

Lecture Ten

Magma—The Building Mush of Rocks

Scope: Most minerals form when they crystallize from magma, which is a combination of molten rock, water, dissolved gases, and solid fragments. Nearly all of Earth's mantle and crust is solid, so special conditions are required for magma to form. Magma occurs for different reasons in different tectonic settings: ridges and rifts, subduction zones, and above hot spots. Most magma is generated beneath oceanic mid-ocean ridges, where plates move apart and rock moves toward the surface to fill the gaps. Magma forms here due to a process called pressure release (the high pressures inside Earth prevent the melting of rock that would otherwise be hot enough to melt at the surface). The magma that forms beneath the spectacular volcanoes at subduction zones occurs because ocean water lowers the melting temperature of mantle rock there. Magma that feeds hot spot volcanoes, which often occur in the interior of plates, may form because the rock is actually anomalously hot, contains a lot of water, or is made of minerals that melt more easily.

Outline

I. Magma, lava, and volcanoes are vital to geologists because they are what our land is made of; this is the start of the rock cycle in a very real sense. A great deal happens before lava can actually flow out of the surface of a volcano.

II. Volcanoes occur when magma reaches the surface.

- **A.** Magma is liquid rock containing dissolved gas and solid crystals.
  - **1.** Magma is underground and lava is at the surface.
  - **2.** Lava tends to contain less dissolved gas than magma.
- **B.** Different volcanoes form from different kinds of magma.
  - **1.** Volcanoes in the Pacific Northwest tend to be cone-shaped, with lava and ash erupting at different times; the rock is an intermediate composition called andesite.
  - **2.** In Hawaii, basalt can be seen oozing out of the surface.
  - **3.** In places like Idaho or Craters of the Moon National Monument, there are very tall, dark cinder cones of ash.

4. These different volcanoes form because of the different compositions, temperatures, and behaviors of magma.

C. If you were to travel down through the crust and into Earth's mantle, you would see solid rock instead of liquid magma.

1. Before the revolution of plate tectonics, people viewed the deep Earth as solid and immobile.
2. Plate tectonics showed that the rock of the mantle behaved in a fluid way, able to flow over time.
3. The mantle is nearly entirely solid; there are only tiny amounts of magma that form in the mantle, and because it is buoyant it rises to the surface to create a volcano.
4. At any given time, there is almost no liquid within the mantle.

III. If magma is so rare within the earth, then why are there any volcanoes at all and how did they form?

A. Four billion years ago, the molten Earth would have crystallized very quickly from the core-mantle boundary upwards because the pressure is so great at that location it compresses rock into solid form.

B. In the three major regions of volcanism—mid-ocean ridges, subduction zones, and hot spots—magma forms for different reasons.

C. Temperatures in the asthenosphere are close to and even reach the melting point of rock.

1. The geotherm is the actual temperature of Earth; the solidus is the point at which rock begins to melt at any particular depth; the liquidus is the point at which all rock melts.
2. Pressure keeps the asthenosphere solid.
3. The geotherm is very close to the solidus; melting begins when the geotherm crosses the solidus.
4. The asthenosphere has more residual heat than would be caused only by compression, so as rock moves from the asthenosphere to the surface, the reduction in pressure causes that rock to suddenly melt.

D. In mid-ocean ridges, hot asthenosphere rock is sucked up to fill the gap between plates, where the pressure release causes it to melt.

1. Melting begins about 100 kilometers down, but the buoyancy and mobility of the melt causes it to percolate upward.

2. An upside-down stream network is formed by channels of percolating magma that coalesce to form a small magma chamber.
3. As the ridge continues to open, the magma rises to the surface to form the new rock that is created in the new ocean crust.

E. In subduction zones, cold ocean lithosphere is stuffed down into Earth.

1. Water, which lowers the temperature at which rocks melt, comes out of the subducting ocean floor and rises into the wedge of mantle rock above it, causing the rock to begin to melt.
2. This melt rises to form subduction zone volcanoes like Vesuvius and Mount St. Helens.
3. Water and gases in the magma erupt violently out of the volcano as steam.

F. In hot spot volcanoes, the rock is usually anomalously hot.

1. Hot spot plumes are still solid as they rise through the mantle.
2. Rock will melt more easily as it reaches asthenosphere levels and then will percolate upward to form a volcano.
3. Not all hot spot volcanoes form for the same reasons (e.g., Yellowstone and Iceland).

IV. Magma's viscosity differs greatly in different geographic and tectonic settings.

A. Viscosity is a measure of resistance to flow (a substance's "gooey-ness").

B. Magma can have viscosities over a wide range, from resembling honey to day-old oatmeal to tar. The viscosity for mantle rock is on the order of 10^{21} Pascal-seconds.

C. The amount of silica within magma tremendously affects viscosity. In rock containing a lot of silica, the strongly-bonded tetrahedra make it very difficult for magma to flow (this happens in places like continental volcanoes, where magma tends to be resistant to flowing and will erupt dramatically).

D. Increased temperature causes magma to become more fluid.

E. Water content in magma can play two very different roles. Water can make magma flow more easily by reducing viscosity, but can also cause explosive eruptions.

V. There has long been a wide range in perceptions of what the interior of our Earth was like and where magma came from.

   A. Several hundred years ago, people viewed Earth as a type of organism or physiological system that self-regulated and maintained comfortable conditions for life at Earth's surface.

      1. James Hutton viewed Earth as an organic system (he coined the term "Gaia" to describe this view).

      2. James Lovelock and Lynn Margulis developed the Gaia hypothesis in the 1960s, which was criticized for describing Earth as being a living organism.

   B. Earth is not alive, but it is a useful metaphor to view Earth as a single organism with a variety of interconnected systems.

   C. With plate tectonics, our model of reality changed so that we viewed Earth as a flowing, moving area that could sustain plate tectonics.

   D. Our models are not necessarily the truth; they are just working models that allow us to make predictions about Earth.

Recommended Reading:

Fisher, Heiken, and Hulen, *Volcanoes: Crucibles of Change*.

Sigurdsson, *Melting the Earth*.

Questions to Consider:

1. Do you think that the rock that makes up oceanic lithosphere, which originates at mid-ocean ridges, is water-rich or water-poor? (Hint: Think about the effect that water has on the melting point of rock.)

2. If hot spot mantle plumes come from the base of the mantle, what would be the source of heat to make that rock anomalously hot?

Lecture Eleven

Crystallization—The Rock Cycle Starts

Scope: When magma cools, atoms begin to form strong bonds with each other by internally organizing themselves in the easiest ways possible. Minerals continue to grow within the cooling magma until there is no liquid left, and the result is an igneous rock. An important aspect of the formation of igneous rocks is the fact that different minerals crystallize or melt at different temperatures. This causes the compositions of igneous rocks to change during the process of melting or crystallizing. Igneous rocks that form underground cool slowly and have large mineral crystals; igneous rocks that form at or near the surface cool quickly and have small mineral crystals. The composition of igneous rocks is distinctly different for continental and oceanic crust. Ocean crust is relatively simple, primarily consisting of a single rock composition that takes the form of basalt (when it cools from lava near the surface) and of gabbro (when it cools more deeply from magma). Continental crust is much more varied and complex in its composition, often containing sedimentary rocks like limestone, shale, and sandstone at the top and a variety of granite-like igneous and metamorphic rocks beneath.

Outline

I. When magma cools below certain temperatures, solid mineral crystals begin to form. With continued cooling the magma will eventually entirely crystallize and create an igneous rock.

- **A.** It is a principle of chemistry that a liquid cooled sufficiently will change phases and convert into a solid. For a common rock like basalt, this temperature is about 1100˚C–1200˚C.
- **B.** There are only a small number of common rock types, but an enormous diversity in the appearances of rocks. Slight changes in the initial composition and in the rates and styles of cooling affect the type and texture of the mineral grains that form.

II. One of the most important aspects of the formation of igneous rock is that different minerals crystallize at different temperatures.

- **A.** This principle, known as the Bowen reaction series, works in reverse for melting: Minerals that are the first to crystallize from a melt are the last to melt from a solid.
- **B.** The Bowen reaction series is important because it means that the composition of a magma will change over time as some minerals crystallize out of the melt.
  - **1.** As a magma cools to about 1200˚C, the first minerals that begin to crystallize are olivine and calcium-rich feldspar; this is followed, in sequence, by the crystallization of minerals pyroxene, amphibole, biotite mica, potassium- and sodium-rich feldspars, and muscovite mica.
  - **2.** The last mineral to crystallize, at about 600˚C, is quartz, solidifying any of the remaining silica.
  - **3.** The sequence of crystallization can cause some unusual rock appearances (e.g., New Jersey's Palisades Cliffs).

III. The rate of cooling affects the appearance of a rock by determining the size of the mineral grains.

- **A.** Rocks that cool deep underground, known as intrusive igneous rocks, cool slowly, allowing individual atoms to arrange themselves into large mineral grains.
- **B.** Rocks that cool at or near the surface, known as extrusive igneous rocks, will cool rapidly.
  - **1.** This does not allow individual atoms to migrate through the magma to make large crystals.
  - **2.** If magma is cooled so rapidly that minerals don't have time to even begin to form, the result is a glass like obsidian: The atoms are arranged in a random amorphous manner.
- **C.** In some cases a rock may cool slowly for a while and then suddenly be rushed to the surface. Both intrusive and extrusive processes are combined, and the result is a number of large crystals surrounded by a matrix of tiny, invisible crystals.

IV. The composition of the magma determines the type of rock that results.

- **A.** Ocean crust has a nearly identical composition due to the common mechanism of extracting melt at mid-ocean ridges.
  - **1.** The extrusive igneous rock that forms at the top part of mid-ocean ridges is called basalt.

2. The intrusive version, which forms the layer of the ocean crust beneath the basalt, is called gabbro; it has visible crystals that are often a centimeter or larger in size.
3. Both basalt and gabbro have the same general composition, which is a combination of olivine, pyroxene and calcium-rich feldspar.

B. A common intrusive igneous rock seen in continents is called granite.

1. Granite often has a speckled appearance with different-colored minerals that include quartz, sodium- and potassium-rich feldspars, biotite, and amphibole.
2. The extrusive version of granite, which is found at intraplate continental volcanoes, is called rhyolite.
3. Typical continental rock like granite, often referred to as sialic rocks, tend to be lighter in color, appearance, and weight.

C. Subduction zone volcanoes at the edges of continents involve melted mantle rock rising through a continental crust, which then end up having an intermediate composition between those of granite and basalt.

V. Intrusive igneous rocks take several different forms depending upon the conditions by which they are created.

A. Enormous bodies of granite, called batholiths, are often found in what were once the deep cores of mountain ranges. They formed when the mountains were forming.

B. Horizontal layers called sills intrude between existing sedimentary layers and cool slowly there. The Palisades Cliffs, in eastern New Jersey, are an example of this.

C. Volcanic necks like Shiprock in Arizona and Devil's Tower in Wyoming are the crystallized former pipes of once-active volcanoes.

D. Vertical sheets of intrusive igneous rock called dikes are often found cutting across existing sedimentary layers.

Recommended Reading:

Decker and Decker, *Volcanoes in America's National Parks*.

Dietrich and Skinner, *Rocks and Rock Minerals*.

Questions to Consider:

1. Why would volcanoes never form at subduction zones if temperature was the only factor?
2. Why are volcanic features like Shiprock and Devil's Tower seen above the surface if they formed underground beneath volcanoes?

Lecture Twelve
Volcanoes—Lava and Ash

Scope: Volcanoes are one of the most exciting and dramatic aspects of geology. Rivers of hot molten lava and explosive eruptions reveal the magnitude of the power of Earth's internal forces. Volcanoes occur when magma reaches the surface and erupts. The magma may flow across the surface as lava or cool quickly to form ash and a variety of igneous rock forms, such as lapilli, bombs, and blocks. In either case, large amounts of gases are released; this degassing is primarily responsible for the existence of our atmosphere. The style of eruption is dependent upon the viscosity of the magma which, in turn, is a function of the composition, temperature, and water content of the magma. The different kinds of volcanoes, like shield volcanoes, cinder cones, stratovolcanoes, and fissure eruptions, are directly connected to the tectonic settings they occur in. The large numbers of volcanoes that rim the Pacific Ocean, known as the Ring of Fire, exist because much of the Pacific Ocean seafloor is subducting beneath the plates that surround it.

Outline

I. Though volcanoes pose threats to people in many parts of the world, they are vitally important for life for a number of reasons.

- **A.** Volcanism at mid-ocean ridges creates all of the ocean seafloor.
- **B.** Volcanism on continents is responsible for adding new rock.
- **C.** Gases ejected from volcanoes are the source of our oceans and atmosphere.
    - **1.** After the T-Tauri phase of the sun, early in the history of our solar system, Earth had no atmosphere.
    - **2.** The atmosphere primarily arose through degassing, where gases initially dissolved in magma (largely carbon dioxide, water vapor, and nitrogen) were released into the atmosphere.
    - **3.** The water vapor ejected from volcanoes is the major source of the water of the hydrologic cycle.
    - **4.** This process can occur on other planets, such as Mars.

II. When volcanoes erupt, magma both erupts as flowing lava and ejects into the air as tephra.

A. Lava is flowing liquid rock, the surface equivalent of magma, though usually with fewer dissolved gases.

1. Lava can flow for many kilometers across the surface and can take many different textures.

2. A common form of lava is *pahoehoe*, which has a ropy, shiny texture.

3. Another common form of lava is *aa*, which has a rough, blocky texture; *aa* usually has fewer dissolved gases in it than *pahoehoe*.

4. Lava tubes form when the top of the lava flow hardens but a river of lava continues to flow underneath.

B. Tephra is the name for material ejected into the air from a volcano.

1. Tephra is usually ejected as a liquid but quickly hardens into solid forms during the ejection process.

2. Tephra can erupt in a wide scale of sizes including blocks, bombs, lapilli, Pele's tears, pumice, cinders, and ash.

3. Fine volcanic ash can be ejected many kilometers into the atmosphere, staying there for months and blocking out sunlight.

4. Hot ash can weld into tuff, a relatively soft rock used by Native Americans to carve out cliff dwellings.

C. How explosive a volcano is depends largely upon how much dissolved gas is in the magma. This affects the amount and type of tephra that is ejected.

1. When the pressure is released on magma, as it reaches the surface, gases like steam and carbon dioxide suddenly leave the magma and rapidly expand; this is like taking the top off a soda bottle after it has been shaken.

2. Tephra often has a frothy appearance because of all of the gas that has suddenly expanded from within the lava.

3. In certain cases, the explosion caused by expanding gases can blow away a significant volume of the volcanic mountain.

III. Volcanic eruptions and the lava and tephra they eject can take several different forms, which are strongly influenced by the tectonic environment they are in.

A. Shield volcanoes are broad, flat volcanoes.

1. Shield volcanoes are made almost entirely of basalt, which has a low viscosity because it is hot and relatively low in silica.

2. The low-viscosity lava can flow for tens of kilometers, broadening the shield volcano at its sides.
3. The Hawaiian Islands are the classic examples of shield volcanoes.
4. Shield volcano eruptions can occur over long times—Kilauea, on Hawaii, has been erupting continuously since 1980.

B. Cinder cones are small, usually perfectly-shaped cones of cinders and ash that are relatively short lived.
1. Cinder cones are usually small, only hundreds of meters high, and may also have lava flows out of their flanks.
2. Cinder cones can occur in isolation but are usually found along the flanks of shield volcanoes and stratovolcanoes.
3. One of the most famous cinder cones, Pericutin, in Mexico, suddenly began to erupt in the middle of a cornfield in Mexico in 1943; by 1952 it had grown 424 meters tall and then stopped, never to erupt again.

C. Stratovolcanoes, also known as composite cone volcanoes, typically occur above subduction zones and form through the alternation of ash falls and lava flows.
1. Different episodes of eruption, involving different magma compositions and degrees of pressure, cause alternations of the ash and lava.
2. Stratovolcanoes often have the classical conic shape (like Mount Fuji in Japan) that is associated with volcanoes.
3. Stratovolcanoes seem to go through a cycle of having many years of occasional small eruptions building up the mountain edifice, followed by a final explosive eruption that can shatter and destroy the mountain.
4. Stratovolcanoes often have a crater at their tops but can develop huge calderas when the magma chamber deflates and the top of the volcano collapses.
5. A large portion of the world's stratovolcanoes exist as part of the Ring of Fire, which is the band of subduction zones that rims the Pacific Ocean.

D. Flood basalts occur when a vast volume of lava erupts at the surface, covering thousands of square kilometers with basaltic lava.
1. Flood basalts happen very rarely and are thought to be the arrival of a mantle hot spot at the surface.

2. The start of the Yellowstone hot spot, currently beneath Wyoming, began as the Columbia River flood basalt 17 million years ago.
3. Another well-known flood basalt is the Deccan Traps in India.

IV. Volcanism occurs frequently in the solar system, though it often takes very different forms from volcanism on Earth.

A. Mars had a period, 3.5 billion years ago, of enormous lava eruption.

B. Between 3 and 3.5 billion years ago, the same thing happened on our moon.

C. Venus shows evidence of episodic volcanism.

D. Jupiter's moon Io erupts both lava and liquid sulfur, which has colored its surface yellow.

Recommended Reading:

Bullard, *Volcanoes of the Earth*.

Decker and Decker, *Volcanoes*.

Questions to Consider:

1. How does water play a dual role with volcanic eruptions, making some eruptions calm and peaceful and others violent and explosive?
2. The rock pumice is sometimes found floating on the ocean surface after an eruption. Why is it so light?

Lecture Thirteen

Folding—Bending Blocks, Flowing Rocks

Scope: Volcanoes are dramatic, but magma and lava are not the norm. Most crust and mantle rock is solid, at least, over short time scales. And yet, the crust and mantle are constantly in motion, bending and flowing. Many years of laboratory experiments have now shown us how rocks deform, or strain, when they are subjected to the stresses of mantle convection and plate tectonics. There are many factors that affect the way a rock will deform when stressed, including temperature, pressure, composition, water content, mineral grain size, the magnitude of the stress applied, and the rate of deformation. However, rock deformation can be generalized into three categories: elastic, plastic, and brittle. For small stresses applied rapidly, such as those accompanying the seismic waves of earthquakes, rock responds mostly elastically. For large stresses applied rapidly, rock will break in a brittle manner. However, for slowly applied stresses, rocks will strain in a ductile manner. This occurs by either the movement of individual atoms through the rock, one atom at a time (diffusion), or the sliding of regions of rock across microfractures, one broken atomic bond at a time (dislocation).

Outline

I. Earth's mantle and crust are solid. If you could travel down deep inside Earth and kick a rock (aside from the fact that you would incinerate from the temperatures and be flat as a pancake from the pressures), you would stub your toe. But the mantle flows like a liquid over geologic time.

- **A.** The concept that solids can behave like liquids over time scales is one of the most important in geology, but one of the hardest for people to grasp.
- **B.** Understanding the material properties of rocks (rheology) is one of the most complicated aspects of our science.
- **C.** A large part of the challenge in understanding rock rheology is that movements of plate tectonics and mantle convection that occur on

the scale of many thousands of kilometers involve physical changes that occur at the microscopic level, one atom at a time.

II. Rocks undergo deformation when forces are applied to them. In geologic terms, we say that rocks undergo strains (the deformations) when stresses (the forces) are applied to them.

A. In general, rocks can deform in three ways: in an elastic, plastic (also called ductile), or brittle manner.

B. These three manners of deformation can be demonstrated with the children's play material Silly Putty.

1. Roll the Silly Putty into a ball, drop it and it will bounce, behaving instantaneously in an elastic manner.

2. Pull on the Silly Putty and it will stretch out permanently, behaving in a plastic manner.

3. Give a sharp tug on the Silly Putty and it will snap and break in a brittle manner.

C. During elastic deformation, the bonds between atoms of the rock behave like springs, stretching out or compressing while stresses are applied, but returning to their original positions when the stresses are gone.

1. Elastic behavior is dominant when the material is stiff, the stresses are small, and/or the stresses are applied for a very short time.

2. Elastic deformation occurs when seismic waves from a distant earthquake pass through a rock—stresses are small and they pass by quickly.

D. During plastic deformation, the material deforms while stresses are applied, the deformation stops when the stresses stop, and the material is left in a permanently deformed state.

1. Plastic behavior is dominant when the material is weak and the stresses are large, or are applied for a long time.

2. Most of the deformation that occurs within the mantle beneath the lithosphere occurs in a plastic way, and acts over long time scales.

E. With brittle deformation, stresses exceed the internal strength of the rock and the rock breaks or faults.

1. Brittle failure is dominant when the material is stiff and the stresses are large.

2. Most faults (the breaking of rock in the form of earthquakes) develop in the lithosphere, where rocks are stiff and plate tectonic forces are large.

III. In addition to the amount and rate of stress applied to rocks, important factors controlling the way the rocks deform include temperature, pressure, composition, mineral grain size, and water content.

A. An increase in temperature will make rock softer and cause it to flow (deform plastically) instead of fracture.

1. This can be demonstrated with two chocolate bars, one taken from the freezer and one left out on a warm day.
2. If you bend them both, the cold one will break with a snap but the warm one will bend easily. (Remember this snap—we will come back to it when we talk about earthquakes!)
3. Earthquakes occur almost exclusively in the lithosphere because it is cold, and therefore brittle like the refrigerated chocolate bar.

B. Pressure confines a material such as rock, and makes it hard to fracture in a brittle way by increasing its internal friction.

1. Earthquakes do not usually occur deep inside the earth because of the high pressures there.
2. One way to see this is with your own hands. Press your palms together and then try to slide them past each other; the harder you press, the more difficult it is to slide them.

C. The way a rock deforms depends upon the composition of the rock. In general, igneous rocks tend to deform less easily than most sedimentary rocks.

D. Rocks with small grain sizes deform plastically, more easily than rocks with large grain sizes. Deformation occurs along boundaries between mineral grains. If there are smaller grains, then there is more total grain boundary surface area.

E. One important factor controlling rock behavior is the amount of water within the rock (This should not be a surprise, given what we have already said about water!).

1. Water makes rocks softer, and brings them closer to their melting points.
2. Water permits atoms to move about freely within the minerals and rocks, providing mechanisms for their deformation.

IV. During plastic deformation, rock flows because of two processes that operate at the atomic level: diffusion creep and dislocation creep.

- **A.** In diffusion creep, atoms move from regions of high pressure to low pressure by diffusing directly through the lattice structure or along mineral grain boundaries.
  - **1.** For example, if you squeeze down on a rock, the top and bottom of the mineral grains will be under higher pressure than the sides.
  - **2.** This causes atoms from the top and bottom of mineral grains to move to the side of the grains.
  - **3.** Over time (lots of time—geologic time!), the minerals will begin to flatten out; the rock flows one atom at a time.
- **B.** During dislocation creep, a mineral deforms by breaking bonds between atoms within a crystal structure, allowing atoms to slide past each other.
  - **1.** The process of dislocation creep is analogous to faulting along a fracture, but it happens one atom at a time, with bonds breaking between atoms but reforming with adjacent atoms.
  - **2.** Over time, the whole rock can change its shape through this continual shifting of atomic alignments.
- **C.** While the process of metamorphism is separate from the process of plastic deformation (involving the formation of new minerals when temperatures and pressures change), the two are related and often occur simultaneously.

V. Interactions between the tectonic plates create dramatic folding associated with mountain building and other geologic processes.

- **A.** Folds are classified according to their appearances.
  - **1.** Anticlines are arched folds with the middle part raised, important because hydrocarbons can rise up and accumulate beneath them.
  - **2.** Synclines are arched folds with the middle part dropped. Folds often occur with repeating anticlines and synclines.
- **B.** Folds can happen in two or more dimensions, making basins or domes or more complicated folds.
- **C.** Fascinating things are happening at the atomic level, one atom at a time.

Recommended Reading:

Karato, *The Dynamic Structure of the Deep Earth.*

Keller and Pinter, *Active Tectonics*.

Questions to Consider:

1. How is it possible for atoms, during the process of diffusion, to simply pass through a mineral crystal? Isn't the mineral solid?
2. Can you think of other examples from daily life where the viscosity of a material is directly related to its temperature?

Lecture Fourteen

Earthquakes—Examining Earth's Faults

Scope: Near the cold surface, rock is stiff and does not flow easily. Stresses from plate motions often exceed the strength of the rock, and the rock breaks. These breaks are earthquakes, occurring along planar faults. More than 200,000 earthquakes are located every year. Most are very small, and most of the total energy released by them is from just the one or two largest quakes. Most of the energy of an earthquake goes into cracking and deforming the rock surrounding the fault, but a small portion, like the snap of a broken pencil, goes into seismic waves. Seismic waves take several forms (P waves, S waves, surface waves), and pose significant hazards in many parts of the world. Seismic waves are used to compute the location and magnitude of earthquakes. They also provide vital information about the forces that move plates, shift continents, and create mountains and valleys. For instance, the direction of faulting during an earthquake is directly related to the plate motions that are causing the deformation. For large earthquakes, seismic waves will circle the globe for many months, causing the entire Earth to reverberate like a gong. The "music" of Earth's reverberations is directly related to Earth's internal structure. All seismic waves eventually damp out, or attenuate, as the elastic wave energy is lost to the heat of friction.

Outline

I. Few aspects of geology have captured people's fascination and fear as much as earthquakes.

- **A.** Earthquakes do not compare to epidemics, floods, and droughts in terms of loss of human life (the Spanish Flu killed at least 20 million people in 1917); however their unpredictability and instantaneous nature make them greatly feared.
- **B.** Earthquakes are a direct result of two aspects of the material behavior of rocks that we previously discussed.
  - **1.** Brittle rupture occurs when rocks are stiff and stresses are large.
  - **2.** Earth's lithosphere is cold, stiff, and deformed by the large stresses resulting from the interactions of the plates.

C. Earthquakes usually occur along plate boundaries, but can and do happen everywhere, and all cultures have memories or legends of them.

   1. More than 200,000 earthquakes occur every year, though most are small.

   2. Earthquakes are not randomly distributed; they provide a foundation for the theory of plate tectonics.

   3. Cultural stories explaining earthquakes reveal a great deal about previous societies.

II. An earthquake occurs on a fault, a two-dimensional surface within Earth (usually within the lithosphere) across which two sides move in opposite directions.

A. The lithosphere must be stressed.

B. At some point the strength of the rock is exceeded, and the earthquake occurs, beginning at an initial location called the focus. The term epicenter is given to the point at Earth's surface directly above the focus.

C. The earthquake ruptures outwardly in all directions from the focus, tearing through the underground rock at a speed of about 2 kilometers per second.

D. The area of the fault that ruptures is usually small, but large earthquakes can be hundreds of kilometers in width and length.

E. A large earthquake is followed by smaller aftershocks that help to balance out the local stresses in the lithosphere.

F. Three categories of faults indicate the tectonic stresses that cause them.

   1. When lithosphere is pulled apart, the result is a normal fault.

   2. When lithosphere is compressed, the result is a reverse or thrust fault.

   3. When lithosphere is sheared sideways, the result is a transverse or transform fault.

III. Large earthquakes release an enormous amount of energy. Most of this energy is expended locally, but a small amount goes into seismic waves that can be recorded around the world.

A. Most energy released by an earthquake goes into breaking rock along the fault and moving and deforming rock on either side of the fault.

B. A tiny amount of the total energy of an earthquake, about one part in 20,000, goes into seismic waves.

1. Seismic waves are recorded using seismographs—sensitive instruments that detect microscopic motions of Earth's surface.

2. The record of Earth's motions recorded on a seismograph is called a seismogram.

C. There are two kinds of seismic waves.

1. P waves are compressional waves, like acoustic sound waves, and occur through compressing or expanding the rock, like a spring.

2. S waves are transverse waves, like light and other electromagnetic waves, and cause oscillations that are perpendicular to the direction of wave propagation.

3. P and S waves that travel through Earth's interior are called body waves, and P and S waves that travel across Earth's surface are called surface waves.

4. Because body waves can reflect off of, refract across, and diffract around the different layers within Earth's interior, they follow different paths through Earth and arrive as separate waves on a seismogram.

IV. Seismic waves are used to learn about the details of an earthquake, including its location, magnitude, and manner of rupture.

A. Seismic waves travel many kilometers per second. Examining the arrival times of seismic waves from the global networks of seismometers reveals the location and depth of earthquakes.

1. Real-time monitoring with seismographs can indicate locations of large earthquakes within minutes after they occur.

2. These real-time assessments are used for earthquake and tsunami hazard warnings.

B. Seismic waves are used to determine earthquake magnitudes, which are given in logarithmic scales.

1. Earthquakes occur globally with a fractal-like distribution.

2. Though we rarely hear about it in the news, there is, on average, a magnitude 6.0 earthquake somewhere in the world once every three days.

3. The largest earthquakes recorded occurred in Chile (1960, magnitude 9.5), Alaska (1964, magnitude 9.4), and Sumatra (2004, magnitude 9.3).

4. The largest earthquake in a year can release more energy than the rest of the year's earthquakes combined.

C. Seismograms also carry information about the way the earthquake ruptured.

1. Analysis of seismograms can determine how long the rupture took to occur, and where along the fault most of the energy was released.

2. Seismograms also show the direction the fault ruptured.

V. For large earthquakes, the seismic waves can be detected circling the globe for many months, which sets Earth ringing like a bell. These reverberations are called modes of oscillation.

A. The periods of Earth's modes of oscillation, just like the tones of a bell or gong, are a direct result of the composition and structure of Earth, and have been used to investigate it.

B. Earth's longest mode, essentially its fundamental note of vibration, is 54 minutes long, corresponding to the surface repeatedly going up for 27 minutes and then going down for 27 minutes. This would correspond to the note of an E, 20 octaves below middle E on a piano!

C. Because Earth is so heterogeneous, the modes of oscillation are very complex. It might be more apt to compare Earth's ringing to banging a dented trash can than to ringing a gong.

D. All seismic waves and modes of oscillation eventually fade away (attenuate) due to anelasticity. Earth's rock is not perfectly elastic, and the seismic energy eventually converts into the heat of friction.

1. The primary cause of anelasticity is temperature: Rock that is hot and close to melting is weak and damps out seismic energy quickly.

2. The presence of water within rock also contributes greatly to anelastic damping of seismic energy.

Recommended Reading:

Bolt, *Earthquakes.*

Brumbaugh, *Earthquakes, Science and Society.*

Questions to Consider:

1. Imagine if both P and S waves traveled through air. How would that affect the sounds that you would hear?

2. Given the way energy is distributed between small and large earthquakes, do you feel that earthquakes are a better example of uniformitarian geology or catastrophist geology?

Lecture Fifteen

Plate Tectonics—Why Continents Move

Scope: It may seem strange that continents can plow through the solid mantle and move and, in fact, it was just this objection that prevented the hypothesis of continental drift from being universally accepted when Frank Taylor proposed it in 1908. But the theory of plate tectonics shows that the continents move in a different way: They are imbedded within the lithospheric plates, which slide over the hotter and weaker asthenosphere layer. Plates move because they are the surface expression of mantle convection. But there are two main forces directly responsible for plate motions: slab pull and ridge push. Slab pull is the gravitational pull of old, cold, dense oceanic lithosphere when it sinks down into the mantle. This is the primary force that moves the plates. Ridge push is also important, causing oceanic plates to slide down and away from the hot, buoyant, and elevated mid-ocean ridges. The ridges are elevated, compared to the rest of the ocean floor, because of the principle of isostasy. Other forces affect the motions of plates. Slab suction may be responsible for the breakup of continents, and continental drag is important in resisting plate motions.

Outline

I. We have been able to identify the "what" of plate motions to an accurate degree: where and how fast tectonic plates (and the continents they contain) move. However, determining the "why" of plate tectonics has been more difficult.

- **A.** We now realize that the mantle convects, but this was not known when the first evidence of continental motions was being discovered.
- **B.** The ideas of Frank Taylor and Alfred Wegener, concerning continental drift, were not accepted largely because no one could figure out how continents could plow through the solid rock of the mantle.
- **C.** The first possible resolution came from the work of a Scottish geophysicist Arthur Holmes, who proposed in 1929 that mantle

convection could act like a conveyor belt, moving the continents about the surface.

II. We now know that mantle convection is responsible for plate tectonics.

A. The plate motions can be seen as simply the top part of the whole mantle convection cell.

B. In another sense, however, it is the motions of the plates that drive the exact patterns of convection within the mantle: The cold sheets of ocean lithosphere sink into the mantle whenever they can.

C. The asthenosphere is also important for plate tectonics. The weak asthenosphere allows the pieces of the lithosphere to be decoupled from the rest of the mantle, allowing them to move more easily across the surface.

D. We can now, however, examine the actual forces that help or hinder the motions of continents. They are slab pull, slab resistance, ridge push, continental drag, and slab suction.

III. The gravitational pull on the dense and heavy subducting ocean plates, called slab pull, is the most significant force directly responsible for moving the tectonic plates.

A. Oceanic crust is more than 1000˚C when it forms at mid-ocean ridges, but cools quickly as it ages and moves away from the ridge.

1. Rock contracts as it cools, becoming denser and heavier.
2. By the time the ocean lithosphere reaches a subduction zone, it is considerably heavier than the mantle beneath it.

B. Once a plate begins to subduct, it goes quickly, like a piece of aluminum foil on top of water.

C. Because heat conducts through rock so slowly, the subducting slab heats up slowly and remains heavier than the surrounding mantle for at least a hundred million years.

D. All of the plates that have a substantial percentage of their circumference subducting beneath another plate (Pacific, Philippines, Nazca, Cocos, Indian, Australian, Juan de Fuca, etc.) move quickly, showing the importance of slab pull.

IV. The slab-pull force of the subducting lithosphere is balanced by the force of slab resistance, which is the frictional force resisting penetration of the slab.

A. As Newton showed, any unbalanced force results in a non-zero acceleration. Because the subducting lithosphere is not accelerating, the force of slab pull must be countered by an equal but opposite force of slab resistance.
   1. This is analogous to the force of frictional air resistance for a falling object, which will accelerate until the force of friction equals the force of gravity. After that the object will fall at its constant terminal velocity.
   2. The velocity at which a slab sinks into the mantle at a subduction zone can be thought of as its terminal velocity.

B. Because the mantle gets stiffer with depth (due to the increasing pressure), slab resistance increases the farther a slab sinks. This is seen in the way earthquakes occur within subducting lithosphere: The sinking slab seems to be stretched at the top of the mantle, but compressed deeper down.

V. The force of ridge push results from the fact that ocean seafloor is elevated near ridges and gets deeper with distance from the ridge, allowing the oceanic plate to slide down off of the elevated mantle. The elevation of the ridge is due to the principle of isostasy.

A. Because the rock of the asthenosphere can flow easily (over geologic time!), the mass of a hypothetical vertical column of rock will tend to change until it is the same as rock adjacent to it. This occurs through a change in elevation, and the process is known as isostasy.
   1. The phenomenon is observed in a glass of water with an ice cube in it. Because the ice is 10% less dense than the water, 10% of the ice cube sticks out of the water. If you raise or lower the ice cube, water beneath the cube will flow until the pressure at that deep level is the same everywhere, and the ice cube will return to having 10% stick out above the water.
   2. As we will later discuss, the deep crustal roots of continental mountains are also the result of isostasy.

B. With mid-ocean ridges, both the ocean lithosphere and the asthenosphere beneath it are unusually hot, with rock flowing up from deeper in the mantle. This hot rock is less dense so, like a less-dense ice cube, it rises higher than the surrounding seafloor.

C. As you move away from the ridge, the boundary between the lithosphere and asthenosphere drops in the shape of a parabolic curve.

1. This allows the oceanic lithosphere to slide down off of the asthenosphere, much like a surfer sliding down off of a wave.
2. Because the effect is cumulative, with the mass of the plate increasing with distance from the ridge, the force of ridge push is actually misnamed; it increases the farther you get from the ridge.

VI. One of the most significant forces resisting plate motions is called continental drag, and it results from the fact that certain parts of continents tend to have deep lithospheric roots.

A. The oldest types of continental crust, called cratons, have deep lithospheres that can extend several hundred kilometers down into the mantle. These roots, known as the tectosphere, have been identified with seismic tomography.

B. The tectosphere extends down through most, if not all, of the asthenosphere, meaning that there is no asthenosphere beneath them.

1. This situation is analogous to the keel of a boat dragging across the bottom of a shallow pond.
2. Because the asthenosphere must flow away and around the continental tectosphere, this poses a huge resistance to the motion of the continent.

C. As a result, all of the plates with large amounts of continental crust move slowly (zero to 3 centimeters per year) compared to plates with no continental crust, which can move up to 10 centimeters per year.

VII. An unusual but important force associated with plate motions is called slab suction, and it is the pull that a subducting plate exerts on the overriding plate as it sinks.

A. If you push a spoon down into cake batter, the cake batter at the surface will flow toward the gap made by the spoon. A similar process happens when oceanic lithosphere sinks down into the mantle.

B. Slab suction is sometimes responsible for pulling the volcanic arc away from the rest of the overriding plate, creating a back-arc basin behind it.

1. The back-arc basin is a spreading center, where new ocean crust is forming.

2. This was responsible for pulling Japan away from the rest of Asia, and is currently creating the Lau basin behind the Tonga trench in the southwest Pacific.

C. Slab suction might be partly responsible for the breakup of supercontinents like Pangaea.

1. A supercontinent will likely have subduction occurring along the majority of its perimeter.
2. This creates outward slab suction forces all around the supercontinent that help to pull apart the supercontinent.

Recommended Reading:

Gurnis, "Sculpting the Earth from the Inside Out," *Scientific American,* March 2001.

Uyeda, *The New View of the Earth.*

Questions to Consider:

1. Will the force of slab pull be stronger or weaker for young or old oceanic lithosphere? What about fast or slow oceanic lithosphere?
2. There used to be a large debate as to whether moving plates controlled the flow of the asthenosphere or the asthenosphere moved and dragged the plates around. From what you have seen here, which do you think is a better model of plate forces?

Lecture Sixteen

The Ocean Seafloor—Unseen Lands

Scope: Where, in the oceans, would you expect to find the deepest and the shallowest regions? If, thinking of a lake, you guess the deepest parts are in the middle and the shallowest parts are at the edges, you would be wrong in most cases. The deepest regions of the seafloor, like the Marianas and Puerto Rico trenches, are at the edges of the oceans, and running down the middle of oceans we often find elevated mid-ocean ridges like the Mid-Atlantic Ridge and East-Pacific Rise. In addition, there are unusual fault scarps that stretch for thousands of kilometers across the major oceans. All of these features seem paradoxical until they are understood in the framework of plate tectonics, where plates are formed at mid-ocean ridges and sink into the mantle at oceanic trenches. The ages of the ocean seafloor can be accurately measured using paleomagnetism. Ocean crust freezes in the present magnetic field when it forms. Because the magnetic field has repeatedly reversed over time, paleomagnetic stripes recorded from the seafloor provide a timeline that allows accurate dating of the age of the crust. It is interesting to note that, because of subduction, ocean lithosphere is related to core convection and the magnetic field in unusual ways.

Outline

I. The bathymetry of the ocean seafloor shows a tremendous diversity of features that are directly related to plate tectonics and the process of mantle convection. However, because they are hidden by several kilometers of water, they remained hidden until the middle of the 20th century.

- **A.** Light doesn't efficiently pass through more than a few hundred meters of water, so 70% of Earth's surface lies hidden from view.
- **B.** World War II and the Cold War with the Soviet Union led the U.S. Navy to map the ocean floor in great detail. This provided the evidence that finally led to acceptance of the idea that the continents move.

1. Submarines give their position away if they use sonar to determine the depth of the seafloor so they needed maps of the ocean depths at all locations.
2. The U.S. Navy mapped not only bathymetry but also anomalous gravity and magnetism.
3. These maps aided U.S. submarines and also provided remarkably valuable geologic information.
4. One Navy captain (and later admiral), Harry Hess, became fascinated with his mapping efforts and went on to become a professor of geology at Princeton and one of the founding discoverers of plate tectonics. Hess discovered, among other things, flat-topped underwater seamounts that he named guyots. The presence of these proved that the seafloor sinks after it forms.

II. The discovery of the ocean's bathymetry was a surprise. Its features were counter-intuitive to what was expected.

A. In most lakes the deepest parts are usually near the center. The deepest parts of the ocean, however, turn out to be trenches associated with subduction.

1. Oceanic trenches are the narrow depressions that mark the boundary between the two colliding plates and are usually located at the edges of oceans, adjacent to continents. They are at the sides, not the middle, of the oceans.
2. Subduction zone trenches can be quite deep. The average ocean depth is 3.7 kilometers, but the deepest trench (Mariana trench) reaches almost 11 kilometers in depth.

B. In addition, continuous mountain chains were found in the middle of the ocean that stretched through all the oceans for a total length of about 70,000 kilometers.

1. These mountain ranges turned out to be the mid-ocean ridges, where new ocean crust was created.
2. The major ridges were the Mid-Atlantic Ridge, East-Pacific Rise, and Indian Ridge (in the three principal oceans).
3. Slow-spreading ridges like the Mid-Atlantic Ridge were narrow but also had a rift valley running along their top.
4. Fast-spreading ridges like the East-Pacific Rise were broader with no axial valley.

III. Straight fault scarps, called fracture zones, were found running across the oceans perpendicular to the ridges. These turned out to be directly related to transform faults along the ridge.

A. Segments of the ridge spreading centers are always separated by small segments of transform faults, where two different plates slide horizontally past each other.

B. Because the seafloor drops in elevation as it moves away from the ridge, beyond either end of the transform fault the two pieces of the ocean crust are of different ages and therefore permanently offset in elevation.

C. The fracture zones are the continuations of the transform fault segments, and because the two sides will forever be of different ages, the offset will continue forever across the ocean floor.

IV. The seafloor is covered with volcanic islands and seamounts (former volcanoes whose tops do not reach the surface of the water). These volcanoes occur both because of mid-ocean ridge processes and because of hot spot activity.

A. Lines of volcanic islands form hot spot tracks that extend in lines across the seafloor.

1. The best known of these is the Hawaiian-Emperor seamount chain.
2. Other hot spot chains include the Line Islands, Louisville Seamounts, and many others.
3. The hot spot tracks lead away from current hot spots (Hawaii, Reunion Island, etc.) in the direction that the oceanic plates are moving.
4. This leads scientists to conclude that the hot spots are relatively fixed in location with respect to the mantle, and that as the plates move across the hot spots a chain of volcanoes is formed.
5. The start of these hot spots is often a massive flood basalt (like the Deccan Traps or Columbia flood basalts), and when this happens in the ocean the result is an ocean plateau. The huge Ontong-Java Plateau is thought to be the flood basalt that represented the birth at the surface of the hot spot that formed the Louisville Seamounts.

B. There are many ocean volcanoes and seamounts, particularly in the Pacific Ocean, that do not seem to be associated with hot spots. Many of these form near the ridges.

   1. Volcanism can still occur in discrete episodes on the flanks of mid-ocean ridges, millions of years after the ridges form.

   2. This episode creates a discrete volcanic island or seamount.

   3. Although these islands might be forming near the ridge, because the seafloor is constantly moving away from ridges, they will eventually be distributed all across the ocean floor.

C. Many of the seamounts have flat tops—the guyots that Harry Hess discovered. These are evidence of the cooling and sinking of ocean seafloor over time.

   1. Charles Darwin, noticed that the geology of the Galápagos Islands suggested that the islands were sinking.

   2. As the Pacific Ocean seafloor sinks, erosion quickly flattens the tops of volcanoes if they rise above the sea surface, and when the islands are finally submerged they retain their flat tops.

   3. Coral reefs will continue to grow on the tops of the sinking islands, forming atolls, but they cannot keep pace with the sinking forever, and will die off due to a rise in sea level or for biological reasons.

D. Details of the ocean floor are hidden by ocean sediment farther away from mid-ocean ridges.

   1. Because seafloor gets older the farther you go from the ridge, the longer it has been collecting sediment that falls from above.

   2. Out in the deep sea, sediment sources include continental streams, wind-blown dust, and organic debris from dead plants and animals.

   3. Sediment thicknesses on the ocean floor range from zero at the ridges to more than 10 kilometers at the passive margins of continents, where streams dump sediment eroded off land surfaces.

   4. Thick sediments give the deep abyssal plains a smooth appearance, but seismic imaging shows that beneath the sediments are the same rifts and fractures and seamounts that form at or near the ridges.

V. The ages of ocean seafloor and the detailed history of plate motions over the past 150 million years derive from the study of paleomagnetism, which is the study of the history of Earth's magnetic field. Oceanic paleomagnetism involves two different components: the behavior of Earth's magnetic field and the way oceanic crust forms at mid-ocean ridges.

A. Earth's magnetic field randomly reverses.

1. One model for magnetic field reversals is that sometimes the convection patterns that cause the magnetic field become unstable, causing the dipolar magnetic field (the part that looks like it is due to a bar magnet!) to weaken to about 10% of its normal strength. When the field powers back up again, which it does naturally because of Earth's rotation, it has a 50/50 chance of coming back normal (the way it is now) or reversed (where the "N" on a compass would point toward the South Pole).

2. The field reversals seem completely random in time, with no observable periodicity.

3. Currently, the magnetic field reverses once or twice per million years, though the frequency has greatly varied over time.

4. These reversals happen fairly quickly, over about a thousand years, and are potentially dangerous to life on land because the weakening of the magnetosphere allows increased levels of solar wind to strike Earth's surface.

B. When rock cools below a certain temperature (called the Curie point after the physicist Pierre Curie), certain magnetic minerals like magnetite "freeze in" and retain the magnetic field that existed when they cooled.

C. Eventually, the ocean seafloor began to heat up, the rate of heat coming out of the core slowed down, and the reversals happened within a more regular rate.

D. As basalt and gabbro form on either side of the spreading mid-ocean ridges, they freeze in the magnetic field, forming bands of rock parallel to the ridges with magnetic fields of alternating patterns.

1. Ocean ships have sailed across the seafloor and used magnetometers to measure the magnetic field anomalies of the ocean crust and map out the bands of alternating (normal and reversed) magnetic field directions.

2. When plate spreading is slow, the bands of magnetic reversals are narrow, as in the Atlantic Ocean. When plate spreading is fast, the bands of magnetic reversals are much wider, as in the Pacific Ocean.
3. A detailed map of ocean crust magnetic anomalies reveals a map of the ages of the ocean seafloor and a record of plate motions over the past 180 million years.
4. The record only goes to 180 million years because that is the age of the oldest ocean seafloor, found in the western Pacific and on either side of the North Atlantic Ocean.

VI. There is another direct connection between ocean seafloor and magnetic reversals.

A. When the supercontinent Pangaea began to break up about 200 million years ago, increased amounts of subducted ocean lithosphere plunged down through the mantle.

B. As these subducted slabs reached the base of the mantle, they pushed aside hot rock at the core-mantle boundary, creating large mantle plumes of rising hot rock.

C. These rising mantle plumes triggered large amounts of flood basalt volcanism that covered the land in many areas and likely altered global climates.

D. The cold subducted slabs also chilled the core (like putting ice packs along its sides), causing heat to flow out of the core more rapidly and causing it to convect more vigorously, preventing it from being able to reverse for a period of 35 million years.

E. This meant a very stable, unchanging magnetic field for a very long time, the record of which was stored in ocean crust that formed at that time and is still at the surface, but will one day return toward the core.

Recommended Reading:

Keary and Vine, *Global Tectonics*.

Menard, *The Ocean of Truth*.

Questions to Consider:

1. Why is it so important for mapping the ocean seafloor that paleomagnetic reversals have occurred in a random pattern?
2. The patterns of heat flow out of the ocean seafloor also provided strong support for plate tectonics. Given what you now know about the formation of oceanic plates, what do you think the pattern of oceanic heat flow looks like?

Lecture Seventeen

Rifts and Ridges—The Creation of Plates

Scope: Oceans undergo reincarnation: They repeatedly die and are reborn. For instance, the Atlantic Ocean is only 180 million years old. Before that, during the time of the supercontinent Pangaea, the Americas were directly connected to Europe and Africa. Before that, however, there was an earlier Atlantic Ocean that separated the continents. Oceans like the Atlantic initiate when continents rift apart. We see this process occurring currently in places like the East African Rift Valley. Someday an ocean will likely separate Africa into two parts. When the rifting continues and the continents separate, new oceanic crust begins to form. This has just happened beneath the Red Sea, where Arabia has recently separated from Africa. Investigations with submersibles and ocean bottom seismometers have revealed the unusual structures of mid-ocean ridges, where lava bubbles onto the seafloor to make new crust and hot water rises from thermal chimneys to support diverse colonies of bizarre life forms. Many scientists believe that life got its first start almost 4 billion years ago at these energetic and dynamic mid-ocean ridge environments. The rich minerals that pour onto the ocean seafloor begin a geologic process that is responsible for creating rich mineral deposits that are the basis of our industrial culture.

Outline

I. If someone told you that they could take you to a place on Earth where you could see a continuous mountain chain of volcanoes almost 50,000 miles long, you might find it hard to believe them. But they would be telling you the truth, though they would need a special kind of submarine to take you there!

A. The mid-ocean ridges are a nearly continuous chain of volcanoes, though they do not behave like volcanoes on land.

B. As the site where new ocean crust is formed, ridges are the start of plate tectonics. They may also have been responsible for the beginnings of life.

II. Oceans can have limited life spans. They are born, grow, shrink, and die.

A. However, they can be reborn and enter a repeating cycle of opening and closing.

1. The Canadian geophysicist J. Tuzo Wilson was the first person to recognize this pattern, looking at the cyclic history of the opening and closing of the Atlantic Ocean.

2. This cycle of the life spans of oceans is named the Wilson cycle in his honor, and is thought to be about 500 million years in duration (give or take a few hundred million years!).

B. The lifecycle of oceans begins with continental rifting.

1. The African rift valleys are the classic example. The African continent is being split into two separate pieces (Somalian and Nubian plates).

2. The cause of continental rifting may vary, but may be the result of tensional forces pulling the continent apart (such as the slab suction force) or a hot spot rising underneath the rift.

3. Continental rifting combines both stretching and faulting of the crust, with the beginnings of volcanic behavior.

4. There are many examples of continental rifting such as the Rio Grande Rift in New Mexico, the Baikal Rift in Russia, and the Rhine Graben in Germany.

5. Most continental rifts stop spreading at some point and never become oceans. Two in North America, the Reelfoot Rift (site of the Mississippi River valley and the 1811–1812 New Madrid earthquakes) and the Mid-Continent Rift (which stretches from Oklahoma to Michigan) never succeeded in breaking North America apart.

C. If continental rifting continues, a new ocean will form.

1. The best current example of this is the Red Sea, which is opening as the Arabian Plate moves away from the African Plate.

2. At some point the stretched and faulted crust thins to the point that basaltic magma begins to form from the pressure release of mantle rock rising to fill the gap, and this magma begins to form oceanic crust.

3. With the Red Sea, continental rifting began about 30 million years ago, and basaltic ocean crust began forming about 12 million years ago.

4. The borders of the continents on either side of the new ocean become tectonically inactive passive margins, but they forever bear the scars of the stretching and rifting.

D. Over time, the new ocean will open into a mature ocean with a spreading center, but no subduction, so that it continues to open. The Atlantic Ocean is an example of this as it continues to increase in size.

E. The next stage involves the development of subduction zones, so that the ocean stops growing in size.

1. The Indian Ocean is staying the same size now because new ocean floor is being created at the Indian Ridge, and current Indian Ocean seafloor is sinking and subducting beneath Indonesia.
2. With the Pacific Ocean there is one spreading ridge (East-Pacific Rise) and subduction occurring on both sides of the ocean, so the Pacific Ocean has begun to shrink in size.

F. In the final stage of an ocean there is only subduction and no longer any spreading, so the ocean rapidly closes up.

1. The Mediterranean Sea is currently closing as the African Plate swings into the Eurasian Plate.
2. The Mediterranean Sea is subducting beneath the southern edge of Europe, causing all of the volcanism in Italy and Greece.

G. If convergence continues once the ocean is entirely gone, the two pieces of continental crust will collide and a mountain range will form along the plate margin.

1. This is currently occurring in the Himalayas, where a now-closed ocean (Tethys Sea) used to exist between India and the rest of Asia.
2. Many mountain ranges in the interiors of continents, such as the Appalachian Mountains in the eastern United States and the Ural Mountains in Eurasia, used to contain a now-subducted ocean between them.

III. Ridges and rifts are tectonically active regions, the sites of large numbers of earthquakes as well as volcanoes.

A. When the two sides of a rift are pulled apart, the tensional stresses often exceed the strength of the rock and normal faults occur.

1. At ridges, this is often accompanied by the rotating and tilting of blocks of newly formed ocean crust.
2. When normal faults occur on both sides of a region of land, the result is a dropped valley in between, called a graben. The African rift valleys are grabens with sides nearly a kilometer high.

B. Ocean ridges are usually in the form of multiple spreading segments separated by short transform fault segments. Seismology has been able to map out the respective ridge and transform segments by using seismograms to determine the kinds of faulting that occurs.

C. Melting begins deep beneath mid-ocean ridges, with small amounts of melt percolating slowly toward the surface.

1. The magma does not immediately rise to the surface, but accumulates in small cylindrical magma chambers less than a kilometer in size directly beneath the ridges.
2. Some of the magma never reaches the surface and cools onto either sides of the magma chamber as gabbro.
3. Magma that comes to the surface does so episodically, rising up as narrow sheets along the opening rift.
4. Some of this magma cools onto both plates as vertical basaltic dikes, about a kilometer thick, and some rises to seafloor where it erupts as pillow basalts.

IV. At a mid-ocean ridge, hot rock drives a pattern of hydrothermal circulation that causes large amounts of mineral-rich hot water to be pumped into the ocean.

A. The high temperatures cause water in the crust to become buoyant and rise toward the ridge, sucking in cold water along the flanks of the ridge and creating a continuous cycle of water flow through the ridge.

B. Hot water has the property of increasing the solubility of metals and minerals. When hot water cools, the minerals and metals come out of the solution and precipitate, forming large chimneys called "smokers."

C. As cold ocean water flows into the ridge zone and heats up to temperatures above 300˚C, it begins to dissolve minerals and metals out of the basalt.

1. When the water comes out of the ridge into the cold ocean, coming out of channels called thermal vents, it chills instantly to temperatures around 0˚C.
2. The minerals precipitate out, both forming tall black chimneys around the thermal vents and blanketing the seafloor with mineral deposits.
3. These mineral deposits will one day be carried into subduction zones, where they will go through further geological processes that will concentrate them into the rich mineral deposits that are mined for human industry.

D. The thermal vents provide a source of energy (hot water) and food (minerals and metals) to support a large community of life forms.

1. Unique species of thermofiles (single-celled organisms that can tolerate high temperatures) thrive around the thermal vents, supporting a large biosystem that includes crabs, fish, and giant tube worms.
2. Because Earth's early surface would have been hostile to life with no ozone layer to block out UV radiation from the sun, many scientists think that life may have first started in just such communities nearly 4 billion years ago.

Recommended Reading:

Cone, *Fire Under the Sea*.

Nicolas, *The Mid-Ocean Ridge*.

Questions to Consider:

1. The water that comes out of thermal vents is about 300˚C, and yet it is water and not steam (remember that water at the surface boils at 100˚C). Why?
2. If plate velocities suddenly started moving faster, what would the effect be on global sea levels? (This is not a hypothetical question. It is a very geologically important one because the situation does arise.)

Lecture Eighteen

Transform Faults—Tears of a Crust

Scope: Transform faults occur when plates slide past each other. They are the least-common form of plate boundary, but not in America, where our best-known fault is a transform fault: the San Andreas. Running almost 1300 kilometers across most of the length of California, the San Andreas is a transform fault that separates the North American and Pacific plates. Los Angeles is actually not in North America (the plate, that is!), and will be a suburb of San Francisco in about 13 million years. Transform faults are actually fault systems that are a few hundred kilometers wide, with earthquakes occurring on many different parallel faults. The elastic rebound theory, which describes the cyclic nature of large earthquakes, was developed following the destructive 1906 San Francisco earthquake. While there are some other well-known continental transform faults, like the Anatolian Fault in Turkey and the Alpine Fault in New Zealand, transform faults on land are actually quite rare. Most transform faults are found in the oceans, separating segments of the ocean ridges. Because it takes much more work to rift plates apart than have them slide past each other, mid-ocean ridge systems evolve to have the least amount of ridge length, supplementing their lengths with transform fault segments.

Outline

I. Transform faults are the least common form of plate boundary on continents, but are the most familiar in America because the San Andreas Fault is a transform fault.

- **A.** There are a few other major transform faults on continents such as the Alpine Fault in New Zealand, the Anatolian Fault in Turkey, and the Queen Charlotte Fault along the west coast of Canada.
- **B.** However, most transform faults occur beneath the oceans where large numbers exist as connections between spreading ridge segments.

II. Transform faults are abundant between spreading oceanic plates because they require less energy to occur than rifting.

A. Processes in nature happen at their lowest energy states, including the way tectonic plates rift apart.

   1. There is nothing mysterious about this. A chain will break along its weakest link: If one thing can happen more easily than others, then it is what will happen.

   2. It takes more energy to tear plates apart than to slide them past each other. Compare breaking a brick to sliding two bricks past each other.

   3. Ocean transform faults occur easily because the rock on both sides is hot and weak, having just formed at the rifts.

B. The boundaries between plates are not necessarily perpendicular to the directions in which the plates are moving.

   1. On a map you can see that the Mid-Atlantic Ridge swerves east and west though the plates are only moving in one direction relative to each other.

   2. If the Mid-Atlantic Ridge were only made of spreading rifts, the orientation of the rifts would curve with respect to the east-west spreading direction of the plates, making for a very long amount of rift.

C. Over time, a mid-ocean rift would break up into a set of spreading centers all perpendicular to the direction of spreading, separated by a set of transform faults.

   1. Transform faults require very little energy and therefore happen easily.

   2. This configuration minimizes the total length of rifting, which occurs with more difficulty.

   3. This is what all ocean spreading boundaries have evolved to, simply because it occurs most easily.

D. The system of oceanic rifts and transforms operates differently in the Atlantic and Pacific oceans.

   1. The locations of the major transforms stay locked in the Atlantic Ocean, so fracture zones extend out from them continuously all across the ocean.

   2. The locations of transform faults along the faster-spreading ridges in the Pacific Ocean can vary, with unusual propagating rifts moving them up and down the ridge.

III. The San Andreas Fault poses a continuous threat to people living in California, but has also continued to teach us about the process of earthquakes and the engineering techniques necessary to protect against them.

A. The San Andreas Fault is the plate boundary between the North American and Pacific plates.

1. It extends nearly 1300 kilometers from the top of the Cocos Plate (west of Mexico) to the bottom of the Juan de Fuca Plate (west of Mendocino, California).

2. The orientation of the San Andreas Fault is in the direction that the Pacific Plate is moving relative to North America (northwest).

3. The western part of California, including Los Angeles, is actually on the Pacific Plate and not the North American Plate, and is moving northward at a rate of 4.2 centimeters per year. (At this rate, Los Angeles will be a suburb of San Francisco in about 13 million years!)

B. The large 1906 earthquake in San Francisco (magnitude 7.9) alerted Americans to the hazards of earthquakes.

1. The fault slipped about 4 meters over several hundred kilometers.

2. The shaking caused widespread fires that burned for 3 days and destroyed San Francisco.

C. The 1906 earthquake and others that have occurred along the San Andreas Fault have given engineers the opportunity and impetus to improve techniques for building structures that can withstand severe shaking.

D. The 1906 earthquake also gave rise to the elastic rebound theory, which suggests that earthquakes along faults like the San Andreas fault occur in a cyclic manner.

E. The buildup of strain that occurs along the San Andreas fault suggests that there will be another big earthquake there, but we cannot predict when it will occur.

F. Fortunately, earthquakes along transform faults can never get very large, at least when compared to earthquakes in subduction zones.

1. Energy released by an earthquake is proportional to the area of the fault, and transform faults are narrow in depth.

2. The San Andreas Fault may be 1300 kilometers long, but it is only about 25 kilometers deep, making it a ribbon of a fault that snakes its way up the California coast.

3. If the entire San Andreas Fault were to rupture at the level of the 1906 quake, the result would be a magnitude 8.3 earthquake, which is only one-thirtieth of the size of the 2004 Sumatra earthquake.

IV. The San Andreas Fault has also taught us that faults and earthquakes are very complex, and may defy an understanding complete enough to be able to predict them.

A. The North America-Pacific Plate boundary is not a simple fault but rather a whole system of faults extending several hundred kilometers in width.

1. There are many parallel faults to the San Andreas, some large like the Hayward and Calaveras faults, most much smaller, that also take up some of the plate motion.
2. Studies of crustal deformation using ground-implanted GPS sensors show that the deformation of the plate boundary is actually a wide band a few hundred kilometers wide.
3. A map of California earthquakes shows such a complex distribution that in most places it is actually hard to pick out the San Andreas Fault.

B. Because the composition and structure of continental rock is so variable, the seismic behavior of the San Andreas Fault varies drastically along its length.

1. Some parts of the San Andreas have characteristic earthquakes that are greater than magnitude 7.0, while some are magnitude 6.0.
2. Some regions of the San Andreas Fault are aseismic—they do not have earthquakes and the two sides of the fault simply slide past each other smoothly.

C. Bends in the San Andreas Fault, such as what occurs just northeast of Los Angeles, cause tremendous complexity.

1. Two pieces of flat wood will slide easily past each other, but if they both have a bend in them, the result will be a lot of cracking and splintering.
2. The crust on either side of the bend in the San Andreas Fault in southern California is highly cracked and splintered.
3. The San Gabriel Mountains have formed along the bend, because the rock has nowhere to go but up.
4. There are a number of active faults in the Los Angeles region, and all of the large earthquakes that have occurred there in

recent decades have occurred on faults other than the San Andreas.

5. Most of the hills in the Los Angeles region actually sit atop blind thrust faults that could reactivate at any time.

V. Though Los Angeles is destined to be continually rocked by significant earthquakes for millions of years to come, it is nowhere close to having the largest seismic risks in America. That distinction lies with the states of Oregon, Washington, and Alaska because they lie atop subduction zones.

Recommended Reading:

Fradkin, *Magnitude 8: Earthquakes and Life Along the San Andreas Fault.*

Winchester, *The Crack at the Edge of the World.*

Questions to Consider:

1. The strongest part of an ocean transform fault is in the middle, capable of having the largest earthquakes. Why? (Hint: Think about what is happening on either side of the transform fault.)
2. The Anatolian Fault runs east-west along the northern border of Turkey, separating the microplate of Turkey from the rest of Europe. Just from this information, what can and can't you infer about the relative motions of Turkey and Europe?

Lecture Nineteen

Subduction Zones—Recycling Oceans

Scope: Earth isn't getting any bigger, so as fast as new ocean crust is created at mid-ocean ridges it is consumed at subduction zones. The ocean lithosphere becomes progressively heavier than the mantle rock beneath it, and eventually sinks down through it. This occurs at subduction zones, which are the most geologically exciting places on Earth. Massive earthquakes occur when the oceanic plate suddenly slides beneath overriding continents. Water brought down with the sinking ocean crust causes mantle rock to melt, and the rising magma creates explosive volcanoes. The slab suction force creates rifting back-arc basins behind the volcanic arcs, and may be responsible for tearing supercontinents apart. The sinking slabs of rock sometimes have a difficult time penetrating down into the lower mantle, accumulating about 500 miles beneath the surface before plunging more rapidly toward the core. There are competing ideas about how subduction begins, but at some point the Atlantic Ocean will have subduction zones at its edges and the ocean will close up.

Outline

I. Though some scientists in previous generations proposed it, the earth is not expanding, so the amount of new lithosphere being created by mid-ocean ridges must be balanced by the amount of lithosphere destroyed at subduction zones.

- **A.** Each year about 3 cubic kilometers of new ocean seafloor is created at mid-ocean ridges, and the same amount sinks into the mantle at oceanic trenches.
- **B.** Subduction zones are the most tectonically active places on Earth, and are significant for several reasons.
  1. The most destructive earthquakes and volcanoes occur at subduction zones.
  2. Subduction zone volcanoes add significant amounts of new land to continents.
  3. Subduction zones are factories for creating rich mineral and metal reserves.

II. A subduction zone forms at a collisional boundary between two plates when one of the plates consists of oceanic lithosphere. The boundary can be between either two ocean lithospheres or oceanic and a continental lithosphere.

A. When the ocean lithosphere subducts beneath the overriding plate, water brought into the mantle causes melting within the mantle, and the magma rises to form a chain of volcanoes.

1. The chain of volcanoes is usually curved and is called a volcanic arc.

2. The arc results from the fact that Earth's surface is curved, and is analogous to the curved indentation on a dented ping-pong ball.

B. With an ocean-ocean collision, it is usually the older segment of ocean lithosphere that subducts into the mantle because it is denser and rests at a lower elevation.

1. The volcanic arc forms a curved line of volcanoes that are called island arc volcanoes.

2. Commonly known volcanic island arcs include the Aleutian Islands, the Mariana Islands, and the Antilles Islands.

C. With an ocean-continent collision, it is always the oceanic lithosphere that subducts beneath the continent.

1. The subduction creates a volcanic arc along the edge of the continent.

2. Well-known continental arcs include the American Pacific Northwest and the west coast of Mexico, Central America, and South America.

D. Ocean-ocean subduction usually converts to ocean-continent subduction at some point.

1. If there is any continental crust embedded within the subducting plate, it will eventually be dragged into the trench.

2. Because continental crust cannot sink into the mantle, the subduction will stop.

3. However, if there are still strong compressional stresses across the boundary, the direction of subduction will reverse and the oceanic plate that had previously been the overriding plate will now begin to subduct beneath the continental plate.

E. For relatively young subduction zones, like the Antilles Arc in the Caribbean, where there has been minimal volcanic activity, the volcanic islands are distinct. For mature subduction zones that have existed for a long time, the volcanoes come together to form long large volcanic islands like Sumatra, Java, Bali, and New Guinea.

F. Subduction zones are complex boundaries that can cause a wide area of plate deformation, sometimes called a diffuse plate boundary. The crust that is part of the diffuse plate boundary is internally deforming, in contrast to the definition of tectonic plates as being internally rigid.

1. Subduction of the Nazca Plate beneath South America causes a diffuse plate boundary that extends almost 1000 kilometers across the Andes and the Altiplano.

2. In fact, about 15% of Earth's surface is plate boundary, actively deforming as part of the plate interactions.

III. A variety of different kinds of earthquakes occur at subduction zones, including the world's largest.

A. Some earthquakes occur as the plate bends and unbends, cracking straight through the 100-kilometer-thick subducting lithosphere.

B. Other earthquakes occur in the overlying plate, compressed and/or extended (through the slab-suction force) by the subduction.

C. The most unusual earthquakes occur deep within the subducting slab, down to a depth of almost 700 kilometers.

1. The cause of these earthquakes is not well-known because extremely high pressures should inhibit faulting (Remember trying to slide your hands past each other when you are pressing them hard together?).

2. Deep earthquakes are likely to occur because the core of the subducting slab stays cold and stiff for a very long time.

3. Mineral phases in which minerals change from one phase to a denser mineral could be a mechanism for deep earthquakes. This can be a runaway process.

D. Giant earthquakes occur along the frictional boundary between two plates, as one slides under the other.

1. These earthquakes can occur on faults that are hundreds of kilometers wide (extending down into the subduction zone) and more than a thousand kilometers long. Large surface areas allow for large-magnitude earthquakes.

2. The largest earthquake ever recorded occurred in Chile in 1960—it was a magnitude 9.5.

3. The second largest, and largest in America, was the 1964 Alaska earthquake, a magnitude 9.4.
4. The largest recent earthquake was the 2004 Sumatra quake, which we will discuss later.

E. Subducted slabs follow a variety of paths as they sink down into the mantle. The angle that the slab enters the mantle ranges from nearly vertical (Mariana Trench) to nearly horizontal (beneath South America), largely dependent upon the direction and velocity of the overriding plate motion.

IV. Accretionary wedges form at trenches where sediments are scraped off the subducting plate. The overriding plate acts as a bulldozer.

A. Most sediment on the seafloor becomes reattached to continents, forming highly deformed layers within accretionary wedges. This keeps eroded continental rock within a near-surface rock cycle.

B. When there is a large amount of sediment, the accretionary wedge can actually make a separate island. This is the case with Barbados, which is made from Amazon and Orinoco River sediments scraped off by the overriding Caribbean Plate.

C. The mineral phase boundary at a depth of 660 kilometers (from a high-pressure phase of the mineral olivine into the mineral perovskite) acts as a temporary barrier, slowing the entry of the subducting lithosphere into the lower mantle.

1. Sometimes subducting plates plunge right through the 660-kilometer phase boundary, but sometimes they lie horizontally along it for a while.
2. The 660-kilometer phase transition to perovskite requires additional energy to occur, so subducted lithosphere may have to lie stagnant there until it warms up enough for the phase change to occur.
3. Once the phase change to perovskite does occur, the subducting oceanic lithosphere may then quickly (geologically speaking, at a few centimeters per year!) plunge across the lower mantle toward the core-mantle boundary. These are called mantle avalanches.

Recommended Reading:

Lopes, *The Volcano Adventure Guide*.

Winchester, *Krakatoa*.

Questions to Consider:

1. When subduction terminates with the pulling of continental crust into the subduction zone, what happens to the island arc?
2. Subduction zones are dangerous places. What might be the reason that so many people often live near them?

Lecture Twenty

Continents Collide and Mountains Are Made

Scope: Continental rock is too buoyant to sink, so when plate collisions bring continents in contact with each other, the result is the formation of mountains. The same motion of the Indian Plate northward that caused the giant Sumatra earthquake is also responsible for the growth of the Himalayan Mountains. The continental collision of India with China has pushed an enormous amount of rock upward and, at the same time, pushed continental crust downward to create a deep root to the mountains. The rocks of the mountains become tremendously deformed and twisted, bent and folded like taffy. The high temperatures and pressures that occur as rock gets pushed downward causes the formation of most of the metamorphic rock we observe at the surface. Metamorphism is a very complex process, and takes many different forms. As mountains erode, the crust rebounds upward, like a mattress when someone sits up from it. This process, over millions of years, brings metamorphic rocks to the surface.

Outline

I. Continents are extremely variable and complex, and much of this complexity is due to the processes that occur when continents collide, creating mountains and metamorphic rock.

- **A.** Continents retain a record of the history of their collisions within the deformed rock that results.
- **B.** Even though there are similarities between mountain ranges, they are different from each other because of what happens to them and how they are attached.

II. The formation of a continental mountain range is the final stage in the life cycle of an ocean, when the ocean closes up between two continents that are colliding. There is, therefore, a great deal of oceanic material that will end up between the two continents.

- **A.** Continental collision usually follows an extended period of subduction, with oceanic lithosphere subducting beneath a continent.

1. This subduction creates an accretionary wedge of continent-derived (and therefore of continental compositions) sediments off the edge of the continent.
2. In some cases, as with Japan, there is also a back-arc basin of oceanic crust between the island arc and the mainland, with a basaltic composition.

B. As another continent is carried toward the subduction zone, it scrapes up the different pieces of the subduction zone and smashes them into the growing mountain.

1. Imagine if a continent suddenly smashed into Japan, pushing it into China. The basaltic back-arc basin, intermediate-composition island arc, and granitic accretionary sedimentary wedge would all be glued together in between Asia and the colliding continent.
2. A continental collision can also scoop up pieces of oceanic crust from in front of the trench and add these into the mountain range. These fragments of ocean crust are called ophiolites, and were geologists' first indication of the composition of ocean crust.

III. When the mountains form, deep crustal roots develop, as well as severe folding of rock layers.

A. When continents collide, the rock trapped in between has to go somewhere: Some go up to form mountains and some go down to support them in the form of crustal roots.

1. Adding mass on top of the land (in this case in the form of a mountain) is not stable—the asthenosphere below will just flow away from the increased pressure.
2. Crustal roots grow at the same time as the mountains do, balancing the added mass by replacing heavy mantle rock with lighter crustal rock.
3. The typical continental crust has a thickness of 35 kilometers, but beneath mountains the crust can be as thick as 80 kilometers (as in the case of the Himalayas), making the mean continental thickness about 40 kilometers.

B. Layers of rock get severely folded in a mountain orogen, sometimes being folded over and turned upside down so that older layers are actually on top of younger layers, as has happened in some places of the Alps.

1. Different rocks have different strengths, so they bend in different ways. Sometimes the folding can have a taffy-like appearance.

2. The folding of rock layers can occur over great distances from the actual mountains, usually getting less severely folded with distance. This can be seen in the hills of Pennsylvania, going westward from the Appalachian Mountains.

IV. As rocks get squeezed and compressed during mountain building, they become altered and undergo metamorphism. This can occur in different ways.

A. The increased temperature and pressure can squeeze rocks into tighter structures, welding mineral grains together.

1. Rocks like sandstone can have their grains welded together to form a denser rock called quartzite.

2. Limestone becomes marble.

B. Directed pressures can give rocks a layered or banded appearance.

1. Mud that is compressed to form the sedimentary rock called shale can be further compressed to make slate, which has a layered or foliated appearance.

2. When a rock like granite is squeezed or sheared, the mineral grains can be stretched or flattened, often through the diffusion of atoms from regions of high pressure to regions of low pressure, turning the rock into gneiss, which has a banded appearance.

C. At higher grades of metamorphism, new minerals will grow from minerals that are no longer stable at the new temperature and pressure conditions, stealing atoms one at a time.

1. If a slate becomes further compressed, flat minerals like mica will begin to grow, giving the rock (now called a schist) a shiny, flaky appearance.

2. In rocks that are pushed down deep into mountain roots, crystals like garnet and tourmaline will begin to grow from the pre-existing minerals.

D. As metamorphism continues, melting of some minerals will begin.

1. Highly metamorphosed rocks often have streaks of quartz running through them because quartz is one of the first minerals to melt.

2. One mechanism for creating the large granite batholiths in the cores of mountains (like the ones that underlie the

Appalachian Mountains) is the continued growth of the mountain root. As rock continues to get pushed down, minerals related to a granitic composition keep melting and rising up into the core of the mountain, where they cool and crystallize to form granite batholiths.

3. When the tops of the mountains are eroded away, the large granite cores become exposed at the surface.

V. The most dramatic example of a continent-continent collision is currently the collision of India with Asia to create the Himalayan Mountains.

A. Only 150 million years ago India was attached to Antarctica. It traveled rapidly across the ancient Tethys Sea and collided into Asia, smashing together everything else in between.

1. India was originally part of a large continental mass called Gondwanaland, comprised of Africa, Antarctica, Australia, South America, and India.

2. When Gondwanaland broke up, India broke away and moved northward into Asia.

3. Several landmasses, including an island arc and a microcontinental fragment, got wedged in between India and Asia as they collided.

B. The Himalayan Mountains formed as a result of the collision, with many consequences for the Asian continent.

1. The Himalayas began to form more than 60 million years ago, with significant effects on global climate.

2. In addition to deformation of crustal fragments at the collision, the Indian crust began to slide beneath the Asian Plate along a very shallow-angle thrust fault. This caused the Himalayan Plateau to form, but also caused the bottom part of the Asian lithosphere to peel off and sink into the mantle.

3. The collision shortened Asia in a north-south direction, and all of modern-day Southeast Asia was pushed off to the east, squirting out like a watermelon seed squeezed between two fingers.

4. The collision of India with Asia also caused rippling deformation for thousands of kilometers northward.

5. This deformation continues today, and is the cause of the large earthquakes that continuously ravage China.

C. The Himalayas are rapidly being eroded by glaciers, with huge amounts of sediments carried to the Indian Ocean by rivers like the Ganges.

   1. These sediments will one day be stuck back on to a continent in a future continent-continent collision.

   2. The rock that is being eroded now at the surface of the Himalayas was once deep within the mountains, which is why there are ocean fossils exposed at the summit, like the fossil described at the start of this lecture.

Recommended Reading:

Emiliani, *Planet Earth: Cosmology, Geology, and the Evolution of Life and Environment*.

Officer and Page, *Tales of the Earth*.

Questions to Consider:

1. Describe two different geologic mechanisms to explain the existence of ocean fossils within crustal rocks in the middle of a continent.

2. How might erosion actually make the tallest peaks of mountain range higher?

Lecture Twenty-One

Intraplate Volcanoes—Finding the Hot Spots

Scope: While most volcanoes occur at plate boundaries, there are some, like Hawaii and Yellowstone, that do not. And there are some volcanoes at plate boundaries, like Iceland and the Galápagos, that emit unusually large amounts of lava. These intraplate volcanoes have traditionally been all lumped together under the label of "hot spots." However, recent work is showing that not all hot spots are equal. Some, like Hawaii, seem to have their roots all the way at the base of the mantle, with rock moving as part of a giant plume, core to crust. Others, like Yellowstone, seem to be limited to just the upper mantle. Iceland emits lots of lava, but it doesn't seem to be unusually hot. Instead, increased amounts of water may be increasing the amount of magma that is generated, or there may be large amounts of previously subducted ocean crust beneath the surface there that is melting easily as it moves slowly toward the Mid-Atlantic Ridge. Understanding the different forms of hot spots is important because volcanoes like Yellowstone erupt violently, blanketing North America with ash. Hot spots may have played an important role in the breakup of supercontinents like Pangaea.

Outline

I. The surface is covered with volcanoes that do not occur at plate boundaries, and therefore do not fit neatly into the plate tectonics model. For years these intraplate volcanoes were lumped together under the catch-all name of "hot spots," but recent work is showing that Earth might have many different ways of making a volcano.

A. Plate tectonics can explain volcanoes at mid-ocean ridges and at subduction zones, but does not address volcanoes that occur within the interiors of plates.

B. Concurrent with the discovery of plate tectonics in the late 1960s was the idea of hot spot mantle plumes, with hot rock rising toward the surface through conduits that are fixed in location within the mantle.

C. Some early studies had catalogs of up to 400 different hot spots, one hot spot for each intraplate volcano.

D. Recent studies are suggesting that there may be less than a dozen genuine hot spot mantle plumes, and the rest of the hundreds of intraplate volcanoes may need to find other causes. This is a subject that is currently under a lot of debate within the geological community.

II. The topic of hot spots is also part of a bigger question about how rock flows between the surface and the deep mantle and back again, and it is closely connected to questions of the thermal evolution of planets.

A. We know that the dominant way rocks flow downward through the mantle is in the form of subducting lithosphere.

B. We are not sure what the dominant mechanism is for upward rock flow in the mantle. Because of how seismic waves travel, seismic tomography is better at imaging cold regions than hot regions. If there were a hot spot, where seismic waves would travel more slowly, the seismic waves would just travel around it, and it would not significantly affect the waves.

III. The traditional model for a hot spot is of a hot mantle plume of rock rising all the way to the surface from the core-mantle boundary (CMB), and the classic example is Hawaii.

A. The rock at the base of the mantle would be very hot and therefore both buoyant and less viscous (able to flow more easily), so it would whisk off the CMB and rise quickly through a narrow conduit. Though the mantle plume would cool off a little as it rose, by the time the rock reached the surface it would still be several hundred degrees warmer than the surrounding rock, and melt more easily, forming hot spot volcanoes.

B. The mantle plume model is supported by several lines of evidence.

1. Seismic tomography shows hot regions extending from deep in the mantle right up to hot spot volcanoes in several locations including Hawaii, Ascension, Azores, Canary, Easter, Samoa, and Tahiti.
2. The locations of these major hot spots are relatively fixed with respect to the mantle—they move relative to each other about 10 times less rapidly than the plates move.
3. The major hot spots have been continuously active for many tens of millions of years, compatible with the existence of a long conduit.

C. Hawaii shows the characteristics of the mantle plume hot spot.

1. The volcanism has been regular and continuous for at least 70 million years, with the seamounts extending across the Pacific seafloor all the way to the Aleutian Trench.
2. The bend in the Hawaiian-Emperor Island chain at Midway Island is thought by many to be due to a change in the direction of the Pacific Plate motion, from NNW to WNW.

IV. A challenge to the mantle plume hot spot theory comes from the observation that many hot spot volcanoes (Iceland, Galápagos, Easter Island, Tristan, Azores, etc.) occur at or near mid-ocean ridges.

A. Mantle plume advocates do not see a problem with this.

1. The plumes could affect plate tectonics, forcing the ridges to stay located over them.
2. The plumes could be sucked toward the mid-ocean ridges by the flow of upper mantle rock toward the ridges: "blowing in the mantle wind," so to speak.

B. Mantle plume objectors provide other possible alternatives for the locations of hot spot volcanism at or near mid-ocean ridges.

1. Slightly elevated amounts of water in the mantle would cause much more magma to form and create active hot spot volcanism without requiring elevated temperatures: "wet spots" instead of hot spots.
2. Pieces of subducted basaltic ocean crust would melt very easily if carried passively toward mid-ocean ridges, causing increased volcanism. This has been proposed as a mechanism for the Iceland hot spot.

C. Other mechanisms have been suggested to explain the existence of intraplate volcanism, including propagating rifts, pressure release, delamination of the bottom part of continental lithosphere, and shallow convective rolls of asthenosphere rock beneath ocean lithosphere.

V. Whatever the cause, hot spot volcanism has scientists very concerned because the largest and most violent volcanic explosions have been from continental intraplate volcanoes like Yellowstone.

A. Intraplate hot spot volcanoes are explosive for several reasons.

1. The lava is very silica-rich (rhyolitic), so it does not flow easily and a great deal of internal pressure must build up before a large eruption occurs.

2. The continental crust is cold, so the temperature of the lava is low, also making it more viscous.
3. There is a lot of water in continental crust, and this water becomes absorbed into the magma, adding to the explosive power of eruptions.

B. The Yellowstone hot spot does not seem to have a deep mantle origin, and its cause is still debated, but it has had the most violent eruptions in North America in the past 2 million years.
1. Yellowstone erupted 2.0, 1.3, and 0.6 million years ago, each time covering much of North America with ash. If that periodicity is significant, then the next eruption would be in the near future (geologically speaking), and would be devastating for humanity.
2. The size of the Yellowstone caldera (80 x 50 kilometers) is testimony to the size of the eruptions, which have ejected more than a thousand cubic kilometers of lava and ash into the atmosphere.
3. Scientists are concerned that recent increases in underground temperatures and the lifting of the caldera by the flow of magma underground at Yellowstone might indicate a greater chance of an eruption in the near future.

C. The largest known volcanic eruption occurred in Colorado about 26–28 million years ago, ejecting about 5000 cubic kilometers of ash (about 4000 times larger than the 1980 Mount St. Helens eruption) that now forms the Fish Canyon Tuff rock deposit. This volume of rock would fill in Lake Erie.

VI. Hot spots may be important in the breakup of supercontinents.

A. When the supercontinent Pangaea broke up, there were several hot spots that first erupted, causing flood basalts.
1. The Iceland hot spot may have been responsible for splitting Greenland away from Europe.
2. The Afar hot spot beneath eastern Africa now seems to be connected to the rifting of Arabia away from Africa and the breaking of Africa into two tectonic plates.

B. One hypothesis is that hot spots beneath supercontinents rise up beneath the continent, lifting up the continent and causing it to stretch.
1. Continental breakup often occurs along former sutures where previous continents came together, and this might be because

these sutures (orogenic belts) have thinner lithospheres than older cratons and the plume rock flows up and under them.

2. The heat from the hot spot further thins and weakens the lithosphere beneath orogenic belts, and if the continent is pulled apart (such as by slab suction forces) then these are the locations where the supercontinents break apart.

Recommended Reading:

McPhee, "Cooling the Lava," in *The Control of Nature*.

Ziegler, *Hawaiian Natural History, Ecology, and Evolution*.

Questions to Consider:

1. Do you think that there would be any way to stop Yellowstone from erupting if it were preparing to do so?
2. Some scientists do not think that the bend in the Hawaiian-Emperor seamount chain 43 million years ago at Midway Island represented a change in the direction of motion of the Pacific Plate. What other explanation could there be for the bend in the islands?

Lecture Twenty-Two

Destruction from Volcanoes and Earthquakes

Scope: Both earthquakes and volcanoes present deadly threats to people in many parts of the world. Volcanoes create powerful eruptions, burning pyroclastic flows, rivers of molten lava, and blankets of ash that can form steaming mudflows when mixed with water or snow. Earthquakes cause violent shaking that topples buildings, liquefies the ground, triggers landslides and urban fires, and generates tsunamis. In terms of hazards, however, there is a big difference between the two. Volcanoes can be easily monitored, and reveal many clues to an impending eruption as the magma slowly forces its way toward the surface. Earthquakes, on the other hand, are not yet predictable. It turns out that nuclear bombs create seismic waves similar to but distinct from earthquakes, and seismometers are currently used to monitor the threat of nuclear proliferation.

Outline

I. Both earthquakes and volcanoes deal with immense energies.

II. Volcanic eruptions pose significant seismic hazards both locally and globally.

- **A.** Lava flows can obliterate towns near the volcano.
    - **1.** In places like Hawaii and Iceland, destruction from slow lava flows are not uncommon.
    - **2.** In general, however, lava flows occur close to the volcano and are not very violent, so are not a large cause of loss of life.
- **B.** The most dangerous volcanic hazard is a pyroclastic flow (also known as a *nuée ardente*), which involves hot gas, ash, and rock rushing down mountain sides at speeds up to or greater than 500 kilometers per hour.
    - **1.** A pyroclastic flow can occur in several ways, including the collapse of a vertical ash column (as with Mount Vesuvius' destruction of Pompeii and Herculaneum) or a lateral blast when part of a volcano explodes or collapses (as with the 1980 eruption of Mount St. Helens).

2. One of the deadliest pyroclastic flows accompanied the 1902 eruption of Mount Pelée on the island of Martinique and wiped out the city of Saint-Pierre, killing 30,000 people.

C. Ash falls can be centimeters to meters thick over large distances, sometimes hundreds of kilometers away.

1. The ash can collapse or bury buildings, and can infiltrate machinery (like cars!) and render them inoperative.
2. Ash mixed with water can create deadly mudflows called lahars, which can destroy villages.
3. Lahars from the 1985 eruption of Nevado del Ruiz buried the city of Amero under 8 meters of mud, killing 21,000 people.
4. Because the tops of tall volcanoes are often covered with snow, some lahars form instantly when hot ash falls on top of snow and melts it.

III. Earthquakes pose a wide array of hazards, most local to the region.

A. Earthquakes kill 8 to 10 people a year on average in the United States, and an average of about 20,000 to 30,000 deaths per year occur globally.

1. However, many parts of the world are under considerably larger seismic risk because of rapidly growing populations.
2. China has had several earthquakes that have killed several hundred thousand people in an instant.

B. The accelerations from ground displacements and seismic waves can knock down buildings. Earthquake engineering is therefore very important in reducing seismic risks.

1. It has been said that "earthquakes don't kill people; buildings kill people." If you are in a field, a strong earthquake may knock you over. If you are in a building, it may knock down the building on top of you.
2. There also needs to be an enforcement of earthquake codes.
3. Particular buildings of particular sizes have resonant frequencies; if the earthquake happens to shake at just the right frequency, it is more likely to destroy the building.

C. Shaking from an earthquake causes other hazards. Many of the largest and most destructive landslides have been triggered by earthquakes.

D. Fires are one of the deadliest and most destructive hazards of earthquakes, as seen with the 1906 San Francisco earthquake.

1. Ground shaking not only topples buildings, which breaks gas pipes and starts fires, but also ruptures the water supply lines needed to put out the fires.
2. During the 1923 Japan earthquake, 140,000 people burned to death from fire storms that raged through Tokyo.

IV. Seismology plays an important role in international peacekeeping by monitoring nuclear testing.

A. Nuclear testing was performed atmospherically until radioactive fallout contaminated grass and milk in both the United States and the Soviet Union, and testing was moved underground in the late 1950s and 1960s.

B. Although seismometers were used initially for monitoring Soviet nuclear tests, ultimately they also provided high-quality seismic data about the internal structure of Earth.

C. Seismology can detect the difference between nuclear testing and earthquakes. India and Pakistan detonated a set of nuclear tests in the 1990s, and seismologists were able to locate and measure them, even identifying which ones had successfully gone critical.

D. Seismometry has also been used to monitor the size and the amount of energy released from the Oklahoma City bombing, the collapse of the World Trade towers, and the collapses of mines and other catastrophes.

Recommended Reading:

De Boer and Sanders, *Earthquakes in Human History*.

———, *Volcanoes in Human History*.

Hough, *Earthshaking Science*.

Questions to Consider:

1. If pyroclastic flows are largely hot air and hot air tends to rise, why do they flow down the sides of the volcanoes?
2. Why is it politically important that the seismic signatures of earthquakes and nuclear explosions are not the same?

Lecture Twenty-Three
Predicting Natural Disasters

Scope: Natural disasters come in many different forms, and pose serious threats to large segments of the population. There are two ways to reduce the loss of human life from natural disasters: reduce the hazards or be able to predict their occurrence. In most cases, the former is not possible. The greatest natural disasters are biological, involving the spread of disease. Many nonbiological natural disasters are weather-related. Volcanoes and earthquakes present an interesting contrast. Volcanoes can be easily monitored and reveal many clues to an impending eruption as the magma slowly forces its way toward the surface. Earthquakes, on the other hand, are not yet predictable. Previous seismic activity can give some guidance as to where earthquakes are likely to occur in the future, a process called forecasting, but don't give clues to exactly when and where a quake will happen.

Outline

I. No one has yet come up with anything to stop natural hazards such as hurricanes, tornadoes, floods, earthquakes, and volcanoes.

- **A.** Natural hazards always have and always will occur, but we can try to reduce the human risks associated with them.
- **B.** We can do this by building better structures to withstand them and trying to predict when they will occur.
  - **1.** The first part involves engineering—making buildings that will not fall down during an earthquake or levees that will not burst during a flood.
  - **2.** The second part involves using everything we have learned from science to give as much notice as possible before a disaster occurs.
- **C.** Predicting natural disasters falls into three different categories which are possible, improbable, or impossible, depending upon the type of disaster.
  - **1.** Predicting the time and place of a geologic catastrophe.
  - **2.** Forecasting the likelihood of a disaster based upon favorable conditions.

3. Detecting and monitoring a disaster as it happens.

II. The deadliest natural disasters involve the outbreak of disease.

A. Outbreaks of disease have caused death over both brief and extended periods (e.g., smallpox, bubonic plague, AIDS, the Spanish flu).

B. There are two parts to the outbreak of a disease:

1. The evolution of a deadly bacterium or virus that is entirely unpredictable.
2. The spread of the disease once it evolves, which depends upon human and environmental factors like population density and medical standards.

III. Most of the worst non-disease-related natural disasters are the result of sudden changes in weather conditions.

A. Flooding has the capacity to kill millions of people at a time. One of the worst hit regions is China; the Yellow River has killed more than a million people on several occasions due to severe flooding.

B. Catastrophic weather-related disasters of hurricanes and cyclones involve strong winds, heavy rains, and local flooding from streams or ocean waves.

C. In the western hemisphere, deaths from weather-related events have not been as severe, but they can still be catastrophic (e.g., Hurricane Mitch and Hurricane Katrina).

D. Tornadoes, while sudden and dramatic, tend to be small and cause minimal damage and loss of life.

E. Blizzards and heat waves are other forms of weather-related catastrophes.

F. These kinds of catastrophes are unpredictable over long time scales, but often predictable over the scale of days with the use of radar and satellite weather tracking.

IV. There has been increasing success in predicting large volcanic eruptions, greatly reducing the risk to loss of life.

A. There are several phenomena that occur and can be monitored leading up to a large eruption.

1. Thousands of small earthquakes occur as rising magma cracks its way toward the surface.

2. The dome of the volcano tilts outward as magma fills the edifice.
3. Venting of hot gases and small eruptions usually precede a large eruption, giving time for evacuation.

B. Several large eruptions in recent decades have been predicted.
1. Evacuations before the 1980 Mount St. Helens eruption reduced the number of deaths to 60.
2. The 1991 Pinatubo eruption that destroyed more than 100,000 homes was predicted before the eruption, allowing for an evacuation of the area reducing the loss of life to 281.

C. False alarms have occurred because volcanoes often go through many small dome-building episodes before a major eruption will occur.
1. A volcanic eruption was incorrectly predicted for Mammoth Lakes, California, in 1982.
2. Public outrage at the damage to local economies led to death threats for the United States Geological Survey (USGS) geologists who made the predictions.

V. Earthquake prediction has remained an elusive target. Emphasis has instead been put toward forecasting earthquakes or determining real-time hazard assessments.

A. Earthquake predictions may be impossible because there seems to be no pattern for what occurs before an earthquake, though there are some precursory phenomena that might be useful one day.
1. To date, only one destructive earthquake has ever been predicted—a 1975 evacuation of Haicheng, China, one day before a magnitude 7.3 earthquake.
2. Earthquakes sometime occur following foreshocks, a period of decreased seismicity, or normal levels of seismicity, making this no basis for prediction.
3. Unusual animal behavior is frequently reported to have occurred before earthquakes, but has not yet been useful as a predictive means.
4. Several large earthquakes have had a change in underground water pressure or electrical conductivity or a change in the levels of gases (like helium or radon) leaking to the surface before a large earthquake.

B. Earthquake forecasts are long-range risk assessments based upon the previous history of seismicity in a region.

1. An important part of seismic forecasting is the determination of the dates of previous large earthquakes using paleoseismicity, which is the use of carbon-14 dating of ground layers that have been ruptured.
2. Forecasting has not been successful, perhaps suggesting that earthquakes occur randomly, without a set repeat time as suggested by the elastic rebound theory.
3. In 1985, the USGS predicted with 95% probability that a magnitude 6.0 earthquake would occur in Parkfield, California, before 1993. The earthquake finally occurred—in 2004.
4. So far, the best assessment has been that earthquakes seem to occur where previous earthquakes occurred.

C. Real-time seismic hazard assessment, using an instantaneous recording of an earthquake to make warnings, is used in areas where there is enough time to reduce damage.

1. In some parts of the world, high-speed trains and gas lines can be shut down if a nearby earthquake is detected.
2. Real-time assessment works very well for tsunamis because the tsunamis take much longer to reach most places than seismic waves, given many hours in most cases to prepare for the waves, which usually would involve moving a few kilometers inland.

D. Professor Wysession was once part of a discussion to determine if St. Louis should install a real-time earthquake warning system. Community leaders were concerned with the risk of another earthquake occurring along the New Madrid Fault area in Missouri.

1. The actual risks were reviewed, as over time stories of earthquakes and their magnitudes had become exaggerated.
2. Current seismic activity also had to be taken into consideration; the New Madrid Fault area had had no magnitude 6.0 earthquakes in more than a century.
3. Should an earthquake occur, there would only be 25 seconds of warning between when the earthquake occurred along the New Madrid Fault and when the waves reached St. Louis.
4. The final decision being to not install the warning system, which is what many regions have decided to do; only areas with a high enough risk warrant putting in an early warning system.

Recommended Reading:

De Boer and Sanders, *Earthquakes in Human History*.

Hough, *Earthshaking Science*.

Questions to Consider:

1. In some parts of the world, large loss of life has occurred when strong seismic building codes are in effect, but not strong legal codes. Why might this be the case?
2. A Chinese seismology textbook, reporting on studies of animal behavior, once stated that "Chickens fly up to trees and hogs stay quiet. Ducks go out of water and dogs bark wildly." What do you see here as an impediment to using animal behavior to predict earthquakes?

Lecture Twenty-Four
Anatomy of a Volcano—Mount St. Helens

Scope: There are many parts of the United States that are prone to volcanism. Kilauea volcano on Hawaii has been erupting continuously since 1980. The Aleutian Islands are a long chain of volcanic islands that hosted the largest eruption of the 20th century: Mount Katmai in 1912. Yellowstone contains the enormous caldera of a powerful volcano that has blanketed the country with ash three times in the past 2 million years. However, none of these volcanoes captured the attention of Americans the way Mount St. Helens did when it erupted on May 18, 1980. In the preceding months, millions of small earthquakes revealed the steady propagation of magma toward the summit. When a magnitude 5.1 earthquake occurred, the shaking triggered the world's largest landslide in recorded history. The sudden release in pressure allowed a lateral volcanic blast and pyroclastic flow that leveled trees over a 600-square-kilometer area and sent a plume of ash 25 kilometers into the air. Mount St. Helens and all of the other volcanoes of the Pacific Northwest, from Lassen Peak in California to Mt. Baker in Washington state, are still active and will repeatedly erupt in the future, posing significant hazards in the form of ash, lava, pyroclastic flows, and lahars.

Outline

I. There are actually many regions of the United States that are volcanically active, but the Mount St. Helens eruption of 1980 remains the most memorable for most Americans.

- **A.** Hawaii is more active, with Kilauea erupting continuously since 1980.
- **B.** Mount Katmai, in Alaska, had the largest American eruption in the past century with the 1912 blast that vented about 35 cubic kilometers of tephra.
- **C.** Yellowstone has had the largest American eruption in the past million years.
- **D.** Though the 1980 eruption of Mount St. Helens was not very large (only 2.8 cubic kilometers of tephra were ejected), its powerful

explosion and large ash plume woke Americans to the hazards of volcanoes in the Pacific Northwest.

II. Mount St. Helens and all the other volcanoes around it exist because of the subduction of the Juan de Fuca Plate beneath North America.

A. The Juan de Fuca Plate is subducting beneath North America from northern California, at the top of the San Andreas Fault, to southern British Columbia, at the bottom of the Queen Charlotte Fault.

1. The Juan de Fuca is a remnant of the once much larger Farallon Plate, which has almost entirely vanished beneath western North America.

2. The sinking seafloor brings water into the mantle, which causes the melting that leads to volcanoes in California, Oregon, Washington, and British Columbia.

B. There are many volcanoes in the Pacific Northwest that remain geologically active.

1. These volcanoes erupt intermittently, with the last dates of activity varying: Lassen (1915), Shasta (1786), Hood (1865), Adams (1000 years ago), Rainier (1894), and Baker (1880s).

2. Crater Lake (Mount Mazama) erupted violently about 5700 B.C.E., ejecting about 25 cubic kilometers of tephra. The collapse of the magma chamber created a 10-kilometer-wide caldera that is America's second deepest lake (600 meters deep).

III. The eruption of Mount St. Helens on May 18, 1980, was powerful and dramatic, though there were precursory signs that gave warning to it.

A. Starting two months earlier, small earthquakes and steam eruptions began to occur, and a crater bulge began to develop.

1. More than 10,000 earthquakes were recorded before the main eruption.

2. This activity gave an indication of the impending eruption and allowed the region to be evacuated.

B. At 8:32 am on the morning of May 18, 1980, a magnitude 5.1 earthquake occurred beneath the volcano.

1. This caused the north side of the summit to slide away in the largest landslide on Earth in recorded history.

2. The landslide traveled for 22 kilometers and the blast cloud spread over 26 kilometers.

3. The blast knocked down whole forests of enormous pine trees as if they were toothpicks.

C. The blast produced a column of ash that rose 25 kilometers in 15 minutes.

1. Winds blew 520 million tons of ash eastward, plunging Spokane into darkness. The ash covered 22,000 square miles, and circled the globe in 15 days.
2. The eruption lasted all day, reaching its peak in the afternoon with enormous pyroclastic flows.
3. The steam and ash mixed with snow and water to make large lahars that rushed down the Toutle River, wiping away 27 bridges.

D. The total energy released by the eruption was equal to 350 megatons of TNT, or 27,000 Hiroshima nuclear bombs.

1. Because of the advance warnings, only 57 people died, including volcanologist David Johnston, who was near the summit at the time and whose famous last words over the radio were "Vancouver, Vancouver, this is it!"
2. The summit of the volcano was reduced in elevation by 1,314 feet.

IV. Following the main eruption, the volcano returned to the long phase of building up the summit again, which may take centuries or millennia before conditions are right for another eruption like the one in 1980.

A. During the rest of 1980, there were five smaller eruptions that sent ash up to 15 kilometers into the atmosphere, and lava began to come out the summit to build a new lava dome.

B. In the decades since, Mount St. Helens has had many small episodes of seismic activity representing magma migration and dome building, and this may occur for a long time before the next large eruption. A very active period occurred in 2004–2005.

C. Though life around volcanoes like Mount St. Helens gets entirely obliterated with an eruption like the 1980 blast, life has evolved in these regions to be able to recover, and both plants and animals soon began to return to the St. Helens region after the eruption.

V. Volcanoes pose the greatest human threats when large populations develop around them, and few volcanoes in America have the potential for human disaster to the same degree as Mount Rainier, which is very close to Seattle and Tacoma, Washington.

A. Mount Rainier is the tallest peak in the Cascade Mountain Range, and with 26 glaciers, is the most heavily glaciated mountain in the 48 states.

B. During volcanic eruptions, hot ash melts the snow and ice to form large lahars that have covered the surrounding areas.

  1. Much of Tacoma and parts of south Seattle are built upon the former mudflows from Rainier's eruptions.

  2. Five thousand years ago an eruption caused the top 500 meters of the mountain to collapse in a large debris avalanche that reached as far as Puget Sound, 80 kilometers away.

  3. When this kind of eruption next occurs, the loss of life to Tacoma and Seattle will be catastrophic.

Recommended Reading:

Longview Publishing Company Staff, *Volcano, The Eruption of Mount St. Helens*.

Rosenfeld and Cooke, *Earthfire: The Eruption of Mount St. Helens.*

Questions to Consider:

1. One person who lived near Mount St. Helens, 84-year old Harry Truman (supposedly named after the former U.S. president) became widely known when he refused to comply with the evacuation. He died, and his body was never found. Should he have been forcibly removed, knowing that staying there was tantamount to suicide?

2. In a few tens of millions of years, the Juan de Fuca Plate will completely subduct beneath North America and there will be no more subduction. What will happen to Mount St. Helens at that point?

Lecture Twenty-Five

Anatomy of an Earthquake—Sumatra

Scope: The islands of Java, Bali, and Sumatra are tropical paradises with lush vegetation and beautiful beaches. The same tectonic forces that made these volcanic islands, however, can also cause devastating destruction for the people living on or near them. This was disastrously demonstrated in December 2004, when a magnitude 9.3 earthquake, including the enormous tsunami that it produced, caused the deaths of more than 225,000 people. The global network of seismometers allowed the rupture of the deadly earthquake to be analyzed and quantified better than any earthquake before it. The sinking of a 1,600-kilometer-long segment of the Indian Ocean lithosphere beneath Sumatra lasted more than 5 minutes, and the rupture tore into the seafloor, causing the largest tsunami in the Indian Ocean since the explosive eruption of Krakatau in 1883. Because tsunamis travel more slowly than seismic waves, future warning systems will provide some advance warning for future tsunamis in these regions, as is already being done in the Pacific Ocean.

Outline

I. Philosopher Will Durant once said, "Civilization exists by geologic consent, subject to change without notice." This sentiment is exemplified by the deadly earthquake and tsunami that occurred in Sumatra at the end of 2004.

- **A.** The Indonesian islands of Sumatra and Java are tropical paradises, with beautiful beaches, lush vegetation, and rich ecosystems. However, the same tectonic processes that have created the islands are also capable of destroying them.
- **B.** The magnitude 9.3 earthquake that occurred on December 26, 2004, destroyed many parts of Sumatra, and the tsunami it generated caused death and mayhem all around the Indian Ocean. Together, more than 225,000 people were killed.

II. The 2004 Sumatra earthquake was unusual not only for its size and tsunami generation but also for the very long duration of its rupture.

A. The earthquake began to rupture 35 kilometers beneath the surface, tearing to the northwest for the next 5 minutes at 2–3 kilometers per second.

  1. Initially the earthquake ruptured outward from the focus in all directions, tearing a modest amount of a few meters.

  2. Thirty seconds after the start of the rupture, the earthquake had almost stopped, and the rupturing had petered out.

  3. After a minute, however, the rupture began to occur with greater amounts of slip, moving only to the northwest, and 90 seconds after its start the earthquake was at its most energetic with a slip of 20 meters occurring across the fault.

  4. After the first 3 minutes, the rupture occurred more slowly, making it hard to detect on seismographs and leading seismologists to erroneously think that the quake was much smaller than it was.

  5. The rupture occurred for about 5 more minutes, extending across a distance of about 1600 kilometers. Because the plate boundary is a curved island arc, its orientation at the furthest end of the rupture is a transform fault.

B. Because the energy was released so slowly, it took several weeks for seismologists to determine the earthquake's true magnitude.

C. It was only through analysis of the normal mode oscillations of the planet (excited by the earthquake) that seismologists could determine that the earthquake had a moment magnitude of 9.3, making it the third-largest recorded earthquake.

  1. This magnitude is equivalent to 25,000 gigatons of TNT, or the total amount of energy the United States would use in about 1,000 years (at current rates). This is equivalent to almost 2 billion Hiroshima bombs.

  2. The oscillation of any object can be described as a set of discrete, independent modes. The longest-period modes are the best indication of a large earthquake's size.

D. The earthquake was large enough to trigger other earthquakes and volcanoes.

  1. In addition to being followed by many thousands of aftershocks, the quake triggered a magnitude 8.7 earthquake on the adjacent (to the southeast) segment of the plate boundary. This earthquake, which occurred in March 2005, is large enough to be the seventh-largest earthquake ever recorded.

2. The 2004 quake triggered volcanism at Mount Talang (Sumatra) in April 2005, and the March 2005 earthquake triggered volcanic activity at the Toba volcano.
3. The seismic waves from the 2004 earthquake were large enough that they even triggered small volcanic activity at Mount Wrangell, Alaska.
4. It is predicted that vertical motions from the 2004 earthquake would have changed Earth's rotational moment of inertia enough to shorten the length of each day by 2.68 microseconds, but this is too small to be measured because it is much smaller than the effects of ocean and atmosphere variations.

III. The 2004 Sumatra earthquake triggered a massive tsunami that was felt in oceans around the world and killed more than 200,000 people around the Indian Ocean.

A. Tsunamis are caused by anything that significantly disturbs the ocean seafloor, including earthquakes, volcanoes, and underwater landslides.

1. A common source of tsunamis is the rupture of a shallow earthquake up into the seafloor, causing a lifting of the water column.
2. A famous tsunami occurred off the coast of Lisbon from an earthquake in 1755 (immortalized in Voltaire's *Candide* as the cause of the sinking of Candide's ship with all the gold from El Dorado).
3. The eruptions of island volcanoes also cause tsunamis. The largest tsunami in the Indian Ocean before the recent Sumatra earthquake was the eruption of Krakatau in 1883, which killed 36,000 people in Java.
4. Underwater landslides, called turbidity flows, can span hundreds of thousands of square kilometers, causing large tsunamis. It has been surmised that giant turbidity flows from Atlantic Ocean islands like Cape Verde and the Canary Islands have created tsunamis greater than 100 meters high that have struck the east coast of America in the geologic past.

5. One such turbidity flow, called the Storegga slide, is thought to have caused a mega-tsunami in the Norwegian Sea around 6100 B.C.E.

B. The tsunami from the 2004 Sumatra earthquake hit Sumatra the hardest but also caused deaths in many other countries.

1. The tsunami was strongest heading westward because of the great length of the earthquake rupture, and more than 50,000 people in Sri Lanka and India (both to the west) died.
2. It took 2 hours for the tsunami to reach Sri Lanka and 7 hours to reach Africa (where deaths also occurred).

C. Sadly, many of the deaths from this tsunami could have been prevented if a tsunami warning system had been in place.

1. Because seismic waves travel so much faster than tsunamis, there is often plenty of time to issue a tsunami warning and evacuate shorelines.
2. Seismologists around the world knew of the size and tsunami potential of this earthquake within 15 minutes after the earthquake, but there was no infrastructure around the Indian Ocean to do anything with the information.
3. A successful tsunami warning system has been in existence in the Pacific Ocean, and tsunami warning systems are now being installed in the Indian and Atlantic oceans.

IV. In our short life spans, we see these events as incredibly catastrophic. If you look over hundreds of thousands of millions of years, however, these events happen continuously.

Recommended Reading:

Atwater, *The Orphan Tsunami of 1700.*

National Research Council Committee on the Alaska Earthquake, *The Great Alaska Earthquake of 1964.*

Questions to Consider:

1. Explain how the connection between earthquakes and volcanoes can go both ways.
2. There were predictions that the 2004 Sumatra earthquake would have added some wobble to Earth's rotation around its axis. Why would this occur?

Lecture Twenty-Six

History of Plate Motions—Where and Why

Scope: Plate motions are determined in two ways: relative motions between plates and absolute motions relative to the mantle. Absolute plate motions are measured with respect to both hot spots and the average of all plate motions. Both give similar results and show that Earth's tectonic plates have been moving for at least as long as we can see back into the geologic record. Sometimes the plates come together to form large supercontinents which, over time, break up into continental fragments like the current distribution of continents. This cycle has repeated many times. The most recent was Pangaea, which existed 350–200 million years ago, but previous supercontinents included Vaalbara, Columbia, and Rodinia. The history of plate motions is responsible for the locations of mountains around the world, which are the scars and sutures of previous plate collisions. Oceanic paleomagnetism has provided a record of plate motions going back 200 million years, but the record beyond that requires measuring the paleomagnetism of continental rocks, which is a much more difficult task.

Outline

I. James Hutton, one of the founders of geology and the principle of Uniformitarianism, once stated that in Earth's geology he saw "no vestige of a beginning, no prospect of an end." Nowhere is that more applicable than in the motions of the plates, which have occurred for at least as long as the age of Earth's oldest rocks.

II. We can see that the plates are moving relative to each other using techniques like the Global Positioning System (GPS), but finding a reference from which to measure all plate motions in an absolute sense is more difficult.

- **A.** We are able to now determine with a high level of precision the velocities of different plates with respect to each other using GPS and Very Long Baseline Interferometry (VLBI) technology.
  - **1.** These methods give relative plate velocities, which are determined by measuring the velocity of one plate with respect to another.

2. GPS also shows the internal deformation of regions of plates that are not behaving in a rigid manner.

B. However, trying to determine the velocities of plates relative to Earth's interior is difficult because we do not have access to the deep Earth.

C. One way to determine absolute plate velocities, which are plate velocities measured with respect to a single fixed reference frame, is to measure them with respect to the hot spot reference frame.

1. This assumes that the hot spots are fixed with respect to the mantle and with respect to each other.
2. It turns out that the hot spots are not fixed with respect to each other, but their relative motions are much slower (by about 10 times) than the plate motions, so a hot spot reference frame is acceptable.
3. The other way to obtain absolute plate velocities is to take the average of all the plate velocities and remove the average from each of the plate motions. This is called the no-net-rotation reference frame.
4. It turns out, fortunately, that plate motions measured with respect to the hot spot reference frame and the no-net-rotation frame are both fairly similar.

III. Determining plate velocities going back far into the geologic past is also challenging and requires the use of continental paleomagnetism.

A. Because the oceans are nowhere older than 200 million years, oceanic paleomagnetism cannot be used to determine the history of plate motions before this; continental rocks must be used.

B. Continental paleomagnetism involves determining the latitude at which a rock is formed by examining the inclination of the magnetic field lines.

1. Earth's magnetic field is dominated by a dipole field, which is the kind of field with a north and a south pole.
2. The direction of Earth's magnetic field lines from the dipolar field vary at Earth's surface; they are horizontal at the equator and become increasingly vertical as you reach the poles.
3. This means that when an igneous rock forms, the angle of the magnetic field lines frozen within the rock (in the same way the magnetic field was retained within cooling oceanic crust) reveals how far away the rock was from the North Pole when

it formed (paleolatitude), and the direction of the field lines gives the direction to the North Pole.

4. As the land that contains the rock moves (which it always does because of plate tectonics), it retains this information about the paleolatitude and orientation of the land when the rock formed; if the age of that rock can be dated, then you know something about where the rock came from.
5. This is a tricky business, because you have to make sure that the rock has not been altered by heating or chemistry (which can alter the magnetic field or the age you would get from radiometric dating) and that it has not been locally tilted or rotated, which would give the wrong location. This is usually done by taking lots of samples in a region and taking the average of their results.
6. Unfortunately, you cannot get any information about the longitude of the rock when it formed, only the latitude, and rocks are harder to find as you go back into time; most older rocks have been buried, eroded, or metamorphosed.

C. Continental paleomagnetic data are combined with other geologic evidence, such as the timing of plate collisions or rifting, to piece together the history of plate motions.

IV. The further we go back in time, the less we understand where the continents were. Maps of continent locations have been extended back to about 750 million years ago, but beyond that there are not enough data.

A. Despite a very common misconception, Pangaea was *not* the only supercontinent. This misconception occurs for two reasons.

1. Pangaea was the supercontinent that Alfred Wegener made famous in his continental drift hypothesis.
2. Seafloor paleomagnetism tracks the motions of continents back to the time of Pangaea but not before because of the young ages of ocean lithosphere.

B. Evidence points to the first rocks surviving at Earth's surface starting about 4 billion years ago, though crystals older than that have been found. Be forewarned that speculations about the early Earth are based on very small amounts of data and are subject to change without notice!

1. At Earth's beginning, surface rocks were cooling and then sinking back into the mantle and melting; however, zircon

crystals (which can be dated because they retain uranium and lead atoms) have been found that are as old as 4.4 billion years, suggesting that rocks were already surviving back then.

2. Starting around 4 billion years ago, continental crustal material began to accumulate into regional bodies, some of which still remain today as cratons, or shields, which are ancient terranes of continental rock that often form the cores of modern continents that have grown in size around them over time.

3. The earliest supercontinent, where subduction brought many continental landmasses together, is often considered to be Vaalbara, which existed from 3.3–2.8 billion years ago, and maybe as far back as 3.6 billion years ago; Vaalbara contained the Kaapvaal Craton of South Africa, the Pilbara Craton of western Australia, and perhaps the Superior Craton of Canada as well.

4. The Kenorland supercontinent was dated to have existed from 2.7–2.5 billion years ago and broke up into the cratons Laurentia (Canadian and Greenland cratons), Baltica (Scandinavia and northwest Russia), Australia, and Kalahari (Kaapvaal and Zimbabwe cratons).

5. A more massive (because there was more land) supercontinent existed during a period of time 1.8–1.3 billion years ago, known as Columbia (also known as Nuna or Hudsonia), and many of the world's major orogenic belts date from this time; India was adjacent to western North America, Australia was next to western Canada, and extended durations of subduction caused enormous volcanic activity that created much of the central and southern parts of the United States.

6. The supercontinent Rodinia existed from about 1 billion years ago to 800 million years ago, with the west coast of South America aligned against eastern North America, and Australia and Antarctica located against the west coast; Rodinia did not fully break up, and its pieces came together to form the short-lived Pannotia supercontinent and then Pangaea.

C. Pangaea was the last supercontinent, which contained all known landmasses and was together from about 300–200 million years ago.

1. Pangaea was c-shaped, with continents connected as (going from the top of the "c" to the bottom) Eurasia, North America, a joined South America and Africa, a joined India and Antarctica, and Australia.

2. The body of water inside of the “c” was called the Tethys Sea, and the giant ocean comprising the rest of Earth’s surface was called Panthalassa.
3. Pangaea began to break up 180 million years ago, first into two large landmasses: Gondwanaland in the south and Laurasia in the north, forming the North Atlantic Ocean.
4. Gondwanaland began to break up 120 million years ago, with India starting to move north (to create the chaos of the Himalayas) and the South Atlantic Ocean opening between South America and Africa.
5. The break up of Pangaea may never be complete because North America and Eurasia are still connected as one landmass (over the North Pole), Africa is rotating into Europe, and Australia is moving northward into Southeast Asia.

Recommended Reading:

Fortey, *Earth: An Intimate History*.

Van Andel, *New Views on an Old Planet: Continental Drift and the History of the Earth*.

Questions to Consider:

1. What do you think drives the cyclic nature of supercontinent formation and breakup?
2. Look at a map of current plate motions. What do you think the next supercontinent will look like a few hundred million years from now?

Lecture Twenty-Seven
Assembling North America

Scope: When you think of North America, you probably think of its political divisions, such as countries, states, and provinces. But there is another way to divide up North America: into the different geologic terranes that have come together over the past 4 billion years to create it. The continent of North America has a fascinating geologic history. Ancient cratons more than 2.5 billion years old are glued together by younger orogenic belts. On both the east and west coasts of North America the continent has grown through the successive addition of rock, but the processes have been different. The old mountains along the east coast, like the Appalachians, formed from a series of large, wide continental collisions. Western America was formed from a large number of individual terranes that were accreted onto the continent during subduction. Most of America's geology can be attributed to its history of plate movements and collisions. The assembly of North America has taught us how continents grow, and that there is a balance between new rock added by accretion, volcanism, and sedimentation and rock lost through plate collisions and erosion.

Outline

I. We have become very familiar with the outline of North America. However, it is important to remember that there is nothing special about this shape, and that this picture would look very different at any other point in the past or future.

- **A.** North America has continuously grown in size through collisions with other continents and will likely continue to do so, though it may also rift apart at some point.
- **B.** Changing sea levels not only affect the shape of the continent, moving the locations of the shorelines, but also affect whether new rocks are being deposited on top of the continent or old rocks are being eroded away.

II. North America has been around for a very long time—more than 4 billion years. Its oldest rock is found in the cratons (shields) of northern Canada and Greenland.

A. Sometime between the birth of our planet and 4 billion years ago, the first continental fragments began to form.

1. The 4-billion-year-old gneisses in the Slave craton of northwest Canada and the 3.8-billion-year-old gneisses in Greenland, some of the oldest rocks in the world, both contain metamorphosed sedimentary rocks, implying that there were older rocks that were eroded to form the sediments found in these rocks.
2. Very little is known about these early continental fragments because the few rocks that remain are highly metamorphosed.

B. By 2.5 billion years ago, many of these small cratonic fragments had come together to form a continent that is sometimes called Arctica, which was the core of what would become North America.

1. At about this time Arctica also became part of the supercontinent Kenorland.
2. When Kenorland broke up, the continent Laurentia, containing the Canadian cratons, moved away as an independent continent.

C. From 2.5 billion years ago until the formation of Pangaea almost 2 billion years later, Laurentia would be a distinct continent that would become part of and then break away from several supercontinents.

1. Laurentia grew in size 1.8 billion years ago when the Columbia supercontinent formed; large orogens (collisional mountain belts) like the Trans-Hudson orogen (extending down into North and South Dakota) and Penokean orogen (in modern-day Wisconsin and Iowa) connected cratons like the Churchill and Superior cratons into a larger landmass.
2. At this point, 1.8 billion years ago, Laurentia extended down as far south as Nebraska and Iowa and as far east as Michigan and west as Wyoming; the rest of what would become the United States did not even exist.

D. Subduction along the southern edge of the Columbia supercontinent, (1.8–1.6 billion years ago) created much of the interior of the United States through the accretion of volcanic rock likely associated with subduction.

1. From 1.8 to 1.7 billion years ago a belt of volcanic rock (the inner accretionary belt) from Arizona to modern-day Chicago

was added to the southern part of Laurentia; from 1.7 to 1.6 billion years ago another belt of volcanic rock (the outer tectonic belt) from New Mexico to Missouri was added.

2. Enormous amounts of granite and rhyolite were emplaced and erupted between 1.5 and 1.3 billion years ago at the southern edge of Laurentia in what is now northern Texas, Oklahoma, southern Missouri, Illinois, Indiana, Kentucky, and Tennessee; the origin of all of this granite and rhyolite is not well understood.

E. Laurentia grew to the southeast with a continental collision, likely with South America, called the Grenville orogeny between 1.3 and 1.1 billion years ago, when the supercontinent Rodinia came together; new land from North Carolina across Pennsylvania and New York to Newfoundland formed during this time.

F. During the breakup of Rodinia, the southern part of Laurentia almost broke apart.

1. A large rift called the Mid-Continental Rift was active about 1.1 billion years ago, stretching from Oklahoma to Michigan.
2. The continent stretched and thinned, and large amounts of basaltic lava flowed into it, but it stopped rifting before the continent broke into two pieces.

III. North America took on its current form during the events that led up to the assembly of the supercontinent Pangaea.

A. A series of plate collisions built up the eastern United States and formed the Appalachian Mountains.

1. During the Taconic orogeny (450–400 million years ago) a volcanic island arc (Iapetus Terrane) accreted to the southeastern edge of Laurentia, forming the land that would become much of New England.
2. During the Acadian orogeny (375–325 million years ago) a continental fragment called the Avalon terrane was added to the eastern coast, forming part of Newfoundland and eastern Massachusetts.
3. The Alleghenian orogeny (320–250 million years ago, sometimes called the Appalachian orogeny) saw the formation of the Appalachian Mountains when Gondwanaland collided with Laurentia as part of the formation of Pangaea; the Appalachians, at their highest, may have been taller than the Himalayas.

4. Simultaneously (about 300 million years ago), the South American ocean lithosphere was subducting beneath Laurentia to form the Ouachita Mountains of Arkansas, which were then taller than the Rockies.

B. Along the western coast of Laurentia, many different small terranes were accreted onto the continent through a very complex and complicated set of subduction events.

1. The western United States was built up through a series of subduction-related collisions including the Antler orogeny (375–300 million years ago), the Sonoma orogeny (280–200 million years ago), the Nevadan orogeny (180–150 million years ago, which formed the Sierra Nevada Mountains), the Sevier orogeny (130–80 million years ago), and the Laramide orogeny (70–50 million years ago, which formed the Rocky Mountains).
2. Along the east coast, orogenies occurred successively outward from the continent, but the Sevier and Laramide orogenies moved progressively inland; this is thought to be the result of the very shallow subduction of the Farallon Plate beneath North America.
3. When North America moved west over the Farallon Plate, hot asthenosphere rock came in direct contact with the western North American lithosphere and likely played a role in the stretching of the Basin and Range region of Nevada and Arizona and in the raising of the Colorado Plateau.
4. The ancient subducted Farallon Plate, still seen sinking beneath North America in images from seismic tomography, is causing the central and eastern United States to be under compression, with the land pulled toward the location of the sinking slab; this compression has given rise to earthquakes like the large ones on the New Madrid Fault between 1811 and 1812.

IV. The types of rocks that are found across much of the central United States are the result of two important factors: sea level changes and latitude.

A. Much of America is covered with flat-lying sedimentary rocks that stretch for thousands of kilometers. These rocks, lying on top of continental crust that usually has an older volcanic origin, are called platform sediments.

    1. Between 550 and 225 million years ago, the sea level had several episodes where it rose high enough to cover many parts of the North American continent.
    2. Sedimentary rock layers (like limestone, sandstone, and shale) formed in the shallow seas across the continent.
  - **B.** For much of this time North America was located at the equator, where climates were warm and moist.
    1. The warm climates allowed for the growth of rich swamps and forests on land and rich marine life in water.
    2. The swamps and other organic materials became compacted and fossilized to become plentiful layers of coal that are found in the North America crust.

V. Examining the history of the formation of North America, it is clear that there are processes both adding and subtracting land from continents. What is not clear is whether the total mass of continents has increased over time, or if the same continental material has simply been repeatedly reworked for the past four billion years.

  - **A.** Continents like North America grow in size and mass in several different ways.
    1. Volcanism adds new igneous rock internally (like granite batholiths) and externally (as lava flows).
    2. Rises in sea level add rock through the formation of platform sediments when the continent is flooded.
    3. Subduction adds new rock to the sides of continents through the accretion of sediments, island arcs, and pieces of ocean crust.
  - **B.** Continents also lose mass in different ways.
    1. Erosion is perpetually tearing the land down and washing it down streams and into the sea.
    2. Continental collisions shorten the continents horizontally while making vertical mountains that get eroded much more quickly than normal continental crust.
  - **C.** The total volume of continents is likely to be increasing over time for two reasons.
    1. Continued mantle convection should continue to help separate lighter minerals out of the mantle and leave them at the surface.
    2. Continued incorporation of ocean crust at continental collisions and mantle-derived magmas deposited in subduction

zone and hot spot volcanoes should make the continents more basaltic in composition over time.

D. However, continental rock could be continually lost to the mantle through the subduction of sediments; because we have so little rock from the deep past, it is still not known whether the amount of continental rock is growing or not.

Recommended Reading:

McPhee, *Assembling California.*

———, *Basin and Range.*

Questions to Consider:

1. Why are there no tall mountains in the middle of North America?
2. States like Nebraska, Iowa, Pennsylvania, and Ohio are covered with thick layers of sediments. Where did these sediments come from?

Lecture Twenty-Eight

The Sun-Driven Hydrologic Cycle

Scope: As fast as plate tectonics creates mountains through volcanic eruptions and the collisions of continents, erosion tears them down. The Appalachian Mountains were once many kilometers higher—the Himalayas of their day—but they now mostly lay at the bottom of the ocean floor in the form of eroded sand and silt. The principal agents of erosion are water and ice, which weather rock into sediment and then carry it to the sea. The rain and snow, however, are part of a continuous cycle of moving water called the hydrologic cycle. The hydrologic cycle is driven by the sun because solar radiation is responsible for the evaporation of water from the ocean surface and the thermal convection in the atmosphere that carries the water vapor over land. We can now see why Earth's surface is such a geologic battlefield: the radioactivity-driven process of plate tectonics is constantly creating new land, but the solar-driven process of erosion is constantly tearing it down.

Outline

I. The hydrologic cycle, also known as the water cycle, is the system by which water molecules travel at, above, and below Earth's surface. The water cycle is the most important geologic process affecting Earth's surface.

- **A.** The water cycle is almost entirely responsible for the appearance of Earth's surface through its role in the rock cycle, controlling the erosion, transportation, and deposition of rock sediment.
- **B.** The water cycle supports both the existence of human life (at molecular and cellular levels) and the nurturing of it through the support of agricultural crops.

II. There are three important aspects to the hydrologic cycle that provide a framework for its analysis: reservoir volumes, residence times, and pathways between reservoirs.

- **A.** Water can be found in several different reservoirs: oceans, glaciers, groundwater, lakes, streams, and the atmosphere.

1. Nearly all of Earth's surface water, 97.2%, is in the oceans in the form of salt water.
2. The remaining 2.8% is freshwater, usable for animal and plant consumption; of this, roughly 80% is currently in the form of glacier ice.

B. Water lasts in different reservoirs for very different durations of time, known as residence times. The residence time for water in the atmosphere is very short (on the order of a day) but can be many thousands of years for oceans or glaciers.

C. The pathways between the different reservoirs are both varied and complex.

III. Water is a remarkable substance, and it is not accidental that life is based upon it.

A. The water molecule has an electrically polar attitude, with the positive hydrogen ions located off to one side of the negative oxygen ion.

1. The polar nature of liquid water makes it efficient at dissolving materials.
2. This provides a solution within which both biochemical and geochemical reactions can occur, allowing for both the existence of life and the means of chemically altering Earth's rocks.

B. The high heat capacity of water and the high latent heats of fusion and vaporization give water a thermally stabilizing effect, which has helped to maintain stable climates through periods of rapid global temperature changes.

C. Water has the unusual characteristic of expanding when it freezes.

1. This has been important for aquatic life, thermally insulating lakes and oceans during cold periods through the development of surface ice.
2. Freezing also provides a dramatic means of erosion, with the expansion of water into ice responsible for shattering and tearing apart rocks.

IV. The water cycle begins with evaporation, which is driven by solar radiation.

A. Electromagnetic radiation from the sun, mostly sunlight and ultraviolet rays, is absorbed by water molecules at the surface of oceans and lakes, causing the liquid water to change phase into water vapor.

B. Heat from the sun's radiation also drives thermal convection in Earth's atmosphere that causes the water vapor to rise and be carried over land.

1. The amount of the sun's radiation received on Earth is greatest near the equator, so this is where most evaporation occurs.

2. The patterns of atmospheric circulation are complex, determined by a variety of factors such as the distribution of continents (this will be further discussed in the lectures on climate).

3. The predominant pattern of the distribution of atmospheric circulation and, therefore of rainfall, is the result of Earth's rotation (this will be further discussed in the discussions of deserts and jungles).

C. The condensation of water vapor causes precipitation, usually in the form of rain and ice, and when it falls on land it drives the rock cycle through the erosion, transportation, and deposition of rock.

V. The hydrologic cycle does an enormous amount of work on land surfaces, rapidly altering their appearances.

A. An enormous amount of energy exists in the hydrologic and atmospheric systems; human wind turbines and hydroelectric dams tap only the tiniest amounts of this.

B. About 400,000 kilometers cubed (km^3) of water evaporates into the atmosphere each year. This is equivalent to a cube of water 75 kilometers on a side.

C. There is an enormous amount of potential energy supplied to the evaporated water as it is lifted into the atmosphere. Some of this potential energy is converted into the work of erosion as the water flows across land surfaces.

D. This energy is on the order of 2.5×10^{20} joules per year, equivalent to a one-kilometer-high waterfall with 50 "Mississippi Rivers" flowing over it.

VI. Though most of the water at Earth's surface is in the oceans and glaciers, the other reservoirs are important to life on the surface of land.

A. The amount of water in the form of glaciers (mostly found in Antarctica and Greenland) is very variable; if all the glaciers melted entirely, global sea level would rise about 100 meters (about 330 feet).

B. Nearly all of the remaining water at Earth's surface that is not in the oceans or glaciers is in the form of groundwater. Residence time for water in shallow soil layers is about a month, but can be years to hundreds of thousands of years for deeper groundwater.

C. Roughly 0.017% of water exists in lakes. Half is in freshwater lakes, which drain to the oceans, and half is in saline lakes, like the Caspian Sea and Utah's Great Salt Lake, which are closed basins.

1. A closed basin results when evaporation rates exceed stream discharge rates, and the water never makes it to the ocean.

2. This happens in the Basin and Range region of the western United States, where water flows into closed lakes that entirely dry up for parts of the year to form salt flats called playas.

VII. There is a potentially enormous amount of water deep in the mantle, perhaps several oceans-full, but as it interacts so slowly with surface systems, it is usually not included in discussions of the hydrologic cycle.

Recommended Reading:

Berner, and Berner, *Global Environment: Water, Air, and Geochemical Cycles.*

Jacobson, Charlson, Rodhe, and Oriens, *Earth System Science from Biogeochemical Cycles to Global Changes.*

Questions to Consider:

1. There may have been times in Earth's past when the surfaces of the oceans have been entirely frozen. What would happen to the different parts of the hydrologic system if this were to occur?

2. What do you think human influences to the hydrologic cycle have been over the past century?

Lecture Twenty-Nine

Water on Earth—The Blue Planet

Scope: Earth's surface is mostly water, and this water is mostly present in the oceans. Much smaller amounts reside in the other reservoirs of glaciers, groundwater, streams, lakes, and the atmosphere. Water is the single most important substance on our planet. It controls chemical reaction rates and has allowed for the evolution of life. Each cell of your body is like a mini-ocean, filled with salt water not unlike that of the oceans. The oceans are constantly in motion, with water moving around the globe in a complicated set of connected convection patterns that are controlled by temperature (and therefore, the sun), salinity, the distribution of land masses, and Earth's rotation (through the Coriolis effect). Though oceans make up the majority of Earth's surface, they contain only a tiny amount of its biomass. This is largely due to the combined limitations of sunlight penetration and the convective mixing of nutrients, controlled by the thermocline.

Outline

I. Earth is unique in the solar system for having liquid water at the surface. The water controls much of Earth's geology, and moves in complicated ways between different reservoirs in the hydrologic system.

- **A.** Most of Earth's water is salt water in the oceans, which circulates around the globe in a complex system of ocean currents and provides the foundation for global climates.
- **B.** A small percent of Earth's waters are freshwater (not salty), and these are usable for human consumption.
- **C.** Water is the foundation for the biosphere (life), and the cells of our bodies are like mini-oceans, filled with salt water not dissimilar from the salt water found in oceans. It could be said that humans are part of the oceans' attempt at land exploration.

II. A very important part of ocean water is its salinity.

- **A.** The water in the ocean is about 3.5% salts, mostly in the form of sodium chloride.

B. Salts come into the ocean from a variety of different channels.

1. Rain dissolves the salts in the rocks and carries them into streams, which wash into the ocean.

2. Volcanoes eject tephra into the atmosphere, which distributes a lot of salt around the globe, most of which falls into the ocean.

3. A significant amount of salt dissolves directly out of ocean crust at mid-ocean thermal vents.

C. Salt is removed from the ocean at the same rate it is brought into the ocean.

1. Salt deposited on the seafloor binds to clay minerals, and either goes down into a subduction zone or gets plastered onto growing wedges of sediments that grow at subduction zones.

2. Waves create ocean spray that puts salt back on land.

3. When salt gets trapped in basins that are left to evaporate, the salt forms layers that precipitate out on the bottom of the sea floor.

4. As a result, the ocean salinity has remained roughly constant for billions of years.

III. Ocean water circulates between all of the oceans in a set of connected deep-ocean convection currents that are affected by temperature (which changes with latitude), salinity, the outlines of the continents, and the Coriolis effect resulting from Earth's rotation.

A. Convection is driven by density, and the density of ocean water is controlled by salinity (how much salt is dissolved in it) and temperature.

1. Freshwater that comes from rain, streams, or glacier runoff is more buoyant, and therefore sinks less easily.

2. Ocean water salinity increases in places where the sunlight is strong, like the Mediterranean Sea, propelling salinity-driven convection.

B. The shapes of the continents constrain the ocean currents.

1. The oceans only connect in the southern hemisphere, around the continent of Antarctica.

2. In the recent geologic past, when North and South America, and also Africa and Eurasia, were not connected there was an equatorial current that ran all the way around the globe.

C. Because of the Coriolis effect, a result of Earth's rotation, currents tend to flow in a clockwise direction in the northern hemisphere and a counter-clockwise direction in the southern hemisphere.

1. When an object goes from the equator toward the North Pole it goes from points on the globe that are moving around Earth's axis quickly to points that are moving more slowly, making them veer to the right; the opposite happens in the southern hemisphere.
2. The effect is large enough to affect the flights of baseballs or cannonballs, and drives the direction of ocean currents.

D. Ocean currents have been well-known for centuries because of their importance for ocean travel.

1. The Gulf Stream current brings warm water from the Gulf of Mexico across the Northern Atlantic Ocean to Europe.
2. The return path for the Gulf Stream waters is from the North Atlantic to the South Atlantic along the bottom of the ocean.
3. Some currents can change direction, such as the Pacific equatorial current, which reverses during a time of El Niño. This change reverses currents along the coast of South America, damaging fishing yields.

E. Mapping out the exact motions of ocean currents has been a difficult task.

1. In the past, oceanographers have had to rely upon fortuitous events such as the Pacific Ocean shipment of Nike sneakers that washed overboard and ended up scattered along the western U.S. coast.
2. A combination of floating buoys and satellite surveillance is now used to chart ocean currents.

IV. The oceans support a complex biosphere that is supported by a balance of sunlight and nutrients.

A. The oceans support about 3.9 billion tons of biomass, which is only one-fifth of 1 percent of the 1,850 billion tons of Earth's global biomass.

B. Photosynthesizing phytoplankton form the basis of most of the ocean food webs.

1. The transfer of energy from one trophic level to the next is very inefficient, and it takes a whole lot of plankton to support a fish.
2. It takes 500,000 units of energy to make 10,000 units of phytoplankton biomass, which (when eaten) would become 1,000 units of zooplankton biomass, then 100 units of small fish (like herring), then 10 units of big fish (like tuna), and finally one unit of biomass in a human.

3. The ocean biosystem is quite fragile, and fish populations world-wide are dropping precipitously.

C. Most ocean life occurs near the water surface because of the availability of light, though life exists throughout the oceans.
   1. Most light is filtered out by a depth of 100 meters, so phytoplankton and fish that feed on them live near the surface.
   2. Life also exists on the seafloor (benthic life), supported by organic matter that rains down through the water from the organic-rich surface layer above.
   3. Tidal areas are often rich and diverse ecosystems, supported by sunlight and land-derived sediments and nutrients washed out through streams.

D. Unlike on land, the equatorial regions of the oceans are generally barren and devoid of marine life.
   1. The strong thermocline (the layer of warm buoyant water at the ocean surface) prevents the mixing of waters between the surface and deeper layers.
   2. Even though there is a lot of sunlight, the top layer of the ocean has no access to nutrients, so there is nothing for phytoplankton to feed on.
   3. At latitudes closer to the poles there may be less sunlight, but there is less of a thermocline, so nutrients (such as those from stream flow) can be circulated to the surface to provide the basis for the food web.

Recommended Reading:

Carson, *The Sea Around Us*.

Kasting, "The Origins of Water on Earth," *Scientific American* special issue: The Solar System, 2003.

Questions to Consider:

1. Suppose it is 1768 and you need to figure out the location of the Gulf Stream. How do you do it?
2. Suppose that all of the glaciers melt. How will this affect the other water reservoirs (e.g., streams, lakes, groundwater)?

Lecture Thirty

Earth's Atmosphere—Air and Weather

Scope: Earth's gravity field is strong enough to hold on to an atmosphere of nitrogen and oxygen, though lighter gases have long since been lost to space. Most of the atmosphere's gas is concentrated near the surface, which is why breathing gets increasingly difficult as you ascend a mountain. The troposphere contains most of the atmosphere's water vapor, often in the form of clouds, and therefore controls our weather. The stratosphere contains the ozone layer, which is vital in protecting land life from the sun's harmful ultraviolet radiation. The atmosphere contains only a tiny amount of water vapor at any given moment, but all of the water of the hydrologic cycle must pass through the atmosphere and does so very rapidly. Circulation of air within the atmosphere is controlled by the distribution of landmasses, the Coriolis effect, and temperature variations—much like ocean circulation. Intersecting air masses cause air to be pushed up, which results in condensation, precipitation, and most of the world's weather.

Outline

I. If you have ever struggled breathing as you have reached the top of a mountain while climbing, you have discovered a very important thing: The air of the atmosphere is concentrated mostly near Earth's surface and thins rapidly as you approach space.

- **A.** This is also the reason why so many home runs are hit in the stadium of the Colorado Rockies baseball stadium, which is in the "mile high" city of Denver.
- **B.** By the time you are 5.5 kilometers (3.5 miles) above Earth's surface, the air pressure is half that of sea level, which means that 50% of the air lies below you. This means you have to breathe twice as much to take in the same amount of oxygen.
- **C.** Even though the atmosphere thins out quickly with height above the surface, it still extends for a great distance up into space and is important to the geology and biology for several reasons.

II. The atmosphere is mostly nitrogen (78.1%), oxygen (20.9%), and argon (1%), with all other gases, such as carbon dioxide and water vapor, much less abundant. This mix is more notable for what is missing (hydrogen, helium, carbon dioxide) than what is present, and is the result of both the size of Earth's gravitational field and how the carbon cycle works.

A. Even though hydrogen and helium are the most abundant gases in the solar system, Earth is not large enough to hold onto them.

   1. If an object leaves a planet's surface with a speed that is greater than the planet's escape velocity, the object will fly out into space and leave the planet forever.

   2. The escape velocity at Earth's surface is about 11 kilometers per second (km/s), and this is less than the kinetic speeds of gases like hydrogen and helium at the temperatures of Earth's surface; therefore, any free hydrogen or helium has long since flown out into space.

   3. However, the normal speeds of molecules of nitrogen, oxygen, argon, and carbon dioxide gases are much slower than Earth's escape velocity, so the planet can hold onto them; the mean gas velocity needs to be less than about one-sixth of a planet's escape velocity for the planet to keep that gas in its atmosphere for more than 4 billion years.

B. Earth is large enough to hold onto carbon dioxide, which was a more dominant gas early in Earth's history. However, carbon dioxide is removed from the atmosphere through a very active carbon cycle and sequestered away in oceans and biomass.

C. Air contains between 0% (dry) and 4% (humid) water vapor, which is vital in controlling precipitation and, therefore, the weather. Even though clouds look substantial they are really not, and (as was described in the last lecture) all of the atmosphere's water vapor would only make a global liquid layer 2 millimeters (mm) thick.

III. Though air thins continuously upward from Earth's surface out into space, we categorize the atmosphere into a set of layers based on their compositions and properties.

A. The troposphere extends from the surface to an altitude of about 10 kilometers, or just slightly higher than Mount Everest (8.85 km).

   1. The troposphere contains almost all of the atmosphere's air.

   2. It also contains all of the water vapor, and therefore is responsible for the world's weather.

3. The greenhouse gases (which are primarily water vapor, carbon dioxide, and methane) are located in the troposphere and are responsible for keeping Earth's surface warm.
4. Temperatures gradually decrease to about -60˚C as you reach the top of the troposphere.

B. The stratosphere extends from 10 kilometers to about 50 kilometers in altitude.

1. Airplanes often cruise at 35,000 feet (10.3 km), which is at the boundary between the troposphere and stratosphere.
2. The stratosphere contains the atmosphere's ozone, which is concentrated in the ozone layer, centered at an altitude of about 25 kilometers.
3. The ozone layer absorbs radiation energy, and so the temperature actually increases from the bottom to the top of the stratosphere (to a temperature of about 0˚C).
4. However, even though the atoms themselves may have a temperature of 0˚C, which is an indication of their energy levels, the air is so thin that you would freeze to death in an instant there.

C. The mesosphere extends from the top of the stratosphere to an altitude of about 80 kilometers. Many small incoming meteoroids burn up in the mesosphere creating streaks across the sky called meteors.

D. The top layer of the atmosphere is the thermosphere, which extends from the mesosphere out into space and does not really have a top boundary.

1. The temperature of atoms in the thermosphere increases with altitude, as with the stratosphere, but there are so few gas molecules that it is close to being a vacuum.
2. The auroras (Northern or Southern Lights) are mostly located in the thermosphere.

IV. The ozone layer, in the stratosphere, blocks out a significant amount of ultraviolet radiation by absorbing it before it reaches the surface.

A. Higher-frequency radiation (ultraviolet rays, x-rays, gamma rays) is much more harmful to life than lower-frequency radiation (infrared waves, microwaves, radio waves).

1. The high amount of ultraviolet radiation emitted by the sun is harmful to living tissue and can cause burning or trigger cancer.

2. When you put sun block on, you are doing the same thing that the ozone layer does—preventing ultraviolet radiation from reaching your skin.

B. When ultraviolet radiation strikes molecules of oxygen gas, it splits the molecule with 2 atoms of oxygen (O_2) into single oxygen atoms which can then join with other O_2 molecules to form ozone, which is a molecule with three atoms of oxygen (O_3). The ozone absorbs further ultraviolet radiation when it splits back into separate O_2 molecules and oxygen atoms.

C. An ozone hole exists over Antarctica during the months of August through December, creating a danger to life there.

1. Certain chemicals like chlorofluorocarbons act as catalysts that break down ozone and prevent its formation.
2. During the 1980s, while chlorofluorocarbons were being increasingly used for commercial aerosols, the Antarctic ozone hole steadily grew larger each winter.
3. With the help of international legislation, a ban on chlorofluorocarbons went into effect; since then, the growth of the ozone hole has halted and it will hopefully begin to shrink.

V. The condensation of water vapor into clouds and precipitation is the basis of our weather.

A. Warm air can support greater amounts of water vapor than cold air.

1. When warm moist air begins to cool, liquid water droplets will begin to condense.
2. Particulates in the atmosphere (e.g., dust, salt) often serve as nucleation points around which condensation begins.
3. Warm air cools when it rises, causing first clouds and then rain to form; this happens when air flows up and over mountains and when two air masses collide, pushing air up.
4. The cooling of air during the night causes the condensation of water in the form of dew or frost.

B. The circulation of air in the atmosphere is governed by similar constraints as water in the ocean: solar radiation as a function of latitude, the distribution of land masses, ocean circulation patterns, and the Coriolis effect due to Earth's rotation.

1. The heating and cooling of the land and water creates high and low pressure regions that move air from one region to another; air flows from high-pressure to low-pressure regions.

2. When air masses collide, warm air masses are pushed up and over cold air masses, causing air to rise and cool and rain to precipitate; this is the cause of storm systems.

C. Storms like hurricanes and cyclones can be some of the most destructive and deadly natural disasters in the world.

   1. One of the places in the world that is worst-hit by storms is Bangladesh, where monsoon rains can cause the Ganges and Brahmaputra rivers to overflow; flooding in 1991 from a cyclone there killed more than 138,000 people.
   2. Hurricane Katrina, which hit the Gulf Coast of the United States in August 2005, killed 1,836 people and did more than $80 billion dollars of damage.

Recommended Reading:

Emanuel, *Divine Wind: The History and Science of Hurricanes*.

Moran and Morgan, *Meteorology: The Atmosphere and the Science of Weathering.*

Questions to Consider:

1. Why do you think airplanes often cruise at a height that corresponds to the top of the troposphere?
2. Why do rains fall on the side of the mountains that face the wind but not usually on the side of the direction that the winds are going?

Lecture Thirty-One

Erosion—Weathering and Land Removal

Scope: Erosion is the weathering and removal of rock, and it begins with the breakdown of rock into sediment through both chemical and mechanical means. Both of these processes are largely controlled by the presence of water, as well as changes in temperature. Water dissolves many minerals, oxidizes others into rust, and breaks down others to form clays. These chemical reactions occur most rapidly in wet climates. Water also causes mechanical weathering by seeping into rocks and expanding when the rock is frozen. This effect can shatter rocks over time with repeated freezing and thawing and can help to erode mountains because high altitudes have greater fluctuations in temperature. In most parts of the world, weathering is responsible for the creation of soil, which forms downward from the surface.

Outline

I. If you visit the White Mountains of New Hampshire, you can walk across granite that was once the deep core of an immense mountain range, many miles below the surface. It is staggering to realize the volume of rock that weathering and erosion has removed.

- **A.** Weathering has broken apart these mountains and moved them great distances down to the ocean.
- **B.** The Mississippi River carries hundreds of tons of sediment to the Gulf of Mexico in the form of solid sediment and dissolved ions.
- **C.** Weathering, the breakdown of rock and minerals by mechanical and chemical processes, is the start of the surface part of the rock cycle that ends with the formation of new sedimentary rock.
- **D.** Weathering is also responsible for the creation of soils. If you travel around Hawaii, you will see ground was only recently cooled black basaltic lava but is now crumbly soft red rich soil.

II. Mechanical weathering is the breakdown of rock into sediment through physical means. There are many ways that this happens.

- **A.** The freezing and thawing of ice, a process called frost wedging, is a primary means of mechanical weathering.

1. Because ice takes up 9% more volume than water, when water seeps into minerals and the cracks within rocks and then expands, the rock is broken apart and shattered.
2. This process is most dominant in latitudes where the water freezes each night and thaws each morning, repeatedly breaking apart the rock.
3. This is the reason why there are so many frost heaves and potholes in roads at the end of the winter.
4. Alternate freezing and thawing is very extreme at high altitudes, which is part of the reason why mountains erode so quickly in relation to rocks at lower altitudes.

B. Even without the presence of water, rapid changes in temperature cause mechanical weathering because the rock expands and contracts more to a greater degree at its surface than within its interior.

1. This is especially true for mountains and deserts, where large temperature changes can occur rapidly.
2. Sudden forest fires can also cause rocks to shatter.

C. In steep areas, the physical abrasion of falling rock can cause additional mechanical weathering. With landslides and avalanches, the falling rock smashes apart rock below.

D. The roots of plants are efficient at physically breaking apart rock. Anyone who has every tried to remove weeds from sidewalk cracks knows this.

1. As plants grow, their roots slowly expand into any available cracks, acting as tiny crowbars that widen the cracks.
2. This process combines chemical with mechanical weathering, because plant roots also release acids that help dissolve surrounding rocks.

E. In dry areas, the formation of salt crystals can weather rock. If groundwater evaporates quickly, salts within the brine can begin to grow crystals, and these can force open bedrock as they form.

III. Chemical weathering is the destruction of rocks through chemical reactions that dissolve the minerals or convert them into other minerals. The three major forms of chemical weathering are dissolution, hydrolysis, and oxidation.

A. With dissolution, acidic waters react with minerals to remove positive and negative ions from minerals and put them into an aqueous solution.
  1. The polar nature of water causes many minerals to dissolve efficiently within it, with the positive (hydrogen) and negative (oxygen) sides of the H_2O molecule binding to negative and positive ions in the minerals.
  2. Rainwater is naturally acidic due to the presence of carbonic acid, which forms when carbon dioxide reacts with water.
  3. The carbonic acid then dissolves away minerals even more rapidly than neutral water.
  4. Salts and limestones are rocks that dissolve rapidly in the presence of water.

B. Hydrolysis is the chemical transition of one mineral to another, catalyzed by the addition of hydroxyl (OH^-) ions.
  1. This most commonly occurs with the weathering of feldspars (the most common surface minerals) to form clays, when the feldspar reacts with water and hydrogen to form flat clay minerals that often end up creating shale; another by-product of the reaction is dissolved silica that can later precipitate to form the cement that holds many sedimentary rocks together.
  2. Basalt contains a large amount of feldspar and is a common source of clays.
  3. Cleopatra's Needle, a granite obelisk that stood unchanged in the desert of Egypt for more than 3,000 years, has had its hieroglyphics nearly obliterated in Central Park during a period of only 150 years.

C. Oxidation occurs when free ions of oxygen join with iron- or magnesium-rich minerals to create new minerals like hematite and limonite.
  1. The rusting process is due to oxidation.
  2. The by-product minerals of oxidation usually have a reddish color due to the presence of iron.

IV. From a human perspective, the most important aspect of weathering is that it is responsible for creating the world's soils.

A. With the exception of sediment that is washed or blown onto land (which is common in some places), the sediment of most soils is formed in place through the downward percolation of water.

1. The downward-seeping water creates the soil by breaking up the rock into separate minerals (sand, clay, rust) and by altering the composition through chemical reactions and the removal of some materials.
2. Soil consists of a set of layers that are a function of how far down the weathering has reached. The top-most layer, called topsoil, often contains a significant amount of organic materials and supports the land's plant biomass and all of our agricultural crops.

B. In general, soil takes a very long time to form—from thousands to millions of years.

1. Topsoil is an important natural resource that we have been very careless with, and about 70 gigatons of topsoil are lost each year due to inefficient agricultural methods.
2. Conservation-conscious agricultural methods are now being employed that greatly reduce the rate at which topsoil is lost.
3. Nonetheless, with a global inventory of about 4,000 gigatons of topsoil, almost 2% of our topsoil disappears each year, and over the past four decades we have lost about one-third of the world's arable land to erosion.
4. Prior to 2.5 billion years ago, sedimentary rock deposits show layers of un-oxidized iron, revealing that the atmosphere before that time did not have substantial amounts of oxygen in it.

Recommended Reading:

McPhee, *Rising from the Plains*.

Powell, *Grand Canyon: Solving the Earth's Grandest Puzzle*.

Questions to Consider:

1. Potholes are a bigger problem in Chicago than they are in a much colder place like Saskatoon, Saskatchewan. Why?
2. The release of sulfur and nitrous oxides into the atmosphere from industry makes rain more acidic. How would this affect weathering rates?

Lecture Thirty-Two

Jungles and Deserts—Feast or Famine

Scope: The circulation of air within the atmosphere occurs predominantly in the form of six large convecting cycles. Very generally, moist air rises at the equator and at 60°N and 60°S, and dry air sinks at the poles and at 30°N and 30°S. When the moist air rises, rain precipitates out; when dry air sinks, it absorbs moisture from the land. The result is that most rainfall occurs in the equatorial and temperate regions, and most of the world's deserts are in the arid zones roughly 30°N and 30°S. Desert and jungle climates don't look like they have a lot in common, but they both support life that has evolved to deal with a serious shortage in a basic resource. Tropical soils have had their nutrients washed down and out by the large amounts of rainwater and are some of the least fertile soils for agriculture in the world. Deserts have unique geology and biology that stems from having often-severe shortages of water. The distribution of biomass mirrors the rates of precipitation on land but, interestingly, not in the oceans—the richest sea life occurs at the edges of continents, where currents can bring mineral nutrients up to the surface and streams carry them from the land.

Outline

I. Desert and jungle climates do not look like they have a lot in common, but they both support life that has evolved to deal with a serious shortage in a basic resource.

- **A.** In deserts, that resource is water. In jungles, the missing resource is fertile soil.
- **B.** With jungles, deserts and all climates, the levels of precipitation are largely due to the distribution of the continents and of the cells of atmospheric circulation.

II. The six cells of atmospheric convection control the distribution of precipitation on Earth. From 0° to 30°N/S, these convection cells are called Hadley cells; from 30°N/S to 60°N/S, these cells are called Ferrell cells; from 60°N/S to 90°N/S, these cells are called polar cells.

A. Because of the Coriolis effect, moving air masses veer in a clockwise direction in the northern hemisphere and a counterclockwise direction in the southern hemisphere.

1. The number of cells is a function of the rate of Earth's rotation around it axis; if Earth were not rotating, it would have only one atmospheric convection cell in each hemisphere, and if it rotated faster, it would have more than it currently does.

2. Planets like Jupiter and Saturn, which rotate very quickly, have atmospheres that are very banded with many circulation cells.

B. Air at the equator warms the fastest, receiving the most direct sunlight, and it expands and rises, driving the rest of the atmospheric cells.

1. The air is moist because evaporation rates are also the highest at the equator.

2. As the air rises it also cools, but colder air cannot hold as much water vapor within it so condensation and precipitation occur.

3. Most of the moisture of the rising air falls right back as precipitation, and the highest rates of precipitation occur along the equatorial belt, giving rise to the equatorial jungles of Africa, South America, and Southeast Asia.

4. The air, now dry, moves north and south away from the equator at a high altitude.

C. Because of the particular rate of Earth's rotation, this air comes down at latitudes of roughly 30°N/S.

1. This air is very dry, so little precipitation falls from it.

2. In addition, because the air warms as it falls, its capacity to hold water vapor increases and it acts like a sponge, absorbing water vapor that has evaporated from the ground.

3. This gives rise to the band of deserts that exist at about 30°N/S around the world.

D. Moist air also rises at the temperate latitudes of about 50°–60°N/S.

1. As this air rises, rain and snow precipitate out, creating the temperate forests of North America and Eurasia, which contain most of the world's biomass.

2. The dry air (after moisture has precipitated out) moves both north and south at high altitudes; some comes down at 30°N/S, and some comes down at the poles.

E. The air that comes down at the north and south poles is very dry, and arctic regions are actually considered to be deserts. The rates of precipitation are actually very low, and it is only because ice stays on land for a very long time that this region does not look like a desert.

III. Equatorial jungles have the most complex and diverse ecosystems in the world, which is a result, ironically, of having the worst soils in the world.

A. So much rain falls in the tropics that soils can be hundreds of meters thick.

1. As a result, any nutrients in the soil have long since been washed deep into the ground, and the soil cannot hold onto new nutrients without them also washing away.
2. Life has had to evolve to keep organic nutrients out of the soils, and biomass is quickly recycled and reused before it can break down and wash into the ground.
3. Ants, for example, will cut up and remove leaves that fall to the ground, carrying the matter to their nests, which are often in trees above the ground.

B. If the jungle canopy is removed, such as for growing crops or raising cattle, the soil is barren and cannot support farming or grazing for more than about a year.

IV. Deserts have unique geology and biology that stem from having often-severe shortages of water.

A. Deserts occur for two main reasons: the atmospheric cell distribution of down-going dry air and the location behind mountain ranges.

1. Major deserts in Africa (Sahara, Kalahari), Eurasia (Great Arabian, Thar), Australia (Simpson, Gibson, Great Sandy, Great Victoria), and North America (Sonora, Mojave, Chihuahua) occur roughly 30°N/S.
2. Other deserts—like the Gobi and Takla Makan in Asia, the Atacama and Patagonia in South America, and the Great Basin in North America—exist because they are in rain shadows; air must travel a great distance, including over mountain ranges, to reach them, by which time the air has lost its moisture.

B. Wind is a very important agent of erosion, transportation, and deposition in deserts.

1. Wind can remove the lighter sediment from weathered ground, leaving larger cobbles behind to form a hard-topped desert pavement; desert pavement can also form through the alternate freezing and thawing of the ground, which forces larger cobbles to the surface.
2. Blown dust and wind can form enormous dust storms, which can extend for hundreds to thousands of kilometers.
3. Significant amounts of sediment that accumulates in the central Atlantic and Pacific oceans consist of wind-blown dust from the Sahara and Gobi deserts.
4. Sand that is too heavy to be suspended by the wind gets moved about in the form of dunes; the sand bounces along by saltation, one grain at a time, similar to the transportation of particles along the bottom of a stream.
5. Wind can also be an agent of erosion, sandblasting away exposed rock; however, even in deserts, most erosion occurs as a result of rain and ice, even if it is infrequent.

C. Life has coevolved with desert climates to deal with the high temperatures and lack of water.

1. Many desert plants are succulents, which can hold significant amounts of water within them and grow very slowly, allowing them to survive extended periods without additional water (e.g., cacti).
2. Much animal life in deserts is nocturnal, becoming active only after the hot sun has set.

D. One of the largest problems for humans is desertification, the transition from a more fertile climate to a desert climate.

1. Most desertification is due to human activities that expose the soil and let it blow away to leave the surface barren.
2. The Gobi Desert, for example, is increasing by 3,500 square kilometers every year, largely due to deforestation and overgrazing.
3. Many early cultures, such as the Indus Valley civilizations, fell prey to this process.

Recommended Reading:

Goudie, *Great Warm Deserts of the World*.

McGregor and Nieuwolt, *Tropical Climatology*.

Questions to Consider:

1. About 50 million acres of rain forest is cut down each year—about the size of England. Because the majority of the world's species exist in tropical rain forests, why do pharmaceutical companies think that is a very bad idea?
2. During El Niño conditions, ocean currents bring unusually warm waters to the west coasts of Central and South America. Why might this be bad for fishing?

Lecture Thirty-Three

Mass Wasting—Rocks Fall Downhill

Scope: Once rock is broken into sediment, gravity makes sure that it heads downhill toward the oceans. Mass movements of rock and soil can occur over a wide range of time scales. Avalanches and landslides are fast and dramatic, but most downhill movement of rock occurs slowly through a process called creep. Landslides and rockfalls occur when the slope of the land is steep, and pieces of the slope break off and tumble and slide down. They are often triggered by the strong shaking of earthquakes. When a lot of water is mixed with the rock and soil, mudflows or debris flows can become dangerous rivers of mud and rock. Slumping occurs when large pieces of rock and soil suddenly slide downhill along curved faults. These often occur along the banks of rivers or along coastlines and have been known to carry entire buildings along with them. At the slowest end of the spectrum, creep occurs as the land is repeatedly lifted a tiny amount up and down through freezing and thawing or wetting and drying, each time sliding a small distance downhill. Some effects of gravity are invisible at the surface, like the loss in elevation from pumping out oil and water from the ground. Mass movements are an important part of all aspects of erosion, including headward erosion, downcutting, and the development of karst topography.

Outline

I. Gravity has a deleterious effect on people, even ones that are made of rock like the Old Man of the Mountain in New Hampshire.

- **A.** Despite many attempts at giving the state symbol a "facelift," the process of mass wasting or mass movements, which is the removal of rock by gravity, eventually tore away the granite blocks that made up the face of the "old man."
- **B.** The process of mass wasting occurs in many different ways (landslides, avalanches, debris flows, slumping, and creep), but they are all driven by gravity.

C. The next several lectures will address many aspects of Earth's surface geology—streams, glaciers, groundwater, and more—but they are all intimately related to gravity and mass wasting.

II. Rock and soil can move downward rapidly in the form of rock falls, landslides, and slumps. This happens when the slope of a region exceeds the angle of repose, which is the steepest slope that can stably maintain rock and soil.

A. With rockslides and landslides, material moves quickly downhill, usually along a well-defined plane of the side of a hill or mountain. The motion of material usually occurs in a tumbling and chaotic fashion.

B. Slumps occur when a cohesive block of soil slides downhill as a single unit, often along a curved or scalloped slope.

C. Landslides are often triggered by the shaking due to earthquakes. Other natural causes include undercutting by streams, overburdening by a buildup of sediment, removal of vegetation that destabilizes the slope, or an excessive amount of water in the soil.

D. Human causes of landslides include overforesting and overgrazing, building road cuts for highways, and mining explosions.

E. Water has a dual role with landslides and debris flows.

1. A small amount of water helps to stabilize slopes because its surface tension helps bind soil grains together; for example, in order to make sand castles you need to add water to dry sand or it will not hold together.

2. If there is too much water, however, then the sand grains are pushed apart and the ground flows like a liquid even if it is mostly made of rock.

III. Flows occur when rock, soil, sediment, and/or water flow downhill in a fluid-like manner. The flow can be cushioned by trapped air underneath and can travel very large distances.

A. A debris flow is the general name for a flow that is a mixture of rock, dirt, and soil.

B. When large amounts of water are in the flow, the flow is called a mudflow.

1. Mudflows can happen following heavy rains when the ground is oversaturated with water.

2. Lahars are mudflows when water mixes with volcanic ash.

C. Avalanches are landslides that are often triggered by an overburdening of snow and ice.

D. An unusual kind of flow called liquefaction occurs when the seismic waves of an earthquake push the soil grains apart in damp soil, making it flow like quicksand.

E. Certain areas of the world, like the eastern side of Los Angeles in the San Gabriel Mountains, are frequently subject to debris flows that can wash away houses and roads.

IV. As dramatic as landslides and debris flows can be, most damage in the United States from mass wasting is due to an incredibly slow process called creep. Creep largely occurs by either freezing and thawing or wetting and drying.

A. In a process similar to frost wedging, the ground can slowly slide downhill though alternate freezing and thawing.

1. When the soil freezes, it expands up and outward, perpendicular to the slope of the hill.
2. When the soil thaws and contracts, it sinks straight down instead of going back toward the hillside.
3. With continued freezing and thawing, the ground slowly zigzags its way downhill, a tiny distance each time.
4. This is most significant in regions where there is continued freezing and thawing, usually each day and night.

B. A similar process can happen in regions that are alternately wet and dry. As the soil wets, it expands outward; when it dries, it drops straight down.

C. Evidence that creep has occurred includes the appearance of trees with bent trunks and fences and poles that are all tilted downhill.

V. The loss of rock through mass wasting is an important part of the shaping of the appearance of the land through the mechanisms of downcutting and headward erosion.

A. Stream action can turn a small valley into the Grand Canyon through the process of downcutting.

1. As the stream erodes its base, it drops downward, making the sides of the valley steeper.

2. Each time the slope exceeds the angle of repose (or events like earthquakes, forest fires, and avalanches occur), the slopes collapse through mass wasting, widening the valley.
3. The stream carries away the collapsed rock and soil, and the process begins again; over time, huge valleys can be made this way.

B. Headward erosion occurs when a soft layer of rock lies underneath a harder layer and the erosion of the softer layer undercuts the top layer, causing it to collapse.

1. This often results in a waterfall; the falling water accelerates the process.
2. The best-known example of this in North America is Niagara Falls, where the falls continue to erode upstream each year.

VI. Rocks fall downhill in some ways that are not always visible from the surface.

A. Land subsidence is a huge problem in many parts of the world where fluids are pumped out of the ground.

1. In places like California, Texas, and Louisiana—where both water and oil have been pumped out of the ground—the elevation of the land has subsided by up to tens of meters.
2. This is a serious problem for parts of the world that are close to sea level—subsidence can actually put them below sea level, requiring the building of levees and dams and leaving them susceptible to catastrophic flooding.

B. As we will discuss, the underground dissolution of limestone can create large cave networks. If these caves are near the surface, they can collapse.

1. Single collapses are called sinkholes, and they can be a problem in suburban and urban areas.
2. Sinkholes have on occasion suddenly swallowed entire buildings.
3. Much of the city of St. Louis is built upon filled-in sinkholes, and no record remains of where they all are.
4. Over time, continued collapse of underground cave systems can lead to a karst topography where very little of the original surface remains; this can lead to very dramatic topography, such as in regions of China and Thailand.

Recommended Reading:

Keller and Blodgett, *Natural Hazards: Earth's Processes as Hazards, Disasters, and Catastrophes.*

McPhee, "Los Angeles Against the Mountains" in *The Control of Nature*.

Questions to Consider:

1. What do you think road engineers could do to help prevent landslides or slumps from occurring along a road cut for a highway?
2. Some large landslides have led to catastrophic floods. How might this happen?

Lecture Thirty-Four

Streams—Shaping the Land

Scope: Once sediment is eroded and moved downhill, streams do most of the work from there. Streams are like a giant network of highways, continuously carrying rock from the mountains to the sea. Every day, about a million tons of rock, largely from the Rocky and Appalachian mountains, is carried down the Mississippi River and dumped into the Gulf of Mexico. While sediment is carried continuously through streams, occasional large floods are often responsible for the bulk of sediment transport, especially for larger boulders and cobbles. Streams play a major role in shaping the surface of the land, eroding rock in some places and depositing it in others. This is often seen dramatically in flood plains, where streams meander about over time. Streams tend to follow a general profile of being steep at the headwaters and flat at their mouths, where they may open out into sediment-rich deltas. Human attempts at controlling rivers through dams and levees have been met with very variable results.

Outline

I. Take a sand castle and start drizzling water on it for millions of years. This is what happens to the land of continents when rain falls on it.

- **A.** Stream systems have evolved so that if a drop of rain falls almost anywhere on Earth's surface, a network of streams can carry it back to the ocean.
- **B.** During the path from raindrop to ocean, water does a tremendous amount of work in shaping the surface of the land.

II. Streams are like continuous conveyor belts carrying sediment to the oceans.

- **A.** Streams have a particular sediment load capacity that is distributed in different ways.
  - **1.** The traction load consists of large cobbles and boulders that roll along the bottom of the streambed but are too heavy to be supported in the water.

2. The saltation load usually consists of sand- and pebble-sized particles that bounce along the streambed, hydraulically lifted by the water.
3. The suspended load consists of silt that is entirely suspended within the water and gives the water a muddy appearance.
4. The dissolved load consists of ions that are dissolved within the water and are invisible to the eye, though they may make up several percent of the weight of the water.

B. The sediment load is dependent upon the speed and volume of the stream.
1. The total amount of water that flows past a certain point in a given amount of time is called a stream's discharge; the volume of a stream's sediment load is highly dependent upon its discharge.
2. The largest size of cobble that a stream can carry is dependent upon its speed, which is a function of its slope and volume; for instance, the lower Mississippi is very flat but because of its great volume it moves much faster than a steep mountain stream.
3. In general, when a stream slows down it will lose some of its sediment load, and when a stream speeds up it will take on additional sediment.

C. Streams are always both eroding and depositing sediment, lifting and dropping, carrying it along.
1. A stream's carrying capacity is the equilibrium point between erosion and deposition.
2. If a stream is carrying less than its capacity, then it will pick up additional sediment, having an erosive effect.
3. If a stream is carrying more than its capacity, then sediment will settle out of the stream, having a depositional effect.
4. Several factors can change the carrying capacity of a stream, but the most common is a change in its discharge, which is usually a result of the amount of rain that has fallen in previous days.

III. If you could straighten out a stream and lay it out in a straight line, you would see that most streams have a characteristic parabola-shaped stream profile that is steeper at the headwaters of its origin and flattens out as it reaches its termination in an ocean or lake.

A. The total sediment carrying capacity of a stream tends to increase along its length because other streams join with it. However, streams tend to be more erosional at their headwaters and more depositional toward their mouths.

B. Streams usually consist of many smaller tributaries that combine together to form the main branch of a stream that empties out into an ocean or lake.

  1. As tributaries continue to combine together, their sediment carrying capacity increases; this can be efficient in rapidly removing rock from a mountainside.

  2. When the stream finally approaches its termination, its speed diminishes and sediment is rapidly deposited, forming a broad expanse of deposited sediment called a delta.

C. The stream naturally maintains its profile. If there are changes in slope that occur, the erosion or deposition of sediment will occur in order to smooth it out again.

  1. If a cliff or waterfall exists, the acceleration of water will increase its carrying capacity and the rock will erode more quickly until the waterfall is obliterated.

  2. The opposite happens with a dam or lake, where water slows down and sediment is deposited; over time the deposited sediments will fill in the dam or lake, and the normal stream profile will be restored.

  3. Lakes tend to be short-lived geologic features formed by tectonic, erosional, depositional, glacial, or man-made processes—deposition eventually fills them in.

D. Man-made dams have many positive purposes, but have drawbacks as well.

  1. Most dams are made to store water for dry periods and to provide hydroelectric power, which is a clean source of energy.

  2. However, sitting water evaporates more quickly, so more of the total water supply disappears with dams.

  3. Sitting water is also more susceptible to breeding insects like mosquitoes, and dams have caused an increase in malaria outbreaks in some parts of the world.

  4. Because sediment builds up inside dams due to the sudden drop in velocity, it can also be expensive to maintain the dam, requiring repeated dredging.

5. Below the dam, where sediment-free water flows out, the stream will pick up sediment again until it reaches its equilibrium carrying capacity, often severely undermining the dam.

IV. Stream systems drain limited geographic regions called drainage basins, whose locations are controlled by topography.

A. The tributaries of a drainage basin often have a fractal distribution (looking like the spreading branches of a tree) so that rain anywhere within the basin can eventually find its way to the ocean.

B. A drainage basin may have thousands of small tributaries but usually comes to its end as a single large stream.

1. If there is a very large amount of sediment being deposited at the stream's mouth, the stream can break apart again to form a wide delta.
2. When an enormous amount of sediment is present, streams can sometimes repeatedly branch apart and join again, forming a braided stream; this is common in streams that are runoff from glacial regions.
3. The world's largest drainage basins in terms of sediment removal are associated with the Ganges, Huang He (formerly Yangtze), Amazon, Tigris, Euphrates, and Mississippi rivers.
4. The divisions between drainage basins are called divides; a divide that separates drainage basins that empty into different oceans is called a continental divide.
5. Some divides are large and obvious, such as the North American Continental Divide that runs along the spine of the Rocky Mountains; divides can also be small and unimpressive, such as the one that runs along part of Ridge Avenue in Chicago.

V. The accumulation of sediment that forms at a stream's end is called a delta.

A. Deltas are historically highly populated regions because the sediment provides fertile soil for agriculture.

B. Some deltas are shaped like the fourth letter of the Greek alphabet called delta (uppercase Δ, lowercase δ), for which they are named.

C. When sediment levels are high and ocean currents are weak, the sediment can be carried out into bird-foot deltas like at the mouth of the Mississippi River.

VI. Streams often change location and move about within the confines of a floodplain, which is bounded on either side by bluffs or valley walls.

- **A.** Streams move about because they travel fastest on the outside of a curve, which leads to the formation of a meander.
  - **1.** Sometimes the meander can cut itself off, leaving the former meander as an "oxbow lake," which is named for curved bow-shape of the lake.
  - **2.** Over time, the meanders will cover all parts of the flood plain.
- **B.** Streams naturally form high banks called levees that grow each time a flood occurs and water tops the levees, where they slow down and deposit more sediment.
- **C.** Though the streams are constantly eroding some portions of the banks and beds, the net effect is usually the deposition of sediment within the flood plain.

VII. Flooding is a natural part of a stream's lifetime, occurring whenever unusually high rates and volumes of precipitation occur.

- **A.** During flooding, the stream discharge and sediment capacity can increase by a factor of more than 100.
  - **1.** For some streams, the largest boulders are only moved during times of high flooding.
  - **2.** This is especially true in arid regions, where streams may be small or nonexistent except in times of flood; in fact, death by flooding is very common in desert regions because of the sudden increase in stream discharge.
- **B.** The worst river flood in the United States in recent times was the 1993 Mississippi River flood, where many regions were flooded for more than half the year.
  - **1.** The flood broke through levees up and down the Mississippi River and came within 2 feet of topping the levees in downtown St. Louis, which were at 52 feet, causing $15 billion dollars in damage.
  - **2.** During the flooding, the Mississippi River discharge exceeded 30,000 m^3 per second—enough water to fill up the nearby St. Louis Cardinal's Busch Stadium in about a minute.
- **C.** Floods have historically been the worst cause of natural disaster outside of disease, though the two are often not unrelated.

D. Urbanization is increasing the damage from flooding.

1. Normally about 10% of rainwater that is not evaporated goes into streams; the rest goes into groundwater.
2. However, this can be reversed in an urban environment, where paving and sewer systems can wash 90% of rainwater rapidly into streams, increasing their levels.
3. In addition, the tall man-made levees that have been built around rivers can cause rivers to flood catastrophically when they finally do top the levees.

Recommended Reading:

McPhee, "Atchafalaya" in *The Control of Nature*.

Smith and Ward, *Floods: Physical Processes and Human Impacts*.

Questions to Consider:

1. Minnesota is the "Land of 10,000 Lakes," and these lakes are remnants of the recent Ice Age. How would you know that the Ice Age occurred quite recently?
2. The world's largest engineering project is the construction of man-made levees along the Mississippi River. Do you think it is worth the cost and the risk?

Lecture Thirty-Five

Groundwater—The Invisible Reservoir

Scope: Most of the rain that falls on land gets quickly re-evaporated, but most of the water that stays on land goes into the ground and not into streams. In fact, there is 100 times more "surface" water in the ground than there is in streams and lakes combined. This water fills in the spaces between mineral grains, as well as becoming part of the minerals themselves. There is usually a layer of rock at the surface that is not saturated with water, and this is separated from the saturated rocks beneath by the water table. In any given region, the water table moves up and down seasonally and with changes in climate. Rocks with a high porosity can contain a lot of water, and rocks with a high permeability allow water to move through them quickly. Rocks that have both, such as sandstone, make good reservoirs of water called aquifers that are very useful to humans. Rocks such as limestone dissolve rapidly from the downward percolation of rainwater, which is naturally acidic, forming underground river channels. When the water table drops below them, large cave systems can be exposed. Much of the water in North American aquifers came from the enormous run-off of melted ice water following the end of the last Ice Age. The tens of thousands of identified North American caves are now exposed to air because water tables have dropped considerably since this time.

Outline

I. Groundwater contains more than 100 times the amount of freshwater in streams and lakes combined, and we are now totally dependent upon it for our agriculture. Groundwater, however, is a delicate resource: hard to get out, slow to refill, and easily contaminated. Despite misconceptions, groundwater almost never consists of underground rivers, but rather the slow flow of water though tiny pore spaces within rocks.

II. We normally think of rock as being solid, but even igneous rocks can contain small amounts of water, which can exist within and travel through the tiniest pore spaces underground.

A. Water accumulates in rocks that have a high porosity, which means that a large percentage of the rock is made of empty pore spaces.

1. Sedimentary rocks like sandstone and shale tend to have high porosities, as well as limestone that have been dissolved away by the underground flow of water.

2. Igneous and metamorphic rocks tend to have low porosities, unless they are highly fractured.

B. Water is able to flow through rocks that have a high permeability, meaning that its pores are well-connected and form channels through the rock. Sandstone and limestone have high permeabilities, though shale does not.

C. Rocks with high porosity and permeability are called aquifers and are good places from which to remove groundwater for human use.

1. It is important to have high permeability so that water can flow and replace the water that has been withdrawn.

2. Sandstone tends to make the best aquifers.

3. Rock layers that are resistant to water flow are called aquitards.

D. Aquifers get their water from rainwater that has seeped down into the ground.

1. A large portion of rainwater that goes into the ground is returned directly to the atmosphere either through absorption into plant roots (and subsequent transpiration out of leaves) or evaporation from soil.

2. Once water gets below the surface layer, however, it can penetrate deep into the surface.

3. Aquifers can supply water for extended periods of time even if the climate is dry; after awhile, however, the aquifer will run dry if it is not recharged by rainwater.

4. Many of the large aquifers in North America and Eurasia contain melted runoff from the end of the last Ice Age and will not be recharged until the next big Ice Age melts; this water should, therefore, be seen as a limited natural resource.

5. The United States grows most of its food from aquifers like the Ogallala in the Midwest, but we are withdrawing water faster than it is being recharged.

III. The water underground forms a water table, which is the surface of the saturated zone of rock and has a contour that parallels the surface.

- **A.** The top part of the ground has water percolating down through it but is not saturated with water.
  - **1.** Beneath the water table the pore spaces are mostly filled with water.
  - **2.** A well must reach the water table before it can pull out water.
- **B.** The water table has a contour that is similar to, but not exactly the same as, the surface—its highs and lows usually are close to the same locations as the surface highs and lows.
- **C.** A stream usually represents the intersection of the surface and the water table.
- **D.** Unlike the surface topography, the water table's location is not fixed and it goes up and down depending upon the amount of rainfall, which usually fluctuates with the time of year.
- **E.** Springs occur in places where the water table either intersects the surface or where water is forced out of the ground through hydraulic pressure.
  - **1.** A perched water table is an aquifer that sits on top of a small aquitard; water flows out of the surface where the aquifer is in contact with the surface.
  - **2.** In some cases water enters an aquifer at a high altitude and flows down the tilted aquifer; if water is allowed to reach the surface through a drilled well or along a fault it will do so on its own—this is called an artesian well and is responsible for many of the oases that exist in the Sahara Desert.

IV. Large air- or water-filled passages (caves) often exist in layers of limestone. These caves can extend for many miles in some cases and contain some of the most spectacular geologic formations.

- **A.** Caves form in water-saturated limestone beneath the water table.
  - **1.** The water, which is acidic because it contains carbonic, tannic, and other acids, dissolves the calcium carbonate, which is the main component of limestone.
  - **2.** The dissolved calcium carbonate washes down through the ground, often feeding into streams that take it to the ocean.
- **B.** When the water table drops, the caves are left as dry caverns.
  - **1.** Caves are found around the world, and many have been recently exposed as water tables that were high following the melting of Ice Age glaciers are now dropping.

2. Once the caves are air-filled, they begin to precipitate cave formations known as speleothems when mineral-rich water evaporates, causing the minerals (like calcite) to precipitate out.
3. The best-known speleothems are stalactites (which hang from ceilings) and stalagmites (which rise up from the floor); both form from the dripping of mineral-rich water that enters the cave through its ceiling.

C. There are tens of thousands of identified caves in the United States, and many others around the world.

1. The largest connected cave system is Mammoth Cave in Kentucky, where 579 kilometers of passages have been mapped so far.
2. The most spectacular cave is often considered to be Lechuguilla Cave in New Mexico.
3. The largest single cave chamber yet discovered is the Sarawak Chamber in Borneo, which is 600 by 400 meters in width and 80 meters high; it could hold several baseball stadiums within it.

D. Caves are interesting biologically because they support entire ecosystems that do not rely upon photosynthesis for the basis of their food chain.

V. Groundwater systems are particularly susceptible to pollution for several reasons.

A. The long times required for water to flow also mean that once an aquifer is polluted, it may take many millennia before the aquifer is rid of pollutants naturally.

B. Different pollutants contaminate different parts of the groundwater.

1. Metal by-products of industry are heavy and will sink to the bottom of an aquifer.
2. Hydrocarbons like gasoline, however, are lighter than water and will sit on top of the water table; this is especially problematic because the gasoline that has leaked into the ground from gas stations will not easily go away.

C. Overuse of groundwater can also create contamination problems.

1. In regions near coastlines, excessive pumping of groundwater eventually pulls salt water into the well, making the water unusable.

2. Excessive water pumping can pull in contaminated water from beneath a landfill or other polluted site.

D. Because we cannot see through rock, we often cannot tell how bad groundwater contamination is until it is too late and an aquifer is polluted.

VI. Water turns out to be crucial for life on other planets besides Earth. A large part of the NASA program of space exploration involves looking for other planets or situations where water might exist.

Recommended Reading:

Clarke and King, *The Atlas of Water*.

Gillieson, *Caves: Processes, Development, Management*.

Questions to Consider:

1. Sometimes a well will suddenly run dry with continued pumping, even if the climate has not changed; then if the well is left alone for awhile, it will resume bringing up water. What might make this happen?
2. People who go into caves are asked to be careful about disturbing the cave environment because it changes so slowly. Why is this?

Lecture Thirty-Six

Shorelines—Factories of Sedimentary Rocks

Scope: Shorelines are very energetic environments where wave energy erodes rock and moves shoreline sediments about. Wave action tends to make shorelines straight, promontories are preferentially eroded due to wave refraction, and bays and inlets are filled in by the deposit of sediments in the slower-moving waters. Longshore currents take sediment deposited at river deltas and spread them out along the coast, sometimes covering up the openings to bays. Coastlines are rarely straight, however, because other factors, such as changes in sea level, tectonic uplift, and delta deposits, keep unstraightening them. Shorelines are like factories of sedimentary rock, depositing the sand, silt, and organic calcite that becomes sandstone, shale, and limestone when compacted. Because the sea level goes up and down by hundreds of meters, shorelines advance and retreat by thousands of kilometers, creating the layers of sedimentary rocks that blanket most continents.

Outline

I. Geologically, shorelines are important because they are like sedimentary rock factories: Most sedimentary rocks are created from sediment deposited at or near shorelines.

- **A.** Waves act as a powerful agent of erosion that is constantly shaping and reshaping continental coasts.
- **B.** At the same time, waves play an important role in moving sediments (mostly washed down from streams) up and down coastlines, and so are important for deposition as well as erosion.
- **C.** Wave action tends to straighten out coastlines, but they never succeed because changes in sea level constantly reshape the shorelines into new configurations.

II. Ocean waves are responsible for the majority of the erosion and deposition that occur at shorelines.

- **A.** Ocean waves, like any kind of wave, are a transmission of energy from one place to another.

1. As waves move past a point, they cause a rolling motion of the surface water; after the wave goes past, the water has not changed location.
2. The source of the energy is usually from wind blowing on the ocean surface; waves get larger during storms when winds blow stronger.
3. Waves can travel all the way across oceans before hitting coastlines.

B. As waves approach the shoreline, their heights increase.

1. Waves travel faster farther from shore where the depth of the water is greater.
2. As waves approach the shore and the ocean depth thins, the heights of the waves increase so that the energy carried by each wave is conserved.
3. Waves crest and break when the base of the wave moves too slowly for the top of the wave.
4. The energy of the waves is transferred to the shore through the impact of the water on the coast.
5. The repeated pounding of the water efficiently shatters and smashes rocks over time.

C. When waves approach the coastline at an angle, they bend toward the shore because of refraction.

1. This angled direction of arriving waves creates longshore currents that run up or down the coastline depending upon the direction of incoming waves.
2. Ocean waves can also diffract around islands, or spits, of land and can reach areas that are not in a direct line of sight.

III. Ocean waves are powerful agents of erosion, continuously trying to straighten out coastlines.

A. Waves will hit hardest any promontories or parts of shorelines that stick out from the shore, with refracting waves wrapping around the promontory and hitting it from all sides. This wears the promontory back toward the shoreline on either side of it.

B. Wave action can create wave-cut terraces that can cut straight into sea cliffs at wave level.

C. A typical erosion rate along coastlines is about 0.5 meters per year.

1. However, erosion has been observed to occur as fast as 30 meters per year.

2. Communities sometimes build jetties of rock that extend out into the ocean in order to try to reduce shoreline erosion. However, while this traps sediment behind the jetties, it can accelerate erosion in front of the jetties.

D. Beaches are mostly made of quartz sand because the mineral quartz is very strong (with a hardness of 7) and all other minerals get smashed and destroyed from the repeated wave action. The main exception occurs in tropical regions, where beaches can form from the calcium carbonate of broken reefs.

IV. Waves help in the deposition of sediment by carrying it along the shore and redistributing it.

A. Sediment that would otherwise accumulate at a river delta gets moved up or down the shore, depending upon the direction that waves are arriving from.

1. Longshore currents cause sediment to move along the shore in a zigzag way that is analogous to the way rock moves downhill during creep.
2. The process can create long spits or barrier islands; the long curved arm of Cape Cod is a classic example of this.

B. Bays and inlets get filled in over time due to several processes.

1. Because water moves more slowly there, sediment is deposited there.
2. Longshore drift can carry sandy spits right across the mouth of the bay.
3. In some climates, mangrove swamps develop in bays, eventually filling them up with organic sediment.

V. Both the erosional mechanisms of waves and the depositional characteristics of wave action will make shorelines straight. Anytime you change the sea level, however, you create an entirely new jagged shoreline.

A. There is a constant struggle between wave action and sea-level change to keep shorelines straight or make them jagged.

B. Changes in absolute or relative sea level make shorelines jagged again.

1. If the sea level rises, the shoreline becomes jagged because of the v-shaped valleys formed from stream erosion.
2. If the sea level falls, the shoreline becomes jagged because of the exposure of undersea canyons that developed from

turbidity flows, and which were often the remnants of ancient valleys.

3. Sea level has risen about 120 meters (400 feet) since the last Ice Age and will rise another 70 meters (230 feet) if the remaining global glacier ice melts.
4. This amount of sea level rise can move shorelines back and forth thousands of kilometers; for reference, Memphis is currently at an altitude of 87 meters (285 feet) above sea level and will be close to sea level when the ice sheets melt.

C. There are two main ways that global sea levels change.

1. Climate change causes the most rapid changes in global sea level. When climates are cold, more ice sits atop continents and sea levels are lower.
2. Plate motions also change global sea levels. When global plate motions are fast, more of the sea floor is young and therefore elevated, pushing water higher up on land.

D. Sea level can also change locally due to several factors.

1. Elevated levels of deposited sediment can move shorelines seaward.
2. Earthquake faulting can suddenly raise or lower land levels.
3. The development of subduction or rifting in the region of the shoreline will usually lower shorelines over a broad region.

VI. Most sedimentary rocks are made at shorelines, and because shorelines can move thousands of kilometers back and forth, this can deposit sedimentary rocks all across continents.

A. At any given point in time, a shoreline typically consists of a sandy beach, a region of mud and clay, and a region of reef or organic sea life. If these regions get compacted with the further deposition of sediment, they become sandstone, shale, and limestone, respectively.

B. As the shoreline moves inland, the sand, mud, and organic sediments get deposited in new locations, making continuous layers across the land.

C. With increased compaction, the sediments get welded and cemented together.

D. When the coastline goes back and forth over a location several times, the multiple sedimentary layers seen in places like the Grand Canyon result.

VII. Another important factor for shoreline formation is tides, the changing of the earth's shape due to the gravitational fields of the moon and the sun.

- **A.** The moon's gravitational field acts differently on parts of the earth that are closest to the moon.
- **B.** The effect of tides is only about half as large from the sun as from the moon because the moon is much closer to the earth than the sun.
- **C.** When the earth, moon and sun all line up, the tidal effects of the sun and moon, add together to create large spring tides. When the moon is located at a 90-degree angle relative to the sun and the earth, the tidal effects of the sun and moon partially cancel out to create weaker neap tides.
- **D.** These ocean tides can cause the sea-level to rise and fall many meters at the shoreline twice a day. This creates inter-tidal environments where life has to survive both within water and exposed to air.

Recommended Reading:

Gross and Gross, *Oceanography: A View of Earth.*

Pugh, *Changing Sea Levels*.

Questions to Consider:

1. The heights of high and low tides change over the course of a month. Why would this occur?
2. More limestone tends to form from sediments in tropical zones than elsewhere. Why would this be so?

Lecture Thirty-Seven
Glaciers—The Power of Ice

Scope: Glaciers occur where it is cold enough for snow to remain frozen and turn to ice when it is compacted by more snow. Alpine glaciers are found in mountains around the world. Continental glaciers contain most of the world's ice. Currently, Antarctica and Greenland are the only two continental glaciers. Glaciers are slowly moving rivers of flowing ice. They move through both ductile flow and sliding along their base. Snow is added to glaciers at the top, where temperatures are colder, and leave at the bottom through melting, sublimation, and calving. In between, the flow of ice is a powerful scouring agent that carves out deep valleys from the sides of mountains and deposits the pulverized rock at the bottom of the glacier into heaps called moraines. Alpine glaciers are the primary agent responsible for the rapid erosion of mountains. When continental glaciers recede, many new features of the land are formed, both erosional and depositional. For example, the "ten thousand" lakes of Minnesota are a result of recent continental glaciation.

Outline

I. Glaciers form the last of the water-based environments where rock is eroded, transported, and deposited to make new sedimentary rock.

- **A.** All these processes are occurring simultaneously.
- **B.** Glaciers take this course into a new direction: climate, because cold weather is needed to make ice.
- **C.** Glaciers can be remarkably efficient agents of erosion, tearing away mountains faster than any other geologic process discussed so far.

II. There are two types of glaciers: continental and alpine.

- **A.** Continental glaciers currently consist of Antarctica and Greenland.
- **B.** Alpine glaciers are responsible for reshaping land surfaces all around the globe, not just near the poles.
- **C.** Almost all glacial ice is contained within Antarctica, a smaller amount in Greenland, and less in alpine glaciers.

III. Glaciers are continuously moving rivers of frozen water.

A. Glaciers accumulate ice upstream in what we call a "zone of accumulation," and lose ice downstream in a "zone of ablation" or "zone of loss." The division between the two is called the "firn line."

B. The accumulation of ice occurs through the falling of snow, which compacts and eventually turns to ice.

C. The loss, or ablation, of ice can happen in several ways.

1. Most of the ice is lost through melting, which happens at the bottom and underneath the glacier and helps to lubricate it and make it flow more easily.

2. Ice can also be lost through sublimation, where water goes directly from a solid to a gas.

3. If the glacier enters any sort of water environment, large chunks of the ice break off and float away to form icebergs. This is called "calving."

D. Glaciers move in two different ways depending upon the slope, size, and altitude of the glacier.

1. Glaciers move by ductile flow—actually flowing downhill. Just like a stream, the flow of a glacier is fastest within the middle and slower along its sides.

2. Glaciers also move by basal sliding. As they slide, they tear rock off and actually shape the surface of the land.

E. Glaciers move slowly, usually centimeters to meters per day. However, they can sometimes surge faster, as when they are reaching the ocean and flowing into it.

1. The speed of a glacier changes with its slope.

2. A glacier will speed up when it goes over a ledge and will crack and open up to form crevasses. If you see crevasses in a glacier, it's a sign that the glacier is increasing its speed.

F. The style of flow for glaciers varies greatly between continental and alpine glaciers.

1. Alpine glaciers are dominated by the presence of very narrow valleys, structures that are reminiscent of the fractal structures of streams.

2. Continental glaciers flow out in all directions, and tend to form narrow channels only when the flow goes through mountain ranges.

G. Glaciers are always flowing downhill; ice is always moving, despite its sometimes stationary appearance.

IV. As the ice flows, it erodes Earth's surface.

A. Erosion by ice plucking occurs when the ice gets into the cracks in rocks as it moves and pries rocks off, making them part of the base of the glacier.

B. Once the rock gets embedded within the glacier, it becomes an additional agent of erosion. Rocks embedded within the glacier, dragging across the surface of the ground, tear off more and more rock.

C. When ice erodes, U-shaped valleys are created, in contrast to the V-shaped valleys created by streams.

1. With a stream, most of the erosion is occurring at the bottom of the valley. As the stream cuts down, it destabilizes the slope. Rock falls down and debris flows into the stream, which, over time, widens its V-shaped valley.

2. With a glacier, the ice is in contact with the valley at all locations and so grinds out the valley into a classic U-shape, with a headwall at the top that's part of a bowl-shaped structure called a "cirque."

D. At the bottom of a glacial valley floor, you'll often find large boulders. When the boulders clog up a stream, a "glacial tarn" is formed.

E. As glacial valleys work their way up a mountain, they sometimes leave only a small peak of rock at the top, called a "horn," which has multiple cirques surrounding it. The Matterhorn in Switzerland is a classic example.

F. Above the firn line, snow continues to accumulate and the glacier is white. Below the firn line, the glacier begins to melt, rock is exposed, and the glacier appears darker.

G. Continental glaciers remove vast volumes of rock from continents through the same mechanisms as alpine glaciers, but on a much larger scale. Huge portions of the United States are covered with thick blankets of Canadian rock scraped off during the last Ice Ages.

H. When mountains and hills aren't totally removed by continental glaciers, they are left as low, elongated, whale-back-shaped hills called “drumlins,” which end up pointing in the direction the ice flowed.

I. Erosion from continental glaciers usually occurs gradually, but can be catastrophic, especially when an Ice Age is ending.

1. Geologists found evidence of water erosion from enormous volumes of water in the northern plains region that puzzled them.
2. It turns out that this erosion occurred from the sudden bursting of glacial lakes that formed as the climate warmed. The water traveled hundreds of kilometers in a matter of days or weeks.

V. Rock torn off lands and carried by water gets transported and deposited by glaciers, water and wind.

A. Alpine glaciers tear rock away from mountains and dump it at the end of the glacier where it forms a “terminal moraine.” Glacial sediment is always completely unsorted. Giant boulders, gravel, dirt, and tiny powdered rock are all jumbled together and dumped in one place.

B. If the climate is changing and the end of the glacier is moving, the sediment can be spread out over large distances.

C. Often a huge amount of sediment dumped at the base of a glacier overwhelms the carrying capacity of the stream when the ice melts. This forms a “braided stream” in which the water winds back and forth across a huge expanse of sediment.

D. Continental ice sheets are so huge that the deposition of sediment occurs on a huge scale and the final, terminal moraines can be enormous. A good example is the line of terminal moraines off the eastern coast of North America that include Long Island, Cape Cod, and Martha’s Vineyard.

E. When glaciers reach water, they often create enormous blocks of ice that float away. The blocks carry rock with them that gets deposited across the ocean seafloor. We can go back in time and find episodes of glaciation by looking at the locations of sediments taken off of the centers of continents and dropped as large blocks carried by icebergs.

VI. There are other features of deposition of sediment torn off from glaciers.

A. One is the formation of thousands of lakes across continents. As ice breaks up on the edge of a continental glacier, it will fall in front of the glacier in the form of large blocks. As the ice sheet recedes, sediment gets dumped around them to form new land. When the ice blocks melt, they form depressions called "kettles."

B. Another result is the creation of pulverized rock, called "rock flour," which is rock that gets ground up into very fine dust. Rock flour provides the base for very fertile soils.

Recommended Reading:

Bowen, *Thin Ice*.

Post and Lachapelle, *Glacier Ice*.

Questions to Consider:

1. Long Island and Cape Cod are in the ocean, yet sediment deposited in the ocean is usually carried away by ocean currents. How is this reconciled?
2. When two arms of a glacier come together to make a larger ice flow, there is often a black line of rock (a medial moraine) within the glacier that separates the different ice sources. How would this line form?

Lecture Thirty-Eight
Planetary Wobbles and the Last Ice Age

Scope: Strange as it sounds, the shape of Earth's orbit affects the size of mammals. There is currently a noticeable cyclical nature to the alternation of cold glacial periods and warmer "interglacials," and this is predominantly due to variations in Earth's orbital characteristics (called "Milankovitch cycles"). Changes in the ellipticity of Earth's orbit around the sun, as well as changes in the tilt and direction of Earth's axis of rotation, affect the amount and distribution of sunlight that Earth receives. This affects global climates and, when it is cold, large ice sheets cover many parts of the continents. The changing amount of ice has some very serious consequences. During the last Ice Age, the sea level was more than 120 meters (400 feet) lower than it was today, increasing the area of land and allowing humans and other mammals to migrate between continents. The ice sheets destroyed most high-latitude environments, and favored the evolution of larger mammals (which lose heat more slowly with lower surface-area-to-volume ratios) like giant mammoths.

Outline

I. The important questions for climate are: What are the systems involved and over what scales do they operate?

- **A.** Some time scales of temperature change we understand fairly well.
  - **1.** The daily cycle of temperature: It's warmer during the day than at night because there is more sunlight.
  - **2.** It's warmer during the summer than in winter.
- **B.** Some time scales are more complicated.
  - **1.** Factors that affect global temperatures on scales of tens to hundreds of years include the output of energy from the sun and ocean circulation patterns.
  - **2.** Over scales of tens of thousands to hundreds of thousands of years, factors that control climate include Earth rotation around its axis and its orbit around the sun.
  - **3.** Over scales of tens of millions to hundreds of millions of years, factors that drive climate change include plate motions, large scale erosion of mountains, and long term distribution of

carbon dioxide cycling between the atmosphere, ocean, and land.

C. The climate may be going up on one cycle and down on another, and humans are doing all sorts of inadvertent experiments with this system as well.

II. Why there are seasons.

A. Earth rotates on its axis in a clockwise direction (assuming that the North Pole is up). That is why the sun rises in the east.

B. The Earth takes 23 hours, 56 minutes, and 4 seconds to make one full rotation around its axis. It has moved along part of its revolution around the sun during this time, so has to rotate an additional 3 minutes and 56 seconds to bring the sun back to the same spot overhead and complete a 24-hour cycle.

C. The seasons occur because Earth's axis is tilted with respect to the plane that it travels in during its revolution around the sun.

D. The northern hemisphere has summer when it is facing the sun (winter in the southern hemisphere). Six months later the planet is on the other side of the sun and the northern hemisphere is facing away from the sun. That causes winter in the northern hemisphere and summer in the southern hemisphere.

E. The characteristics of Earth's rotation around its axis and the revolution around the sun change slightly over scales of tens of thousands to hundreds of thousands of years. This is why we have Ice Ages.

F. For the most part, life is dependent upon the existence of sunlight. Life on Earth exists in a fairly delicate balance concerning the sunlight that it gets. Small fluctuations in Earth's orbit change the amount and distribution of sunlight across the globe, and this can have serious effects on global climates over intermediate time scales.

III. When we look at a record of global temperatures over the last few hundred thousand years, several patterns become apparent.

A. Our climate occasionally jumps up into brief stable periods of warm temperatures called "interglacials."

B. Interglacials are followed by a gradual decline in global temperatures toward colder climates and also, more importantly, very variable climates.

IV. It is challenging to try to figure out past temperatures. We use other kinds of data, called "proxies," to provide the past record of temperature change.

A. One important method is to drill into ice cores in Greenland and Antarctica. Ice within these two glaciers can be as old as a million years in places.

1. This technique looks at different isotopes of hydrogen atoms and tracks the presence of a rare hydrogen isotope called deuterium.

2. Elevated levels of deuterium suggest that snow fell during a warmer climate when the temperatures of the air and water were higher.

B. We can also get temperature change information from a technique using marine shells to analyze ratios of oxygen isotopes in the oceans.

C. During Ice Ages, the ocean was rich in O_{18}, so fossil shells from that time are also rich in O_{18}.

D. The deuterium isotope values in ice cores and the O_{18} isotopes in marine fossil shells give us very similar results. This gives us a sense that we are accurately measuring ice volume and temperature going back over hundreds of thousands of years.

V. The pattern of climate change is related to the slight changes in Earth's orbital parameters (called "Milankovitch cycles") which occur in three ways and affect the amount and distribution of sunlight that the earth gets.

A. The ellipticity (eccentricity), obliquity (tilt), and axis of Earth's rotation all change.

B. During a planet's elliptical orbit around the sun it moves fastest when it is closest to the sun and slower when it is farther away.

C. The more elliptical a planet's orbit, the less total sunlight a planet will receive over the course of a year, and the colder it will be.

D. The range of the oscillation is from about 95,000 years to about 400,000 years, with a dominant period of a little more than 100,000 years. We saw in the records of temperature change that 100,000 years is roughly the amount of time between interglacial periods.

E. Earth's axis is currently tilted 23.5 degrees with respect to the ecliptic. The greater the axis is tilted, the greater the temperature difference between winter and summer.

F. The Earth's North Pole currently points at a star we call Polaris, the North Star. In another 12,000 years, the axis will point in a very different direction toward the star of Vega. This is called axis precession.

1. The precession does not change either the amount or the distribution of sunlight.

2. However, it's timing in relation to the change in ellipticity of Earth's orbit and the tilt of the axis does effect climate change.

3. Whether the North Pole is pointing away from or toward the sun when Earth is farthest away from the sun changes the way sunlight gets distributed around the planet.

G. All three factors play a role, but it is most significant that the times of the interglacials line up with the pattern of changes in the ellipticity of Earth's orbit.

H. These small variations in Earth's orbital parameters are what cause Ice Ages. The most recent Ice Age was about 70,000 to about 10,000 years ago and, at times, covered much of North American and Eurasia with ice. It also caused much of the dramatic geology discussed in this course.

VI. Times of global cooling like these last Ice Ages have very important effects on life and living organisms.

A. As global climates cooled, regional climate bands all around the planet were shifted.

B. Alpine environments would have dropped to much lower elevations and zones of temperate forests would have extended to lower latitudes in areas that weren't entirely covered with ice.

C. During the recent Ice Ages, cold favored the evolution of larger animals because larger animals retain heat more efficiently.

D. The drop in sea levels during the Ice Ages resulted in enormous expanses of exposed land, which, in turn, resulted in increased rates of erosion.

E. The glacial sea level drop also caused fertile biologic marine environments to be quite narrow, limited to steeper continental shelves.

F. The resulting larger continents would have been dominated by monsoon-type climates, with a large annual alternation between rainy periods and dry periods.

G. When sea levels drop, continents become connected. Eurasia, North America, and South America were one continuous land mass.

1. Twenty thousand years ago, wooly mammoths that had evolved in Eurasia crossed from Siberia into North America.
2. Humans followed soon after into North America from Asia, about 14,000 years ago, bringing their domesticated dogs with them. In Southeast Asia, the lowering of the sea level connected Australia with the rest of Asia. Ancestors of native Australian aboriginals came over at that point, able to walk across or traverse very shallow regions.

H. This all came to a rapid end 10,000 years ago because of the effects of the Milankovitch cycles. This marked the end of the glacial period and the start of the next interglacial, and coincided (not coincidentally) with the start of human civilization.

Recommended Reading:

Broecker, "*Glaciers that Speak in Tongues and Other Tales of Global Warming," Natural History*, October 2001.

Macdougall, *Frozen Earth: The Once and Future Story of Ice Ages.*

Questions to Consider:

1. Can oxygen-18 isotope age dating work for freshwater fossil shells from lakes? Why or why not?
2. How would the composition of the ocean change after the end of the Ice Age?

Lecture Thirty-Nine

Long-Term Climate Change

Scope: Throughout the geologic record, there is a strong correlation between global temperatures and the levels of carbon dioxide in the atmosphere. This is because carbon dioxide (and water vapor, ozone, methane, and others) is a greenhouse gas. The greenhouse effect, whereby radiation from Earth's surface is absorbed and held in the atmosphere by greenhouse gases, is essential for the existence of life on Earth. However, if carbon levels in the atmosphere get too high, Earth's surface can overheat. Carbon dioxide levels are kept low through the sequestration of carbon by the oceans and by photosynthetic biomass. Earth has gone through many periods of extended freezing, some of the most notable being the "Snowball Earth" conditions that occasionally existed between 800 and 600 million years ago when carbon dioxide was significantly sequestered into marine sediments. The long time-scale variations in climate are largely controlled by plate tectonics. When large plate collisions occur, erosion rates increase along with the growth of mountains. The increased erosion pulls more carbon out of the atmosphere in the form of carbonic acid, which reacts with mountain rocks to make by-products like carbonate molecules. These molecules get carried by streams to the oceans, where they become stored on the ocean seafloor as rocks like limestone. The global cooling that has occurred over the past 50 million years is largely due to the formation of the Himalayan Mountains.

Outline

I. The discussion of long-term climate change.

- **A.** The insulating effect of the greenhouse gases—water vapor, carbon dioxide, and methane—makes our planet livable; however a runaway greenhouse effect is not good.
- **B.** Global climates over Earth's history track closely with changes in the greenhouse gases.
- **C.** Milankovitch cycles changed climate patterns on Earth over time scales of tens to hundreds of thousands of years.

II. Plate tectonics drive climate change over tens to hundreds of millions of years. Mantle convection and plate tectonics, through interactions with the process of weathering and with the carbon cycle (and therefore with the greenhouse effect) have shaped the evolution of life on our planet.

- **A.** One hundred million years ago (during the time of the dinosaurs) there were very high global temperatures.
  - **1.** The continents were flooded and there was no ice at the ice caps.
  - **2.** It was very hot and the amount of carbon dioxide in our atmosphere was more than double the levels that it is today.
- **B.** If you look over all the different time scales from shortest to longest, you see a very strong correlation between Earth's global temperature and the amount of atmospheric carbon dioxide.
- **C.** In order to understand this, we need to examine how the greenhouse effect works, and then how the whole carbon cycle works.
- **D.** Water vapor, carbon dioxide, ozone, and methane in our troposphere form the basis of our greenhouse effect.
  - **1.** This greenhouse effect traps heat near Earth's surface.
  - **2.** It keeps the land warm enough to support liquid water.
  - **3.** It is absolutely requisite for the existence of life as we know it.

III. How does the greenhouse effect work? What happens?

- **A.** Sun's radiation, as it reaches Earth's surface, is peaked in the visible range and bleeds over into the ultraviolet range.
  - **1.** This is why your eyes have evolved to see radiation at frequencies corresponding to what we call "visible light."
  - **2.** The only difference between visible light and other forms of electromagnetic radiation is simply the wavelength of that radiation.
- **B.** As that radiation from the sun hits the surface of Earth, it goes through a complicated series of reflections, absorptions, and re-emissions.
  - **1.** Thirty percent gets directly reflected back out into space.
  - **2.** Twenty percent of that is absorbed by the atmosphere and is then re-radiated right back out into space again.

C. When that sunlight and ultraviolet radiation hits the atoms of Earth's surface, the atoms absorb the energy. The electrons jump to a higher level of activity, called a "quantum leap."

D. The radiated energy gets momentarily stored within the atom as a higher level of kinetic energy, but this state is not stable. The electron drops back down to its ground level, re-emitting that energy in the form of new electromagnetic radiation.

E. The radiation that gets emitted by Earth's surface is not in the same form as the radiation that it received. The amount of energy is the same, but it takes a different form because the energy that gets re-radiated is determined by the surface temperature.

   1. Why? The Earth's surface is colder than the sun's: about $14^{o}C$, compared to $6000^{o}C$.

   2. The Earth takes the sunlight's energy and re-emits it as infrared, which is at a longer wavelength than visible and ultraviolet radiation.

F. Greenhouse gases in the atmosphere preferentially absorb infrared radiation, not visible and ultraviolet.

   1. Sunlight coming directly from the sun passes right through these greenhouse gases and hits the surface of the earth.

   2. When the earth re-emits it as infrared, the atmosphere absorbs this energy because it is at a frequency that corresponds to the atomic structures of these molecules.

   3. Once the atmosphere absorbs that radiation, it re-emits it right away. Some of it heads off into space and is lost, but some of it goes downward and is re-absorbed by Earth's surface.

   4. That infrared energy begins a series of bounces back and forth between the surface and the troposphere, warming the atmosphere and the surface of the planet and making it livable.

G. The mean temperature of Earth's surface is currently $14^{o}C$, but this changes significantly over geologic time so that the energy balance is zero: The amount of sun's energy received at Earth's surface is balanced by the amount leaving it.

IV. The greenhouse process occurs primarily because of the existence of water vapor, carbon dioxide, and other greenhouse gases.

A. Water vapor is much less plentiful than carbon dioxide but more important as a greenhouse gas because of how efficiently it absorbs infrared radiation.

B. Ozone operates differently because it is primarily located much higher, in the stratosphere, not in the lower troposphere.

C. Methane is 21 times more efficient at absorbing infrared radiation than carbon dioxide, but it is not as significant because there is much less of it in the atmosphere.

V. One potentially dangerous aspect of climate is that several factors can lead to a runaway greenhouse effect.

A. Increasing temperature actually increases the greenhouse effect through a set of positive feedbacks, which then increases the temperature even more.

B. When climates warm, the amount of surface ice is reduced, ice caps shrink, and the sea ice at the North Pole is reduced.

C. This decreases the planet's reflectance, a quantity we call the "albedo."

D. More sunlight is then absorbed by the surface and re-emitted in the infrared range to be absorbed by the atmosphere, which makes the atmosphere warmer and melts more ice.

E. Warmer air holds greater amounts of greenhouse gases. If you make the atmosphere warmer it can hold more water vapor in it, and water vapor is a very efficient greenhouse gas, which then absorbs more infrared radiation, makes the surface warmer, causes more water vapor to form, and so on.

F. This creates a cycle of positive feedbacks, making global temperatures rise very quickly.

VI. In order to understand why plate tectonics would be responsible for climate change, the carbon cycle needs to be examined.

A. The carbon cycle is a set of interlocking processes that move carbon back and forth between several different reservoirs including the ocean, the biosphere, and the soil.

B. The carbon cycle has two parts: shallow surface and deep Earth.

C. First the shallow part. Earth's atmosphere would be mostly carbon dioxide if it weren't for two factors: oceans and vegetation.

1. Most surface carbon actually exists as dissolved carbon dioxide in the oceans: 40,000 billion tons of carbon. Carbon also exists in marine life and in organic sediments on the ocean floor.

2. The pathways between these different carbon reservoirs turn out to be very complex. Every year about 120 billion tons of carbon are moved back and forth between the atmosphere and the entire vegetation/soil system.
3. Humans are adding about 7 billion tons of carbon to the atmosphere every year. That is enough to upset the equilibrium.
4. Some of the added carbon is being absorbed by vegetation. Forests are getting stronger and healthier.
5. Most of the rest is going into the atmosphere and raising global temperatures through an increase in greenhouse gases.

D. Over geologic time the deep Earth interacts with the carbon cycle both by adding and subtracting carbon from it.

1. Carbon from deep Earth gets added to the atmosphere primarily in the form of carbon dioxide emitted from volcanoes.
2. Carbon gets added into oceans largely through the erosion of limestone and other carbonate-based sedimentary rocks.
3. Carbon gets removed from the ocean through sedimentation, through the production of calcium carbonate rocks, through compaction of material at accretionary wedges during subduction, or through subduction of the sediments themselves when the seafloor subducts into a trench.

VII. Carbon also gets removed from the atmosphere through weathering during dissolution.

A. When carbon dioxide combines with water, it forms carbonic acid. This dissolves rock, and the carbon goes into bicarbonate molecules that are washed down streams and into the ocean.

B. In the oceans the bicarbonate molecules combine with materials like calcium to make reservoirs of limestone.

C. This is why we don't have 95% carbon dioxide in our atmosphere. Our carbon has largely been locked away in limestone.

D. Now we can begin to discuss how plate tectonics affects global climates.

1. About 150–180 million years ago the climate was steadily warming. That was a period of increased hot spot volcanism.

2. This period of intense volcanism may have put enough carbon dioxide into the atmosphere to start one of the positive-feedback loops of global warming.
3. Several times in the past half-billion years were periods where global climates cooled considerably, and each of these corresponds to a period of continental collisions. As mountains rise, weathering increases. Carbon goes into bicarbonate ions which go into rivers, then oceans, then into the shells of marine animals and then onto the bottom of the seafloor where they become carbonate rocks like limestone.
4. Increased growth in mountains has meant an increased removal of carbon dioxide from the atmosphere and an increased cooling of the entire planet.
5. If it weren't for the collision of India into Asia and the formation of the Himalayas, our global climate would probably never have cooled to the point of its having the large Ice Ages that it now has on a regular cyclical basis, driven by the Milankovitch cycles.

VIII. There is geologic evidence for several periods of extreme glaciation between about 800 and 600 millions years ago.

A. During these Snowball Earth periods, glacial sediments were embedded within icebergs and then deposited onto the ocean floor long distances from where these glaciers first entered the ocean.

B. Several times during this period the climate swung between runaway greenhouses (very hot periods) and periods so cold that entire ocean surfaces were possibly frozen over. It would have been very hard for life forms and it is probably not a coincidence that there is no fossil evidence for multicellular life until after this time.

C. These large changes in climate may have been possible because of the lack of multicellular life; particularly because of the lack of worms and other creatures that live in ocean sediments.

1. Worms churn up marine sediments, preventing methane and carbon dioxide from getting locked away within them.
2. Once worms evolved, greenhouse gases may have been better kept in circulation.
3. Although it seems as though humans are working hard to become the planet's most significant agent of geologic change,

we have a long way to go before we attain the same level of impact as the worm.

D. Plate tectonics drives long-time-scale climate change primarily by changing weathering rates.

E. Milankovitch cycles drive intermediate-time-scale climate change by slightly changing the amount and distribution of sunlight.

Recommended Reading:

Alley, *The Two-Mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future*.

Hoffman and Schrag, "*Snowball Earth," Scientific American*, January 2000.

Questions to Consider:

1. The global temperature changes during the past 500 thousand years correlate very well with carbon dioxide changes in the atmosphere, yet the amount and distribution of sunlight Earth receives does not directly affect CO_2. Then why are they correlated?
2. Will global forests become more or less healthy during periods of extreme continental collisions?

Lecture Forty
Short-Term Climate Change

Scope: Climates change on shorter time scales than the tens of millions of years of plate tectonics and the tens of thousands of years of the Milankovitch cycles. Circulation of water in the ocean is responsible for carrying heat around the globe, and when these patterns change, regional climates change. For instance, global warming can flood the North Atlantic with freshwater, shutting off the Gulf Stream, and thus chilling eastern Canada, Greenland, and Western Europe. A reversal of equatorial currents in the Pacific (called El Niño) can bring warm waters to western South America, shutting off coastal circulation and killing plankton and fish communities. Changes in radiation output from the sun also change Earth's climate: There is a correlation between sunspot activity, indicative of solar convection patterns, and Earth's global temperature. In addition, sudden changes in climate can occur from volcanic eruptions. Dust and aerosols ejected from volcanoes can block incoming solar radiation, lowering global temperatures. However, volcanoes also have a long-term warming effect through the emission of carbon dioxide into the atmosphere.

Outline

I. Climate can change rapidly over short time scales and has always done this long before people came into the picture.

- **A.** Several factors affect climate at shorter time scales and cause rapid, instantaneous changes that have a tremendous effect on humans. These include variations in sunlight, ocean current fluctuations, and the eruptions of volcanoes.
- **B.** There are many different interactions between the geosphere, biosphere, hydrosphere, cryosphere, atmosphere, and solar input. All of these work together to affect change.
- **C.** Identifying causes for climate events is still a very speculative field of research.
  - **1.** There is not necessarily a direct causative effect between correlated events.
  - **2.** There may be two or more causes for a certain event.

3. There may be events occurring due to causes and mechanisms not yet identified.

II. Our whole surface geology system is driven by the sun, so changes in sunlight (“insolation”) have tremendous effect on Earth’s climate.

A. There is one mechanism for going back in the past and figuring out the sun’s historic output: sunspots.

B. The sun is an average sized star with fusion occurring at the core, where energy gets released. Three hundred forty trillion trillion trillion protons fuse to form helium nuclei every second. The process of nuclear fusion destroys a small amount of mass, which gets converted into electromagnetic energy, and some of that energy heats the surface of Earth.

C. Inside the sun the temperature is so great that heat gets transmitted out of its core by radiation, which drives a large convection zone on top of it. In the convection zone, solar plasma convects in tall, narrow columns with a bumpy, knobby appearance at the top.

D. Although the sun doesn’t really have a surface, we call the photosphere the sun’s surface because it is the boundary for visible light.

E. The sun’s photosphere has a temperature of 6000 degrees Kelvin (K) that determines its radiation. It is primarily peaked in the visible spectrum of electromagnetic radiation but also contains large amounts of ultraviolet and infrared radiation.

F. The bumpy surface of the sun has some unusual characteristics. It appears to have spots on it.

1. The number of sunspots at any given time can range from none to a couple hundred.
2. Sunspots are regions of very strong magnetic fields that partially inhibit the sun’s convection. They are slightly cooler and therefore appear darker to us.
3. Sunspots occur at times when the sun’s photosphere is slightly hotter elsewhere and emitting slightly more energy.

G. Over the last few decades we have seen a strong correlation between the number of sunspots and the amount of radiation the sun emits.

H. The sunlight we receive varies only between 1365.5–1366.5 watts per square-meter. However that is enough to affect Earth’s climate.

I. If you look back over the last few hundred years at the number of sunspots on the sun's surface, you see long-term variations.

   1. In the 1600s and 1700s there were hardly any sunspots. We call this time the "Maunder minimum"—a minimum in solar output received at the earth.

   2. The number of sunspots peaked from 1900 to 1950. The increase in global temperatures in the first part of the 20^{th} century is partly due to this increase in solar output.

   3. Since 1950, the sun's surface has cooled off a little bit, and the number of sunspots has decreased.

J. The record of solar insolation only goes back to the 1600s because before then there were no telescopes, so we don't know how the sun's output fluctuates over longer timescales.

K. The Little Ice Age between 1550 and 1850 corresponds to a decrease in solar output (the Maunder minimum and the Dalton minimum).

   1. Sea ice around Iceland that had been nonexistent during the warmer Middle Ages clogged the seas for weeks starting in about 1600, and peaked by 1800.

   2. In 1690 it was so cold that Eskimos landed in Scotland and many Scots moved southward, immigrating to Northern Ireland and setting the stage for future political unrest there.

L. Some historians attribute the explosion of culture that happened during the Baroque period to the fact that it was cold and people spent more time indoors.

M. We see climate change at the end of the Little Ice Age (approximately 1840), when the increased warming led to a period of high humidity in Europe. This led to the potato blight in Ireland that killed millions and caused the migration of millions of others to America.

III. Another geologic cause of sudden climate change is ocean circulation.

A. We have a similar problem for ocean circulation that we have for sunspots: no physical record. We only have human historical accounts.

B. Satellite monitoring provides us with a direct record of surface temperatures and patterns of motion, but this is very recent.

C. Oceans are huge reservoirs of heat. Ocean currents, therefore, carry heat all about the surface to various parts of the world. If there is a change in the patterns of ocean currents, there will be significant changes in regional climates.

D. One of the most important patterns of ocean circulation changes is the El Niño effect. El Niño is often followed by La Niña conditions. The whole cycle is called the El Niño Southern Oscillation (ENSO).

1. With El Niño, warm Pacific equatorial currents that usually go from east to west change their direction to flow west to east.
2. Warm water arrived on the coasts of Central and South American with deleterious effects on fishing yields there.
3. El Niño is also a coupled ocean atmosphere system, with large changes in atmospheric circulation patterns.
4. When El Niño affects ocean currents, it produces extensive droughts on the eastern side of the Pacific. On the western side there are large typhoons and thunderstorms.
5. El Niño is followed by a La Niña condition that involves warm waters moving farther west. The system acts like a big spring, with waters flowing one way with El Niño, then reversing and flowing back again with La Niña.
6. This large-scale oscillation of the ocean convection pattern occurs over a short time scale (3–8 years) and is of variable strength.
7. The ENSO is clearly the strongest of the current ocean oscillation phenomena, but we do not yet know what drives its size, strength or timing. It involves a very complex set of interconnected systems.

E. Another example of changes in ocean oscillation is what occurs when the Gulf Stream is halted. The Gulf Stream does not shut down on a regular basis, but when it does it can have dire consequences for Europe.

1. The Gulf Stream is an ocean current of warm water from the equatorial Atlantic flowing in through the Gulf of Mexico, up along the east coast of North America, across the top of the Atlantic, toward the North Atlantic, and then sinking down, to return southward at a deeper level.
2. If there is a sudden flood of fresh cold water from melting glaciers, the whole circulation pattern of thermohaline convection stops and shuts down.
3. Ironically, you can have a period of global warming shut down the Gulf Stream and end up sending Western Europe into a

deep freeze. We think that is what happened during 500–400 B.C.E.

4. During this time of intense cold, many Europeans moved south to find better places to grow crops. As part of this, the Macedonians moved southward from central Europe and invaded Greece, setting the stage for the Macedonian king Alexander the Great to form the first giant civilization encompassing Europe and parts of the Middle East.

IV. Some of the most dramatic, sudden, and catastrophic changes in climate are due to volcanic eruptions.

- **A.** Greenhouse gasses such as carbon dioxide and water vapor erupt out of volcanoes and, over long periods of time, cause global warming.
- **B.** Over short time scales, volcanoes have the opposite effect because fine dust and aerosol particles ejected from the volcano block out sunlight.
- **C.** This blocking of the sunlight can reduce global temperatures by greatly increasing the reflectance of sunlight by Earth's atmosphere.
- **D.** Aerosols are more important than dust particles because they can last in the atmosphere for months to years.
  1. For example, Krakatau erupted in 1883. Sulfate aerosol levels in the atmosphere increased by a factor of five, and remained high for half of a year.
  2. Global temperatures were unusually low for three years following the eruption.
  3. The atmospheric dust and aerosols cause richly colorful sunsets. Edvard Munch's painting *The Scream* shows a dramatic red, almost violent sunset in the background. He started painting it right after the Krakatau eruption.
- **E.** The French revolution occurred in 1789 because of two volcanic eruptions, the Hekla volcano in Iceland and the Asama volcano in Japan, both of which began in 1783.
  1. Tremendous amounts of aerosols that spewed out from these volcanoes decreased temperatures around the globe.
  2. The winter before the storming of the Bastille was the coldest of the century. Crops failed and massive starvation occurred.

3. France was only one of about a dozen governments in Europe that collapsed. There was widespread change in the whole socioeconomic situation in Europe, where mass starvation led to significant political unrest.

F. After 1815 there was a large push of Americans heading westward.

1. This was prompted by large crop failures in the eastern United States that were the result of the eruption of Mount Tambora, a volcano in Indonesia.
2. The year after the eruption, 1816, became known as the "year without a summer," and was the coldest year since 1601 (which, interestingly, followed a large volcanic eruption in Peru).

G. The eruption of Mount Tambora in Indonesia was the largest in over a thousand years.

1. It ejected about 100 cubic kilometers of tephra into the atmosphere.
2. Global temperatures dropped rapidly due to all the dust and particulate matter ejected into the atmosphere, and sent many parts of the world, including Europe, into a deep freeze.
3. Spectacular sunsets were also observed after Tambora's eruption. The paintings of Joseph Mallory Turner feature dramatic sunsets, however his earlier sunsets don't have the same colors in the years before the Tambora eruption.

H. Interestingly, a study in 2007 of more than 500 paintings showed that the sunsets of painters such as Turner, Rembrandt, Reuben, Degas, Copley and Gainsborough, were significantly more colorful in years following a large volcanic eruption.

I. During 1150–1136 B.C.E., Hekla volcano in Iceland had a large eruption. Ashes rained on China for 10 days and some anthropologists have suggested that 90% of the population of Scotland and England died at that time.

J. According to Chinese historian Pan Ku, in 209 B.C.E. great famines killed more than half the population as a result of an eruption in Iceland. Stars weren't seen at night the following year for about 3 months.

K. The Byzantine historian Procopius wrote that in the year 536 C.E. 80% of the population starved to death. Population losses on the order of 80%–90% are hard for us to imagine in today's world, but we can go back over just the last few thousand years and find several times when volcanic eruptions have caused this to happen.

V. However, there was one eruption that may have been more significant than any of the others.

A. Within the climate record there is a period of severe Ice Ages that began about 75,000 years ago and correlates with the start of modern human. If you look at the mitochondrial DNA of *Homo sapiens*, it seems that most living humans evolved from a small set of common ancestors about 75,000 years ago.

C. We think *Homo sapiens* originated in Africa about 200,000 years ago, but we are not descended from all of these people.

D. We may have descended from just a small group of people that lived about 75,000 years ago.

E. Also occurring about 75,000 years ago was the largest eruption in the last 100,000 years: Toba Volcano, in Indonesia. The explosion of this volcano was equivalent to a gigaton of TNT, and ejected 280,000 cubic kilometers of tephra into the air. The caldera from this eruption is 100 kilometers in length; the largest in the world.

F. Some anthropologists propose that the strain on the environment was so severe that most humans died. In a few places like the warm, sheltered rift valleys of Africa a few tribes would have survived, and all modern humans would have descended from those survivors.

G. These sorts of phenomena don't happen often, but they always have the potential of happening again.

Recommended Reading:

Cox, *Climate Crash.*

Linden, *Winds of Change.*

Questions to Consider:

1. How is it that volcanoes can both cause global cooling and global warming?

2. Some short-term climate is global, and some is regional. Explain which of these is more commonly the case for changes in solar insolation, ocean convection changes, and volcanic eruptions?

Lecture Forty-One

Climate Change and Human History

Scope: The evolution of life depends upon the natural selection of individuals within particular environments. Because local and global climates are continuously changing, the kind of life that exists on Earth is also continuously changing. The mass extinctions of life that mark out the different periods of the geologic record occurred because of changing conditions on Earth, due to both internal (volcanism, plate distribution, ocean circulation) and external (meteorite impact) factors. Mammalian and human evolution was greatly shaped by changing climates. Even the course of human civilization, which began at the same time as the warm, stable climates of the current inter-glacial period, is strongly tied to small changes in global and regional climates.

Outline

I. This lecture discusses the history of climate change and human history. Human migrations, establishment of civilizations, history of wars, and even the development of countries would all have been totally different with only a slightly different set of climate controls.

- **A.** The past 10,000 years have been the warmest, mildest, and most stable weather conditions for which we have evidence.
- **B.** When the climate returns to its usual, more variable patterns, the challenges to human existence may be severe.

II. Looking back across time, we can see that relatively small changes in climate have had significant affects on the course of human history.

- **A.** About 100,000 years ago *Homo sapiens* were emerging as the dominant hominid species. Anthropologists have suggested there may have been an evolutionary selection for large brains during the strong Ice Ages that occurred 120,000 to 90,000 years ago. You needed to be able to think to survive through these challenging times.
- **B.** During 60,000–40,000 years ago there began a huge diaspora of people from Africa, spreading all around the globe. Temperatures were more stable, food sources were better, and there were more stable coastline locations. Sea levels were low, so there were land

bridges between many different land masses to facilitate movement.

C. The beginnings of agriculture and the first pre-civilization communities evolved about 10,000 years ago. This was the beginning of a warm and relatively stable climate, typical of the ending of a period of Ice Ages.

D. The rapid increases in temperatures that began about 16,000 years ago were probably the result of a runaway greenhouse effect. This was a dynamic feedback resulting from warm temperatures reducing ice coverage on land, causing increased infrared radiation from more exposed Earth surface.

E. Another factor in the runaway greenhouse effect may have been a rapid release of methane from ocean sediments eroded when sea levels were low.

F. Global temperatures suddenly stopped increasing about 13,000 years ago, especially in the northern hemisphere, and dropped back into another 1,200 years of extreme cold. This was probably due to a shutdown of the thermohaline circulation in the northern Atlantic Ocean.

   1. There is evidence for a large comet exploding over Canada at this time, and the rush of melted water into the Atlantic could have caused the Gulf Stream to stop flowing.

   2. However, an episode of cooling in the southern hemisphere had begun 1,000 years earlier, and its cause is not yet known.

G. It is often not appropriate to talk only about global climate change because regional weather patterns are so variable. For example, from 22,000 to 5,500 years ago the Sahara Desert went from an arid desert to a fertile savannah and back again.

H. In spite of regional effects, however, civilization began to emerge simultaneously in several different places about 6,000 years ago. There were probably two reasons for this.

   1. The sea level stopped rising, which resulted in the stabilization of shoreline communities.

   2. This, combined with the warmer climates caused and a large increase in plant and animal biomass that could sustain larger communities of people.

I. The rise in sea level that followed the Ice Ages permanently forced all shoreline communities tremendous distances from their initial homelands (explaining why many cultures have myths about being expelled from an Eden).

J. Between 3600 and 2800 B.C.E. was a period of climatic deterioration, with alternating droughts and floods, which gave rise to developments such as the large irrigation and drainage systems in the Indus Valley.

K. About 2900 B.C.E. extreme flooding brought about the start of the Sumerian Empire. This may have been the basis for the story of Noah's Ark, which is from a Babylonian version of a Sumerian legend called the *Epic of Gilgamesh*.

L. Between 2200 and 1200 B.C.E., weather conditions brought about a collapse of many Bronze Age civilizations with an abandonment of agriculture and shift to more nomadic lifestyles.

M. Between 800 and 500 B.C.E. the climate moved into a warmer period, leading to prosperity in the Middle East, the spread of the Celts in Britain and the start of the Roman culture along the Mediterranean.

N. The continued warming in Asia created large-scale trade between Europe and Asia, including the opening of the "silk route."

O. Between 0–100 C.E. warm, stable climates allowed the Roman Empire to thrive and expand. However, in 400 C.E., the climate went into an extended period of freezing. Starving Europeans migrated south and eventually overrode the Roman culture, contributing to its demise.

III. The cold spell that started around the year 1300 had serious consequences for the entire world.

A. The colder climates caused severe snows in winter and cold, hard rains in summer, and this led to the Great Famine of 1315–1317.

B. In China, the cooling climate caused massive floods that drowned more than 7 million people along the Yellow River in 1332. With so many people dead, no one was left to bury the bodies, which were left at the surface. This led to a boom in the rat population.

C. The rats carried the fleas that carried the bubonic plague, also known as the Black Plague.

D. Many regions were importing grain to help alleviate the famine, and ships carrying grain from China went to the Middle East and Europe, bringing the rats with it.

E. The plague spread out from all of the port cities, eventually killing 70% of the British population by the end of the century (and a quarter to two-thirds of other regions as well).

F. The plague may also have contributed to the Little Ice Age that followed. Millions of trees sprang up in now-abandoned fields, pulling carbon dioxide out of the atmosphere and cooling the climate.

G. The plague changed the social and economic structures of Europe and Asia.
   1. The Catholic Church lost tremendous support and its membership was severely decimated.
   2. Significant racial discrimination began resulting in the permanent relocation of many Jewish communities to parts of Eastern Europe.

H. In Western Europe, the loss of population led to a loss of cheap labor, bringing about the end of serfdom and beginnings of capitalism.
   1. It began an era of free-enterprise and entrepreneurship that continued with the industrial and scientific advances of the Renaissance.
   2. In Eastern Europe, where the plague did not hit as hard, the social structure remained in place and serfdom continued until the late 19^{th} century.

I. The whole course of history was changed forever because of rains that came with the cooling that followed the ending of the "Medieval Warm Period."

Recommended Reading:

Gore, *Earth in the Balance* and *An Inconvenient Truth.*

Mithen, *After the Ice*.

Questions to Consider:

1. Do you think civilization would have been able to evolve if there had not been such a warm, stable period of climate beginning about 10,000 years ago?
2. What do you think the effects on humans will be if the climate continues to warm precipitously? What about if the climate starts to cool and go back into a glacial period?

Lecture Forty-Two
Plate Tectonics and Natural Resources

Scope: Did you ever wonder why there is gold in California, coal in Indiana, and oil in Iraq? Geologists have spent centuries wondering this as well, but it wasn't until the history of plate motions was interpreted that the causes of the distribution of the world's geology became apparent. Humans rely heavily upon Earth's natural resources (An old saying goes "If you don't grow it, you mine it."), and it is through plate motions and interactions that most mineral and petroleum resources are formed. For example, the large oil fields in the Mid-East come from underground anticlines that have formed during the Arabia-Eurasia plate collision.

Outline

I. This lecture discusses natural resources and the economic effects of geology and their connections to the history of geologic change.

- **A.** Your home, work environment, and modes of transportation are all based on the mineral, metal, and fossil fuel resources we get out of the ground.
- **B.** Every year more than 25,000 pounds of new, non-fuel minerals must be provided for each person in the United States to make the items that each of us use every day. This comprises about $2 trillion of our annual $13.2 trillion gross domestic production.
- **C.** The issues involved with maintaining this supply are incredibly complex; natural resources need to be available in social, political, and economic ways, as well as geologic ways.
- **D.** The United States has to import 100% of many of these minerals because they do not exist within our boundaries.

II. Political conflict has always resulted from the uneven distribution of natural resources.

- **A.** The author Jared Diamond believes this uneven distribution contributed to Europe's ability to achieve dominance over the Americas and other parts of the world.
- **B.** The uneven distribution of resources is a direct result of the geologic roulette wheel; resources just happened to be created in

some places and not others, depending upon the particular history of plate motions.

C. Many of these resources are very limited and may run out within the 21st century.

D. "Mineral reserves" are a known quantity of a substance; mineral resources are projected quantities based upon previous geologic discoveries.

E. The way we handle limited reserves of petroleum and other resources will determine the future of humanity, not only in the distant future, but in the near future as well.

F. Archaeologists often define human history in terms of the sequence of discovery of what are called the "seven metals of antiquity": gold, copper, silver, lead, tin, iron, and mercury.

III. The processes of plate tectonics—ocean rifting, the motion of the ocean seafloor across the mantle, the subduction of that material, and the subsequent volcanism—concentrate metals and minerals to levels that make them usable for us.

A. The key ability of the tectonic process to concentrate these minerals is that atoms for large elements do not sit well within the silicate mineral structures.

1. Minerals must meet two criteria: the electrical charges of the different ions have to balance to zero, and the different sizes of the ions have to match.
2. A large atom like gold or silver does not fit well within a mineral structure; as a result, these minerals tend to be the first to dissolve and leave a rock the first chance they get.

B. This process of concentrating useful metals and minerals occurs at mid-ocean ridges, where the materials get concentrated on top of the ocean seafloor.

C. When the ocean seafloor enters a subduction zone, the minerals are concentrated further.

1. This can happen during a future continent-continent collision, with subsequent erosion.
2. This can also happen when some of the mineral-rich material gets carried down into the subduction zone.
3. If the material flows upward with the water, further concentration occurs by hydrothermal circulation at the island

arc volcanoes or continental arc volcanoes through similar processes as at the mid-ocean ridge.

D. If your country has former subduction zone rock, you likely have access to concentrated metals that you would not have in a country that hasn't had subduction as part of its geologic history.

E. Continental volcanoes can also be places of mineral concentrations because of the presence of hydrothermal circulation there.

IV. Other mineral resources form in a variety of different ways.

A. Gems such as amethyst, agate, turquoise, and malachite form through precipitation of crystals directly out of water, analogous to the way salt forms.

B. Quartz-rich crystals called pegmatites form from precipitation of silica directly out of the hot fluids in the last stages of the cooling of magma underground, and can often contain a variety of valuable minerals and metals.

C. Gems like zircon, topaz, and ruby sometimes form from crystallization within pre-existing gas bubbles of volcanic rocks.

D. Garnet, jadeite, and tourmaline form in high-pressure metamorphic environments.

E. Diamonds have to form at least 150 kilometers beneath the surface. They came up to Earth's surface many billions of years ago in conduits called "kimberlite pipes."

V. The United States and other industrialized nations face several large issues concerning mineral reserves and resources.

A. The United States is dependent upon a wide range of metals and minerals that have specific and unique applications in our technological world.

1. Many of these are either very small or are being used at very rapid rates.

2. The uneven distribution of these resources has caused industrialized nations like the United States to be tremendously dependent upon foreign imports.

B. For example, at the start of the 20th century, cars were made of only five materials: wood, rubber, steel, glass, and brass. They are now made of at least 39 different minerals in addition to those five materials.

C. Some functions of cars use very specific minerals with no known substitutes.

D. Many minerals have resources that may run out within the century.

1. Humans use 15 million metric tons each year of copper because it is the best material for conducting electricity.
2. There are likely more than 1.6 billion tons of copper geologically available, but this may last only 100 years.
3. However, more resources will be discovered and extracted as the price of copper goes up, but there are not infinite supplies.

E. The best examples of minerals that have critically limited supplies are "rare Earth metals."

1. These include europium, erbium, cerium, neodymium, samarium, gadolinium, and several others.
2. Most of these rare Earth metals (about 75%) come from China.
3. Nations of the world must rely upon global trade to obtain these metals, and that requires countries to cooperate with each other.

F. Another critically limited resource involves the platinum group metals.

1. About 80% come from South Africa, while only 5% are found in North America.
2. These act as catalysts for a huge number of chemical reactions.

G. One thing that helps to extend the lifetime of many of these mineral and metal resources is recycling.

1. Recycling and reusing is a great benefit that mineral and metal resources provide over nonrenewable resources like fossil fuels.
2. As recycling becomes more economically advantageous, the projected lifetimes for many of these will be greatly extended.

VI. Another large area of natural resources is in fossil fuels: hydrocarbons like coal, oil, and natural gas.

A. Coal forms primarily from land-based plant matter. It is sedimentary rock that is essentially fossilized swamp and bog.

B. If shorelines are advancing and retreating, swamp material becomes deposited over broad regions like shoreline sediments.

Areas like the Florida Everglades, for example, are sites of future coal reserves.

C. Organic material goes through several stages of sedimentation and metamorphism to become the coal we use.

D. Material dug up from a current-day swamp is "peat." It contains about 50% carbon. It will burn when ignited, but is a dirty source of energy.

1. Over time, peat gets compacted and becomes lignite.
2. After more time, lignite becomes bituminous coal (about 86% carbon).
3. Eventually the coal becomes anthracite, which can contain 98% carbon.
4. Most of the world's coal-based energy is in the form of bituminous coal, as anthracite is very rare.

E. As an energy sources, coal is very abundant.

1. Most coal today formed from swamps and bogs that existed during 300–250 million and 150–100 million years ago.
2. Coal will continue to form naturally, but does so too slowly for significant amounts to be produced during our lifetimes, which is why we consider it to be a nonrenewable source of energy.

VII. Another major source of hydrocarbons exists in the petroleum products of oil and natural gas.

A. These hydrocarbons form in oceans from shallow marine sediments.

B. Unlike coal, petroleum needs special conditions not only to form but also to survive underground.

1. Organic sediments must be rapidly buried, compacted, and "cooked" from increased pressure and temperature to extract the hydrocarbons.
2. The heating and compression breaks down the complex molecules into a waxy substance called "kerogen."
3. The kerogen breaks down with further compression and heating into simpler hydrocarbons either in a liquid form (oil) or a gas form (natural gas).
4. Unlike coal, oil and natural gas are mobile, lighter than rock, and will eventually rise to the surface, where bacteria consume them and return the carbon into the surface carbon cycle.

C. Special geologic conditions are required in order to trap these hydrocarbons underground.

   1. You need either a domelike structure, an anticline, or some other structure where the overlying rock traps these liquids and gases as they rise up.

   2. You also need a reservoir material like sandstone to hold the petroleum that is both porous and permeable. Oil and natural gas can be pumped out by drilling into the sandstone.

D. Petroleum forms in several different tectonic settings.

   1. A common environment for finding petroleum is an incipient rift zone.

   2. When sea levels drop, water evaporates, and a layer of salt is left. When ocean water floods back in again during a period of warmer climate, a layer of organic marine sediment gets deposited on top of the salt layer. Over time you get alternate layers of salt and organic sediments.

   3. With continental collisions, folding of rock underground occurs, and the sedimentary layers can form large anticlines. That is what happened in the Middle East.

   4. Geologic events going on among Arabia, Africa, and Asia, creating the large underground petroleum reserves, are just happenstance of where we are now in the plate tectonics process.

   5. Ironically, the Persian Gulf was the cradle of civilization, and now the same region is once again the focal point for the world's civilizations, but for a very different reason: That's where the petroleum is.

Recommended Reading:

Diamond, *Guns, Germs, and Steel*.

Yergin, *The Prize: The Epic Quest for Oil, Money and Power*.

Questions to Consider:

1. Why are coal and petroleum called "nonrenewable" resources if they continue to be made in many parts of the earth?

2. Why is the prospect of future use of precious metals better than for fossil fuels?

Lecture Forty-Three
Nonrenewable Energy Sources

Scope: Humans consume energy at an incredible rate—more than 15 trillion watts. Most of human industry runs on oil, natural gas, and coal, which are the fossil remains of ancient dead organisms. However, the process of turning marine organic sediments or ancient forests and swamps into petroleum and coal takes an incredibly long time, and most of these reserves are hundreds of millions of years old. As a result, we have a limited supply of them. Oil and natural gas form when the remains of ocean organisms get deeply buried by subsequent sedimentation. Methane gas hydrates, layers of methane-bearing ice found in off-shore sediments, provide another source of hydrocarbons. Nuclear fission provides another kind of energy source altogether, but it is also nonrenewable because Earth has limited supplies of uranium and plutonium, which get destroyed in the fission process.

Outline

I. Vitally important natural resources that are extracted from the ground include the nonrenewable sources of fossil fuels and nuclear power.

- **A.** Few topics are as important, relevant, all-encompassing, and politically charged as energy. Wars are fought over it, the future depends upon it, and most of it comes out of the ground.
- **B.** Humans are consuming energy at a rate of about 15 terawatts (TW), which is one-third of the rate at which Earth is cooling off and losing its heat out into space.
- **C.** Eighty-six percent of the energy we consume comes from carbon-based fossil fuels. Including nuclear fission, 92% of all our energy comes from nonrenewable sources—sources created by geologic processes that are far too slow to be significantly produced during our lifetime.
- **D.** More than one-third of the world's energy supply comes from oil.
  - **1.** Twenty-five percent comes from coal.
  - **2.** Twenty-three percent comes from natural gas.
  - **3.** Six percent comes from nuclear fission.
  - **4.** Five percent comes from hydroelectric power on rivers.

5. Three percent comes from everything else.

E. Production of electricity is not efficient; we are only able to use about 40% of the energy that goes into making electricity.

II. Almost all of our energy comes from fossil fuels. This is not really a feasible long-term plan because they exist in limited resources.

A. Unlike mineral and metal resources, nonrenewable fuels cannot be recycled and reused.

B. Energy use and energy sources are not evenly distributed around the world.

1. Industrial nations have a very small portion of the world's population but use most of its energy.
2. For example, India uses about one-twentieth of the energy we use in the United States, but has one-sixth of the world's population.
3. China's population is four times that of the United States and consumes about as much energy now as America does.

III. Because of the important role oil plays in powering the whole industrial complex of the world, it is arguably the most important substance in the world.

A. Oil is consumed at a rate of about 31 billion barrels every day. World reserves add up to about one trillion barrels, which means we have about 32 years worth of oil reserves.

B. The amount of new reserves discovered each year, however, roughly equals the amount used.

C. The United States uses about one-fourth of the world's oil but only has about 2% of the world's reserves.

1. The U.S. oil supply would last less than 3 years without the addition of foreign oil.
2. The world is in a politically unstable situation regarding oil because its dependence upon just a few countries.

D. The distribution of petroleum throughout the world is very uneven.

1. Five countries—Saudi Arabia, Iraq, the United Arab Emirates, Kuwait, and Iran—have two-thirds of the world's oil.
2. Saudi Arabia covers just one-third of 1.0% of the earth's surface and contains just 0.4% of the world's population, but owns 25% of the world's oil.

E. Using seismic imaging, all parts of the earth's crust have been well-examined, and we can identify where rock layers are saturated with liquid and gas. We are not missing any big oil fields.

F. Most petroleum is in liquid form, but other sources include tar sands and shales that contain raw kerogen. This is a much more expensive source of petroleum because it is harder to extract.

G. The ease of taking liquid oil out of the ground and then converting it into gasoline makes it the fuel of choice when mobility is important. Most of the world's transportation uses liquid petroleum.

IV. Another major source of hydrocarbons is that of natural gas.

A. Natural gas is primarily methane, which has a formula of CH_4 (one atom of carbon to four atoms of hydrogen). Natural gas also contains other hydrocarbon gases like ethane, butane, and propane.

B. About 7% of the natural gas pulled from the ground contains helium.

1. Helium is a noble gas—it does not bond with anything else.
2. Helium is one of the by-products of the radioactive decay of uranium and thorium that heats Earth's mantle and drives the thermal convection that drives plate tectonics.
3. Most helium rises to the surface and flies off into space, but some gets trapped beneath the same underground capstones that trap oil and natural gas.

C. Because natural gas is a gas, it is easily piped, compressed, and even liquefied.

D. World reserves for natural gas are about 180 trillion cubic meters.

1. We use about 2.6 trillion cubic meters of natural gas per year.
2. Our known natural gas reserve should last about 70 years.
3. More is found all the time, but we do not know how much longer our resources will last.
4. Most of the world's natural gas reserves are in Russia, Iran, and Qatar.
5. The United States has about 5.7 trillion cubic meters of natural gas and uses about 600 billion cubic meters per year. Without imports, the United States has about 9 years' worth of natural gas.

V. The other major source of hydrocarbon is coal, which is fossilized swamp matter.

A. Unlike oil, coal is more abundant and much more evenly distributed.

B. The known world coal reserves are about one trillion tons. The world consumes coal at the rate of about 5.5 billion tons per year, so the known reserves would last about 180 years.

C. Coal resources are probably much larger and will probably extend the lifetime of coal to many centuries.

D. The United States has more than one-fourth of the global coal reserves. At its rate of use, its known supply would last about 275 years.

E. Coal is well-distributed throughout the world.

F. China is the largest consumer of coal, using 1.3 billion tons per year (a rate that is rapidly increasing).

G. Because coal is solid, it can only be removed by mining.

1. Surface strip mining is now replacing underground mining.

2. Strip mining is cheaper, but has serious consequences for the surface.

3. U.S. strip mining is largely done with a process that involves immediately reclaiming the land.

H. A major concern with coal is that burning it adds a lot of carbon dioxide to the atmosphere.

1. Of the 7 tons of carbon we put into the atmosphere each year, most of it is from coal; this seriously contributes to global heating.

2. Burning coal also adds a variety of pollutants like sulfur oxides and nitrous oxides into the atmosphere.

I. Current technologies can remove more than 95% of the carbon from coal. In the long term, it is cheaper to remove the carbon from the exhaust than to manage the consequences of not doing so; as technologies improve, the process will also get cheaper.

J. We should not be pessimistic about the problems of energy sources. Humans have become the greatest agent of geologic change, but we have the ability to handle problems as long as we understand what the problems are and make that understanding widely known.

VI. One more source of hydrocarbons that is very exciting and very interesting is that of "methane gas hydrates," also known as "methane clathrates."

- **A.** These are frozen deposits of methane-containing ice. It looks like snow, but if you light it, it will burn. As the ice evaporates, methane trapped within the ice begins to be released.
- **B.** Clathrates form naturally in marine sediments, permafrost, and tundra regions as a by-product of bacterial processes or from a thermal breakdown of more deeply deposited organic sediments.
- **C.** There are enormous quantities of methane clathrates.
- **D.** There is a large engineering challenge in getting clathrates out of the ground without having them evaporate and be lost into the atmosphere.
- **E.** Clathrates have been discovered in many regions all around the world.
- **F.** The amount of carbon stored in clathrates is very high. Recent assessments have brought initial estimates down somewhat, but it is still likely that clathrates contain about half as much carbon as all other fossil fuels and 10 times as much carbon as natural gas resources.
- **G.** There is a growing sense that methane gas hydrates play an important part in rapid climate change.
  - **1.** The rapid heating at the end of each of the recent Ice Ages was probably due to a runaway greenhouse effect from the rapid release of frozen methane hydrates.
  - **2.** We need to keep close track of these clathrates because they have the potential to quickly release a tremendous amount of methane.

VII. The last major area of nonrenewable energy is in the form of nuclear fission.

- **A.** Nuclear power is not a fossil fuel, but it is a nonrenewable energy source because we have limited amounts of uranium and plutonium.
- **B.** Nuclear fission involves the controlled release of energy from splitting either uranium-235 or plutonium-239 isotopes.
- **C.** About 15% of the world's electricity is generated from nuclear fission.

1. About 21% of the energy in the United States comes from nuclear power generated by 103 nuclear reactors at 64 different power plants.
2. Some countries in Europe get more than 50% of their electricity from nuclear power.

D. During the nuclear fission process, a neutron bombards a uranium isotope at high energy and breaks it apart, forming two smaller atoms (krypton and barium) and two highly charged neutrons that fly off and continue a chain reaction. A small amount of mass gets destroyed in the process, converted into radiation energy.

E. Usually, in a nuclear reaction, uranium is stored in rods which are submerged in water. The heat gets absorbed by the water, and the chain reaction is controlled.

F. The radiated energy is used to turn water into steam and drive turbines to make electricity. It is enormously efficient; 1 kilogram of uranium produces as much energy as 1,500 tons of coal.

G. The world reserves of uranium oxide are currently 3.5 million tons. The United States' resources are roughly 10 million tons.

1. The world consumption rate is about 75,000 tons of uranium ore per year.
2. This would provide 100 to 150 years of nuclear power at the current usage.

H. The large upside of nuclear fission is that it does not produce any greenhouse gases.

I. People have made serious objections to nuclear power on both political and environmental bases.

1. Reactor meltdown has always been a large concern; there are additional risks of a reactor meltdown in the context of global terrorism.
2. A more important and larger concern is the disposal of radioactive by-products. During the past 20 years, the United States has created an estimated 28 million tons of radioactive waste with no centralized location to put it.
3. There is a lot of debate and discussion as to where to put these wastes.
4. Transportation of radioactive waste across the country is another safety issue.

VIII. In summary, there are two major forms of nonrenewable energy sources: fossil fuels and uranium.

A. They power the major part of our world's economy.

B. They are going to be around for our lifetimes and our grandchildren's lifetimes.

C. Over time, however, the increased problems of dealing with by-products and dwindling resources will make them less attractive, and the world will shift toward renewable energy sources.

Recommended Reading:

Aubrecht, *Energy*.

Deffeys, *Beyond Oil: The View from Hubbert's Peak*.

Questions to Consider:

1. It has been estimated that the true costs of gasoline are more than double what we pay at the gas pump. What do you think the major contributors to this are?
2. Imagine that you are an engineer tasked with getting methane clathrates up from 1000 meters deep in shallow offshore marine sediments without their melting. How would you do it?

Lecture Forty-Four
Renewable Energy Sources

Scope: Humans will soon get almost all of their energy from solar-driven sources. The reason is simple: There is so much of it available, and it won't run out for many billions of years. Earth receives 174,000 TW (terawatts or trillion watts) from the sun. This is about 10,000 times the human energy use of 15 TW. Solar energy comes in many different forms: active solar (using silicon-based solar panels), passive solar (using the heat from sunlight), wind power (using sun-driven atmospheric circulation), hydroelectric power (using the sun-driven water cycle), and biomass fuels (using sun-driven photosynthesis). All of these energy sources are becoming more attractive as technologies improve and the prices of fossil fuels increase. There are also some renewable energy sources, such as geothermal and tidal, that do not rely upon sunlight. Portability of some solar energy sources is problematic, in particular, for use in cars, but battery and hydrogen fuel cell technologies are being developed to address this.

Outline

I. This lecture will address renewable energy sources.

- **A.** The amount of energy we get from the sun is relatively unlimited and essentially never-ending.
- **B.** The Earth receives more solar energy every hour than the total amount of energy that humans use in a year.
- **C.** Earth receives about 174,000 TW from the sun—10,000 times the total human energy use of 15 TW.
- **D.** We have to figure out how to convert the sun's energy into forms we can use in our daily life.
  - **1.** We need electricity to power lights.
  - **2.** We need heat to stay warm.
  - **3.** We need portable energy for transportation.

II. Electricity is a wonderful form of energy because it is easily movable due to the equivalence of electricity and magnetism.

A. One of the four fundamental forces of the universe is the electromagnetic force. A turbine creates electricity from magnetism by spinning large coils of wire through a magnetic field.

B. Water is usually used to spin the coils—either through flowing water or expanding steam.

C. The big concern is efficiency. Energy conversions always include some loss of energy to heat.

III. Solar energy is usable in both direct and indirect forms.

A. Direct solar energy is the use of solar radiation to create electricity using photovoltaic cells and steam turbines or to directly heat water or buildings.

B. Indirect solar energy involves the natural conversion of solar energy through geologic processes.

C. There are many benefits of using solar energy, in addition to the fact that there is so much available.

1. Solar power is pollution free; there is no release of carbon dioxide, no acid rain, and therefore no clean up.

2. Although initial expenses can be high to set up a solar power facility, operating costs are generally low because they tend to run without much intervention or maintenance.

D. Solar power comes in several forms and can be adapted to different climates and different regions.

E. Energy futures are highly dependent upon government and corporate policy.

IV. Direct solar power uses sunlight for heating or electricity.

A. Passive solar power is using sunlight directly for heat and involves designing homes and buildings to take advantage of the sun that hits the building. Active solar power is the conversion of sunlight into electricity.

B. One challenge here is the efficiency of solar panels.

C. In North America, the land receives an average insulation of about 125 to 375 watts per square meter. If you took a square region of 600 kilometers by 600 kilometers, you could generate all of the world’s energy needs.

D. Energy demands are increasing, but silicon solar panel technology is improving, and we have no shortage of silicon on the planet!

E. To maximize efficiency, it is best to create power locally and distribute it over small distances; active solar power also works well in areas that are off the grid.

F. Large power plants that generate electricity to power large regions use large reflecting mirrors to concentrate sunlight, heat fluids, and drive turbines.

G. We could eventually get more energy with solar collectors put into orbit in space.

H. One day we may need more than 10,000 times the energy we use now, and we have that power in the form of the sun.

V. We harness a small portion of the work water does as it washes off the land as hydroelectric power, which is currently the most utilized solar energy source.

A. Advantages of hydroelectric power are that it is inexpensive and clean.

B. Disadvantages of hydroelectric power include a loss of water to evaporation, an increase in mosquito-borne diseases, potential interference with animal and fish migration, and area limitation to regions with large streams and steep slopes.

C. Hydroelectric power works best in temperate and tropical regions. The largest producers of it are China, Canada, Brazil, and the United States.

VI. Wind power is another form of solar power. This is the energy source with the most rapid advances in technology.

A. Only about 1% to 3% of sunlight actually goes into wind; however, that is still a lot of energy.

B. The strongest winds occur high up in the atmosphere; however, there are places on Earth's surface such as the plains states, mountainous regions, and shorelines where the wind regularly blows quite strongly.

C. Winds are often strong at near-shore or offshore locations because of the large changes in temperature there.

D. The advantage of the wind turbine over the old windmill is that technological engineering advancements, such as allowing it to rotate more slowly, have made it more efficient, more durable, and less of a threat to birds.

- **E.** The largest wind turbines, in ideal conditions, currently each generate enough electricity to power about 160 homes. Recent studies indicate that wind power could be scaled up with today's technology to provide five times the current global energy use and 40 times the current electricity requirements.
- **F.** Wind power is clean and inexpensive to maintain.
- **G.** New technologies are being developed to harness the energy in another form of energy that comes from wind: ocean waves.

VII. Biomass is another way to convert sunlight into energy (e.g., through photosynthesis).

- **A.** Biomass is the use of plants to produce biochemical energy. We currently can convert certain crops into biofuels.
- **B.** In the long term it may not be sustainable. We may need crops to feed an increasing human population.
- **C.** Garbage is another source of energy. Biogas is methane extracted from waste treatment plants.

VIII. There are two major sources of renewable energy that are not powered by sunlight: Earth's heat and the gravitational pulls of the sun and moon in the form of tides.

- **A.** Geothermal power can be used in volcanic regions where shallow drilling will allow access to the hot rock that will provide steam for turbines.
  1. The largest single steam field in the world comes from The Geysers in California.
  2. Iceland gets more than 50% of its electricity from geothermal energy.
  3. On the island of Heimay, people heat their houses with geothermal energy from the same volcanic processes that almost destroyed them.
- **B.** Tidal power can be tapped to run turbines and generate electricity. Tidal swells can be more than 10 meters in some places, and you can use them to run turbines. It is very efficient, but limited to just a few locations.
- **C.** One form of renewable energy that was once considered the likely source of future energy is nuclear fusion; however, we have not

been able to re-create the process of fusion in an economically feasible way.

D. Portability of energy is a big concern. One option is using hydrogen fuel cells, which are not a source of energy but a means of converting it from one stationary source into a portable form that can be used in cars and trucks.

E. Electric cars are a proven technology—they work well and there is a huge demand around the world for them.

IX. If we play our cards right, there is no reason humans cannot be around for hundreds of millions of years.

A. The foundation of this will be to find a sustainable way to live. An important component of this will be renewable energy from the sun that is clean, efficient, and limitless.

B. The only questions will be how long it takes to move to a sustainable lifestyle and how smooth will that transition be.

Recommended Reading:

Flavin and Lenssen, *Power Surge: Guide to the Coming Energy Revolution.*

Hinrichs and Kleinbach, *Energy, its Use and the Environment*.

Questions to Consider:

1. Given that we have a growing population that is on the verge of starvation in many parts of the world, how sustainable do you think it is to grow crops to burn in cars and planes?

2. Given the part of the world you live in, what do you think would be a logical mix of renewable energy sources for your region?

Lecture Forty-Five

Humans—Dominating Geologic Change

Scope: We are an integral part of Earth, continuously sharing our atoms with the rest of it. We have also become the most significant agent of geologic change. The amount of paved surfaces in the United States now exceeds an area greater than the state of Ohio. We have altered rivers, increased cloud cover, and moved mountains to get at the mineral reserves underneath. We have tripled erosion rates with our agriculture and deforestation, and filled the space around Earth with the debris of our space missions. The release of carbon dioxide from fossil fuels and methane from our cattle is raising global temperatures, changing climates, and causing global sea levels to rise. Human activities are causing the extinction of enough species such that this century will mark the end of the 65-million-year-old Cenozoic era.

Outline

I. There is nothing new about life altering the planet. What is remarkable is the speed with which one particular species, us, humans, are doing this.

- **A.** There are many previous examples of life significantly changing Earth's surface.
  1. Photosynthetic cyanobacteria 2.5 billion years ago removed carbon dioxide from the atmosphere and produced oxygen.
  2. Ocean worms ended the Snowball Earth runaway greenhouse effect by churning up marine sediments.
  3. Corals and shells created limestone.
  4. Leafy trees became a massive store of carbon dioxide, buffering the climates.
  5. Single-celled bacteria and archaea catalyze almost all surface geochemical reactions.
- **B.** What is unusual is that we have managed to significantly alter our planet in just 200 years through a scientific understanding of how the earth works and through the development of this information with engineering and industry.

C. It may sound like a litany of bad deeds, but humans are a young species like children, and like children we make mistakes. Each mistake, however, is an opportunity to teach and to learn.

  1. We passed legislation that stopped the production of chlorofluorocarbons, and the growth of the ozone hole has largely stopped.

  2. In 1973 the United States began to phase out lead in gasoline, and lead is now almost entirely gone from streams.

  3. Nuclear testing was moved underground, and now such testing is almost nonexistent around the globe.

II. We are putting a lot of junk up into space.

A. There are currently more than 600,000 objects—remnants of previous satellite launches—of at least one centimeter in size that orbit around the earth.

B. The U.S. Strategic Command tracks the location of the largest 10,000 of these objects. They pose serious hazards to the international space station, all other space missions, and all of the satellites we have up there.

III. Humans are significantly changing the appearance of many parts of the land.

A. Erosion rates have increased dramatically primarily through the removal of vegetation and increase in agriculture.

B. For the past 10,000 years humans have been removing forests, and this has had a tremendous effect on the biosphere and atmosphere. Currently about 35% of the world's lands are now used to produce human foods.

C. Each year about 70 gigatons of valuable topsoil is lost, although that number is decreasing as better agricultural practices have been developed.

D. Wetland regions have been drained or filled in, removing water from the land and local atmosphere, making regions more arid. This also causes larger seasonal temperature changes.

E. The amount of the United States that is now paved is greater than the area of the state of Ohio. This affects land temperatures, which in turn affects storm patterns.

F. Paving also affects water flow patterns because it increases the amount of water that is removed from land and put into streams. It prevents water from going into the ground—it all gets washed out to the sea. This is a huge problem in urban areas.

G. In the United States, humans generate about 450 million tons of garbage each year.

   1. Recycling has gone up quite dramatically in the United States since 1991.

   2. Places like Europe recycle an even higher percentage of their waste.

   3. This is a lesson that humanity is successfully learning.

IV. Humans have had a significant effect on streams and lakes.

A. The Clean Water Act went into effect between 1972 and 1977 and began cleaning up polluted lakes and streams.

B. Streams are now mostly clean.

C. Many streams, however, still have very high levels of pathogenic bacteria due to livestock and human wastes. Part of the reason for this is that our population is increasing and so are our food supplies.

D. Groundwater reserves in many parts of the world have been significantly contaminated.

   1. Contamination comes from a variety of sources: industry, dumping, petroleum spills, and agricultural chemicals in farming areas.

   2. It may be thousands or tens of thousands of years before the groundwater recovers from the impact we have had on it.

E. Rivers around the world have been significantly altered.

   1. Part of the year not a single drop of the Colorado River actually reaches the ocean because it all gets removed to grow food in places like California's Imperial Valley.

   2. Water resources across the United States have been diverted and rerouted to provide drinking water for its growing populations.

V. One of the largest effects of human activities has turned out to be on the atmosphere.

A. Carbon dioxide and other greenhouse gases have been increasing in the atmosphere.

B. Pollution from particulates and aerosols also causes an increase in cloud cover.

C. Sulfur oxides and nitrous oxides have significantly increased the acidity of rain.

  1. Acid rains have removed life from many lakes and ponds that cannot handle the high level of acidity.

  2. Added acidity in the rain has increased chemical weathering, and therefore the rate at which our land erodes.

D. Carbon dioxide levels had fluctuated within a narrow range for millions of years, but starting with the burning of coal during the Industrial Revolution about 200 years ago, the levels began to increase rapidly and are now on their way to levels they haven't been at since the Cenozoic era.

E. Atmospheric pollutants can both heat and cool the land.

  1. Our increase in carbon dioxide and methane production leads to heating.

  2. Clearing the forests and the production of aerosols have both had cooling effects.

  3. Taking into account all factors, the net effect is an increase of heating of about 1.5 watts per square meter.

F. There are increases in droughts, especially in the western United States (which has caused an increase in forest fires).

VI. All indications were that until the last 200 years, we were heading back into another period of Ice Ages. However, estimates are that within the next 100 years the temperatures will increase by 2–5 degrees, which is an enormous amount.

A. In many parts of the world, temperature increases could be more than 8 degrees by the end of the 21st century, bringing droughts to many parts of the world that are already environmentally stressed.

B. Glaciers are melting, sea levels are rising, and regions along the eastern United States are sinking from pumping water and petroleum out of the ground. These areas will be at tremendous risk of flooding.

C. The situation for eastern Asia is even more critical because coastlines there contain some of the world's densest populations.

D. Returning to the population levels of the 1930s would be ideal, but war, disease, and famine (the traditional ways of controlling population) are not very good options for doing this.

VII. One of the greatest impacts we have made is on the biosphere.

- **A.** Much of this is through our trade and travel all around the planet.
- **B.** Countless species have been introduced to new regions by human activities, either intentional or accidental. We have no idea what the environmental consequences of this transfer of organisms will be.
- **C.** A big part of this transfer is germs. Bringing germs into other parts of the world can have devastating effects on population.

VIII. The extinction of organisms is currently happening at a catastrophic rate due to pollution in the waters and atmosphere, changes in habitat and climate, and the transfer of organisms around the planet.

- **A.** Inadvertently, we have single-handedly brought about the end of the Cenozoic era. We have ended a 65-million-year era of time.
- **B.** Many of the mistakes we are making are not irrevocable. We need to understand and change them, not ignore or deny them.
- **C.** We are making mistakes that any civilization or species would do as it makes the leap from being just the latest of a long chain of simians and hominids to a species that can teach a course about it.

Recommended Reading:

Diamond, *Collapse.*

Pimm, *The World According to Pimm: A Scientist Audits the Earth*.

Questions to Consider:

1. What do you think the geologic consequence will be of the continued paving of America?
2. The population of the southwestern United States is booming, groundwater supplies in this region are dwindling, global heating is causing severe droughts in this area, and already the Colorado River often doesn't reach the sea. What do you see as a possible solution to this situation?

Lecture Forty-Six

History of Life—Complexity and Diversity

Scope: Life on Earth began at least 3.85 billion years ago. The path of evolution since then has been a remarkable one, and an integral part of Earth's story. For the first few billion years, life existed as simple single-celled prokaryotes (bacteria and archaea). Sometime after 2 billion years ago more complex single-celled eukaryotes evolved. Multicellular life began less than a billion years ago, and only a half-billion years ago developed hard shells and skeletons. There are two ways to look at this. The path of evolution from worms to fish to amphibians to reptiles to early mammals to humans shows increasing degrees of complexity. However, on a tree of genetic diversity, all of multicellular life is a single small branch (variations on a single theme) while the real diversity occurs at the unicellular level, which probably happened early on. In fact, it is possible that no new metabolic strategies have evolved for billions of years. Even with multicellular life, an incredible diversity of life forms existed during the "Cambrian explosion" of life, but the plants and animals that survived it were mostly variations on a few successful biological strategies.

Outline

I. This lecture will discuss evolution and the history of life on Earth from the perspective of how conditions on a planet affect life.

- **A.** The evolution of life is intimately interconnected with the environmental conditions that shaped it.
- **B.** It cannot be emphasized strongly enough how powerful evolution is as a tool for solving the biological riddle: What kind of life is best suited to a particular environment?
- **C.** The simplicity of natural selection makes it powerful. The better model survives—gets the food, reproduces, and has offspring—the others don't.

II. Evolution on Earth has three major components to it: reproduction, mutation, and natural selection.

A. Whether it occurs asexually or sexually, reproduction allows the transmission of genetic code, DNA, from one organism to its offspring.

  1. When some parts of the DNA are not copied correctly, genetic drift occurs, allowing species to change over time.

  2. If a single population is spread out geographically, different parts of the population can drift genetically so that they can no longer interbreed. They become separate species.

B. Sometimes these genetic mutations are significant and allow the organism to better survive.

  1. Earth plays a role in this mutation through solar radiation, which damages DNA structures.

  2. There is an optimum mutation rate: If mutation is too slow, the species cannot keep up with climate change. If mutation is too high and there are too many birth defects, the species is unstable.

C. Natural selection occurs when an individual organism lives long enough to reproduce. As climate and geologic and geographic conditions change, species that may have been previously well-suited to their environments may no longer be so.

III. The path from single-celled organisms to humans is a remarkable story.

A. The only record we have of the first organism is the DNA of modern organisms, which we have been able to interpret and read back in time.

B. The first step was the creation of organic compounds, making the stuff of life. Amino acids are the building blocks of protein and they form naturally in the conditions that existed in the earth's oceans.

C. The next thing you need is a cell membrane. Many amino acids naturally polymerize, and join in masses to form "peptides." Peptides formed "microspheres," and microspheres made of lipid bilayers (from fatty acids) provided the basis of cell membranes.

D. Next you need biochemistry and catalytic activity. The microspheres began to grow and to interact with both each other and the outside environment by ion exchange across membranes. Natural selection evolved because the molecules that replicated most efficiently began to multiply and take over.

E. The first life consisted of single-celled organisms. All of the biochemistry in multicellular animals, plants, and fungi also occurs in single cells.

F. Early life was in the form of single-celled organisms called prokaryotes, which still dominate the biosphere. They come in two major forms: archaea and bacteria.

1. The first fossil evidence is from 3.85 billion years ago.
2. Almost as soon as there were oceans, there was life on Earth.
3. The early archaea and bacteria experimented with a tremendous number of metabolisms and biochemistries.
4. There was a huge amount of organic material to feed on, so organisms quickly evolved to eat methane, nitrogen, sulfur, and many other different materials—there was a great amount of biochemical creativity.

G. About 2.5 billion years ago, one form of bacteria, cyanobacteria, developed photosynthesis. The bacteria figured out how to make its own food.

H. Simple single-celled organisms, sometime between 2.1 and 1.2 billion years ago, evolved into more complex single-celled organisms we call eukaryotes.

1. Eukaryotes developed a symbiotic relationship with mitochondria and that became the foundation for all multicellular life, which evolved from eukaryotes.
2. Eukaryotic plants developed a symbiotic relationship with another protobacterium called a chloroplast, and they became the basis for all modern plants.

I. There are three major life forms.

1. Bacteria and archaea are separate branches, although they have a common ancestor from before 3.8 billion years ago.
2. The third branch, eukarya, also consists of single-celled organisms.
3. Animals, plants, and fungi are a small branch off of eukarya.

IV. The most significant period of evolutionary diversity for multi-cellular life began about 600 million years ago, the start of the Cambrian period.

A. Starting 540 million years ago, shells, spines, claw, jaws, and all sorts of other creative body parts became common. The most important fossil outcrop from this time is the Burgess Shale in Alberta, Canada.

B. Life started on a long road of experimentation, with life evolving to fill every possible ecological niche where water existed.

C. Reproduction, body metabolisms, and shape and style of organisms changed to survive in different environments.

D. Animals learned to move through a diversity of mechanisms.

E. Plants and fungi figured out how to disperse their spores and seeds.

F. Animals learned to find food in a variety of ways.

G. As fast as predators evolved, prey evolved a remarkable array of techniques to avoid being eaten.

H. Some of the most fascinating evolutionary survival mechanisms involve symbiotic relationships between different organisms.

   1. Sometimes a symbiotic relationship can look like a single organism.

   2. Sometimes symbiosis occurs between separate cooperative individuals.

I. A whole host of mechanisms for survival have evolved.

V. The path that led to humans is remarkable.

A. Perhaps the most important organism, from a human perspective, that we have found from the Burgess Shale is a flatworm called pikaia, because it is the first known animal with a primitive spinal cord.

B. The evolutionary path from flatworms to mammals only took 300 million years because not much change was needed. All vertebrates are very closely related.

C. The structure of a vertebrate is very efficient and effective and nearly all large organisms are vertebrates.

D. Flatworms evolved into ray-finned fishes and then lobe-finned fishes.

E. Lobe-finned fishes had sturdy fins that let them go on land to find food.

F. Amphibians evolved from fish and dominated the shorelines from about 350 to 300 millions years ago until reptiles evolved from them and eventually replaced them.

G. Reptiles diversified into a huge variety of forms. The path to mammals is led through a reptile called a therapsid.

VI. The fossil record is filled with large extinction events that mark out the many divisions between the geologic periods.

A. The largest of these occurred at the end of the Permian, 250 million years ago. About 90% of all marine species died off. On land, 70% of all vertebrates went extinct, including almost all of the reptiles.

B. The loss of most of the large reptiles allowed for the dominance of the dinosaurs and the start of the early mammals.

C. Mammals weren't really significant for more than a hundred million years; they simply couldn't compete with the dinosaurs.

D. The extinction of the dinosaurs didn't immediately cause the dominance of the mammals, but opened the door for their expansion and diversification.

E. The Cretaceous/Tertiary extinction 65 million years ago was caused by the impact of a large meteoroid that hit the Yucatan Peninsula and created the Chicxulub crater.

F. The earliest primates existed before this meteorite impact and were most closely related to flying lemurs and tree shrews.

G. Apes and monkeys diverged from them about 30 million years ago, and humans diverged from other apes about 13–10 million years ago.

H. This history is not an ascent of man, but rather a random walk of evolution, shaped by unique climate histories that existed on Earth at the time. It will likely not end with the species *Homo sapiens.*

Recommended Reading:

Schopf, *Cradle of Life.*

Westbroek, *Life as a Geological Force*.

Questions to Consider:

1. What do you think it is about the vertebrate structure that makes it so successful as a large animal form?

2. What kind of new *Homo* species will out-compete humans? By what criterion will it be evolutionarily selected?

Lecture Forty-Seven

The Solar System—Earth's Neighborhood

Scope: One of the best ways to understand how Earth works is to compare it to the other objects that formed along with it. Each of the planets and their moons has a very unique structure and history, which is strongly dependent upon its location in the solar system. The compositions of objects are a function of the temperatures that existed at the start of the solar system: rock and metal for the inner planets, ices for the outermost objects. The inner terrestrial planets, like Earth, are mostly rock and metal. The further out you go in the solar system, the less rock is found and the more that planetary bodies are comprised of ices and gasses. The Jovian planets grew large enough that they could hold on to hydrogen and helium, so they grew very large. Many of Earth's geologic processes (volcanism, earthquakes, erosion, etc.) are found on other planets or their moons. Examining this diversity of planetary bodies gives us a better appreciation of how unusual and unique our own planet is.

Outline

I. As the previous 46 lectures have shown, many remarkable and complex factors have gone into forming our planet and its biosphere.

- **A.** The last two lectures will review the many geologic processes that have not only created our planet, but continue to sustain it.
- **B.** This will be presented in the context of answering a simple question: Are there any more planets like Earth?
- **C.** We can initially start with our own solar system. Life exists here on Earth, so we know that our sun is a suitable star to foster the evolution of life.
- **D.** What are the chances of finding life on other planets like ours? If you start with Mercury and work your way outward across the solar system, you will notice some patterns emerging:
  - **1.** Each world in our solar system is very different from the others.
  - **2.** In spite of this, many share similar aspects of geology such as sand dunes, ice caps, volcanoes, rivers, and hurricanes.

II. The four inner planets of our solar system—Mercury, Venus, Earth, and Mars—are called the "terrestrial planets."

A. These four are all similar to each other, but very dissimilar to the other four planets, the gas giants Jupiter, Saturn, Uranus, and Neptune.

B. Like all of the terrestrial planets, Mercury has an iron core, a rocky mantle, and a crust. However, being closest to the sun, it has the highest percentage of iron, with a very large core.

1. Part of Mercury's outer core is likely to be still liquid, as it has a strong magnetic field for its size.
2. Mercury is very small, and so has a weak acceleration of gravity and no atmosphere.
3. Mercury is geologically dead; its interior and surface have been unchanged for more than 4 billion years. This has occurred because of its small size: smaller objects have greater surface area-to-volume ratios, which causes them to cool off more quickly.
4. Being close to the sun, Mercury is hot and has no water and, therefore, no life. Its temperature varies dramatically from -175°C on the side away from the sun to 425°C on the side facing the sun. Humans will never live there.
5. Mercury has an unusual orbital pattern, rotating three times for every two revolutions it makes around the sun. This pattern of having an integer variation between revolutions and rotations is common in the solar system, and is a result of tidal resonance.

C. Venus is close to Earth in size with a radius that is 95% that of Earth.

1. Venus has a thick atmosphere that has a pressure of 90 atmospheres at the surface (90 times that of Earth's atmosphere) and is 95% carbon dioxide. Venus has a runaway greenhouse.
2. Venus has an iron core and probably a liquid iron outer core, but no magnetic field. This is probably because Venus rotates so slowly: It makes one counter-rotation every 243 Earth days.
3. The thick carbon dioxide atmosphere makes the planet very hot, with a mean surface temperature of 460°C, so there is no water on the planet (though there are traces of sulfuric acid in the atmosphere).

4. All these factors combine to make Venus an incredibly inhospitable planet for the existence of life and, as a result, NASA and other space programs have little interest in further exploration there.

D. Earth's moon formed at the same time Earth formed and has a similar composition, though with much less iron and therefore a much smaller core.

1. Because the moon is much smaller than Earth, its surface gravity is only one-sixth of ours, and it cannot hold on to an atmosphere.
2. Like Mercury, the surface of the moon has been largely unchanged for billions of years. Light-colored areas on the moon are highlands, which occupy most of the planet's surface. Rocks there date back to about 4 billion years ago. Dark areas on the moon formed more recently—about 3.5–3.0 billion years ago.
3. The dark areas are called "maria," which is Latin for oceans. However, the moon's maria are flat flood basalts, and no water has been found there.
4. The moon is the only planetary body we have visited, but without water, it is unlikely that it will ever support human colonies: It would be too difficult to transport water there.

E. Mars is the most Earthlike planet and the focus of a lot of attention because it has had ample water at its surface in its past and therefore may have once supported life.

1. With its thin atmosphere, Mars is roughly as cold as Antarctica, so it's almost livable. There are several Earthlike environments on Mars such as ice caps, deserts, sand dunes, and dust storms.
2. Mars has a thin atmosphere that is mostly carbon dioxide (good for plants!). The temperatures at the poles are cold enough that carbon dioxide exists there as small frozen polar ice caps.
3. Mars had a tremendous amount of volcanic activity about 3.5–3.0 billion years ago (like the moon), though some lava flows are much more recent. One of its volcanoes, Olympus Mons, is the largest volcano in the solar system.
4. Although there is no liquid water at the surface now, there is evidence that it may be frozen beneath the surface and even occasionally leaking out of cliff walls, and the NASA program

is investigating this. If water is discovered on Mars, the planet will be the most likely site for human colonization.

F. Between the orbits of Mars and Jupiter is the asteroid belt, consisting of countless small rocky objects.

1. Of the million or so of these asteroids, 160,000 have been named. The largest of these is Ceres, which is now considered to be a dwarf planet.
2. The asteroids are likely the remnants of the early solar system, planetesimals that never became planets because of the strong gravitational force of Jupiter.
3. Asteroids have no water, no life, and haven't much interest for us as places to live.

III. The giant planets Jupiter, Saturn, Uranus, and Neptune formed with rock and metal like the terrestrial planets, but because they formed beyond the condensation point for ices, they also accumulated water, ammonia, and methane. This allowed them to quickly become very large.

A. Jupiter and Saturn are quite similar to each other, as are Uranus and Neptune.

1. Jupiter and Saturn are made mostly out of liquid hydrogen and helium, so the term "gas giant" is really a misnomer. They do not have solid surfaces, although they do have active weather in their atmospheres, where methane and ammonia form colorful bands that change as they move.
2. Both Jupiter and Saturn rotate very quickly: Jupiter's day is only 10 hours long, and because it is so large, the velocity of its rotation at the equator is about 45,000 kilometers per hour. This causes a very large Coriolis effect and the formation of many bands of atmospheric circulation.
3. Jupiter is the largest planet, with a diameter about 11 times that of Earth (and therefore a volume about 1000 times larger!). The large red spot on its surface is a storm that has been there as long as we've been observing the planet: at least several centuries.
4. Saturn has the lowest density of the planets, less than a gram per cubic centimeter. While all four of these planets have rings, Saturn's are the most prominent, though the thickness of the rings is remarkably thin: only tens of meters thick.

5. Uranus has an unusual orientation relative to its orbit, with an axis of rotation that is tilted on its side.
6. Neptune is 30 astronomical units from the sun, the farthest planet. It takes 165 Earth years for Neptune to make one revolution around the sun. Because of its tilted axis, it has seasons.
7. Neptune had a large storm spot that was observed in 1989 by the Voyager 2 mission, but was gone by 1994.

B. In our search for other Earthlike planets, there isn't much to recommend of the four giant planets. Their rocky surfaces are thousands of kilometers beneath thick mantles and atmospheres of ices and gases at unbelievable pressures.

IV. It is the moons of the giant planets, however, that have the more Earthlike geology, and even hold the most hope for the current existence of life.

A. Jupiter has four large moons that were discovered by Galileo in 1610: Io, Europa, Ganymede, and Callisto.

B. Io is the most volcanic place in the solar system; with constantly erupting volcanoes of lava and liquid sulfur that turn the surface yellow.

C. Europa is made of rock, but also has a large saltwater ocean beneath a frozen icy crust. This icy crust is very cracked, permitting water to come to the surface. It is the most likely place in the solar system, other than Earth, where life could exist.

D. Ganymede is half rock and half ice. It is the largest planetary moon, and has a crust that is 4 billion years old. Ganymede has a reduced magnetic field that is probably the result of a layer of salt water beneath a thick icy crust. It is less likely to have life than Europa, but is still a possible candidate.

E. Callisto is also half rock and half ice, but smaller and farther from Jupiter than Ganymede or Europa, and therefore has insignificant tidal heating. NASA considers Callisto a good possibility as a base for future outer solar system exploration.

F. One of the most unusual places in the solar system is Titan. It is the largest of Saturn's moons and the second largest of the solar system. Titan, the only moon with a dense atmosphere, 50% thicker than Earth's atmosphere and like ours, is largely nitrogen. The atmosphere contains hydrocarbons like methane and ethane, and the surface has lakes and rivers of liquid hydrocarbons. Titan has changing seasons and climates, clouds, wind, rain, and surface features similar to those of Earth. However, the temperature is very cold (about -180°C), so it is unlikely to have life, but might be a good place to stop and refuel a rocket ship.

V. There are many other smaller objects in the solar system that are not planets or moons—dwarf planets like Pluto, centaurs, trojans, trans-Neptunian objects, comets, and meteoroids. They are mixtures of metal, rock and ice.

- **A.** Pluto used to be a considered a planet, but was demoted in 2006 to the status of a new category: dwarf planet.
- **B.** A planet has now been defined as requiring to orbit only the sun, be large enough to be a sphere, and uniquely occupy the space in its orbit. Pluto does not meet the last condition, as it swings inside the orbit of Neptune.
- **C.** Pluto is part of the Kuiper belt, which, along with the scattered belt objects, contain many planetoids extending out to about 55 astronomical units (AU). One AU is equal to the distance from Earth to the sun.
- **D.** Many tiny icy comets comprise the diffuse Oort cloud, which extends out past 100,000 AU. When these comets get deflected into the inner solar system they lose their ice making long tails that can be spectacular, stretching for many millions of kilometers.

VI. Is there anything else in our solar system that looks like Earth? Is anything alive? Is there any place where we could live?

- **A.** Earth has had a liquid ocean at the surface, plenty of heat and nutrients, and it still took 3 billion years for multicellular life to evolve here.
- **B.** It is unlikely that anything other than single-celled life could exist anywhere else in our solar system, although we have a sun that supports complex life on Earth.
- **C.** Many places have water and rock to support life, and some might even support human colonies.
  - **1.** We will need a source of energy. Nuclear power could be suitable, but is in limited supply.
  - **2.** Tidal heating would be adequate on planets like Io, but Io lacks sufficient sunlight.

3. Mars would be suitable if there is water that could be found underground.

D. Living farther from the sun would require giant space-based solar reflectors to concentrate the weak sunlight.

Recommended Reading:

Morrison and Owen, *The Planetary System.*

Robinson, *Blue Mars*.

———, *Green Mars*

———, *Red Mars.*

Questions to Consider:

1. Do moonquakes within Earth's moon and volcanism on Jupiter's moon Io both have the same origin? (Clue: Io is the closest of Jupiter's moons.)
2. What do you see as being the most important planetary characteristic required for the existence of life?

Lecture Forty-Eight

The Lonely Planet—Fermi's Paradox

Scope: What are the chances that there are other civilizations in our galaxy that, at this moment, are wondering how many other civilizations there are in their galaxy? Many scientists used to think that the number was high. However, recent geophysical and astrophysical research suggests that the conditions required to have liquid water continuously available at a planet's surface for billions of years, which was needed for us to evolve, may be quite rare. Earth needed to be the right size, with the right mix of compositions, the right kind of moon, the right-shaped orbit, and the right distance from the sun. The solar system needs to have planets like Jupiter and Saturn, with nearly circular orbits, to keep asteroids from continuously bombarding Earth yet not destabilize the orbits of other planets and the asteroids. Our sun needs to be the right size star, in the right location, and in the right kind of galaxy. Put all of these requirements together, and it suggests that there may be only a handful of planets in the Milky Way galaxy like Earth, if any others at all. Life is probably common, starting up wherever there is liquid water. But the stable conditions required for the evolution of something that becomes aware of its own existence may actually be unique to Earth.

Outline

I. In 1950, the famous physicist Enrico Fermi was discussing recent experiments about the origin of life with his colleagues. It seemed that life might start on any planet that had liquid water and an atmosphere. Fermi asked a simple question that has puzzled scientists ever since: Where is everybody? This became known as Fermi's paradox.

- **A.** Given the size and age of the universe, there should be other civilizations in existence, but no one has contacted us from any other planet.
- **B.** We know there are many planets. In fact, in 2007, the first Earthlike planet, Gliese 581c, was discovered only 5 light years away from us. But does it have intelligent life?

C. How many of these planets we are discovering have life? In how many cases is that life complex, multi-cellular or intelligent? Is anybody out there? If so, where is everybody?

II. There have been many attempts to answer Fermi's paradox.

A. Maybe other civilizations have tried to contact us but we don't recognize the signs.

B. Maybe we aren't looking in the right places, or at the right things? Maybe the creatures are too alien to be able to communicate with us? Maybe they all eventually choose to be nontechnical?

C. Maybe civilizations don't last long? Maybe it is the nature of intelligent life to destroy itself? Or to destroy others?

D. Maybe they are intentionally avoiding contacting us? This is called the "zoo hypothesis."

E. Perhaps they just aren't there. Earth is a remarkable planet, and maybe there are few like it.

1. Earth's processes are delicately and sensitively balanced with a solar heat engine shaping the surface and driving climate change, water flow, weathering and erosion within narrow fluctuations in temperature.
2. Maybe the requirements to make a planet like Earth are remarkably stringent.

F. There was a time when scientists calculated that there might be numerous civilizations in the galaxy.

1. Frank Drake, a famous astrophysicist, in 1960 constructed a formula designed as a thought problem to try to address Fermi's paradox. His Drake equation took the form of a product of probabilities that would give the number N of inhabited planets.
2. Carl Sagan, the famous astronomer and author, said that because there were billions and billions of stars in our galaxy (it's now thought to be between 200 and 500 billion), and there are more than 100 billion galaxies in the universe, there must be trillions of civilizations.

III. It is remarkable that we even have planets, because the very existence of stars and planets requires extremely narrow bounds on the fundamental laws of the universe.

A. If the relative strengths of the four fundamental forces of the universe were only slightly different, planets and people and all of matter could not exist. This is known as the Anthropic Principle, or Goldilocks Enigma.

B. A wide variety of solutions have been put forward in order to explain the Goldilocks Enigma.

1. According to the absurd universe, it just happens to turn out this way (by random chance).

2. According to the unique universe, there is a deep underlying principle of physics that requires the universe to have worked out this way; some theory of everything that we just haven't found yet.

3. One proposal is that we are living in a fake universe; a kind of virtual reality.

4. Some have proposed a universe designed by an intelligent creator specifically to support complexity and the emergence of intelligence. However, this does not address the troubling question of who created the creator, and we have to go through the whole analysis again, replacing "universe" with "god."

5. A popular solution is that there are multiple universes existing in parallel. Many physicists favor this because it is one outcome of string theory. Because this model is not currently testable, however, it doesn't really fall within the realm of science.

IV. Recent work suggests that even in a universe favorable to the formation of planets, like our universe, the conditions required to support complex life on a planet may be incredibly small, and Earth just happened to have the right conditions. This presents a whole new Goldilocks Enigma.

A. Earth is in the right location in our galaxy.

1. Most stars in a galaxy are close to the center, but nearby star passes would throw trillions of comets into any planets causing very high rates of bombardment. In addition the intense radiation and frequent explosions of large stars would prevent the existence of life near galactic centers.

2. At the edges of galaxies, star light suggests that star systems are starved for metals, with very low levels of silicon, iron, magnesium, and all the other requirements for planets and the building blocks of life. This is because stars are small so they last a long time, and there have not been enough supernovae to produce the heavier elements needed to make rock.

3. Outer galaxy stars also show low amounts of radioactive elements, so even if there were planets they would be geologically dead.
4. There is only a narrow zone in spiral galaxies, maybe 5%–10% of the total number of stars, that is sufficiently metal-rich and could support life.
5. Many galaxies, such as elliptical and irregular ones, seem to be metal-poor and therefore likely unable to support life. Only spiral galaxies (like ours) are metal-rich but, even then, only near the centers.

B. Our sun is just the right size.

1. Large stars have very short lifetimes and emit too much ultraviolet radiation. The habitable zone for our sun is about 5% closer than Earth is now, and 15% farther away.
2. For smaller stars the habitable zone is closer to the sun because they emit lower levels of energy. However, planets close to the sun risk danger from solar flares. They also tend to be tidally locked so that one side always faces the sun and burns; the other always faces away and freezes.

C. Jupiter is just the right kind of shepherd.

1. Jupiter prevents Earth from getting bombarded by probably 10,000 times the number of comets and meteoroids that actually do hit it by flinging them out into space.
2. If Jupiter's orbit were slightly more elliptical or if it were much larger, it would have the opposite effect and gravitationally destabilize Earth's orbit and the asteroid belt.
3. All of the Jupiter-sized planets that have been observed so far in other solar systems are bad Jupiters with very eccentric orbits.

V. Earth seems to be the right kind of planet to support life in terms of its location in the galaxy, its sun, and its own geology.

A. Earth is large enough to hold onto a thin atmosphere, but not too large to be smothered with hydrogen and helium like the gas giants.

B. Earth has the right balance of rock and metals.

C. Earth has a nearly circular orbit that keeps it at just the right distance from the sun to maintain liquid water.

D. Earth's large moon is at just the right distance from Earth to behave like a gyroscope and minimize the changes in the tilt of Earth's axis. This keeps the Milankovitch cycles small enough to maintain a relatively stable climate.

1. The formation of the moon is important for giving Earth a fast rotation rate which keeps day and night temperature swings from being too great.
2. The moon also provides Earth with its steadily tilted axis, which gives us seasons. Seasonal climate variations have been an important stimulus for natural selection and the evolution of life on the planet.
3. When the protomoon hit Earth, Earth absorbed most of the protomoon's iron core, making Earth's core larger, and giving it a strong magnetic dynamo and a large magnetic field. That magnetic field produced the magnetosphere which protects Earth from solar wind and solar particles that are constantly shot out at us from the surface of the sun.
4. Earth has sufficient carbon to aid in the development of life. It has both oceans and land mass enough to balance and regulate that carbon cycle.
5. Earth has enough radiogenic isotopes to keep it warm and geologically alive with mantle convection, plate tectonics, air, land, water and the many ecological niches and microclimates that have promoted tremendous biodiversity.

E. In short, Earth seems to be just the right size, just the right distance from just the right kind of star, and just the right distance from the center of just the right kind of galaxy. Intelligent life on Earth may have occurred in spite of overwhelmingly strong odds against it.

VI. In light of the many challenges to providing stable conditions for life on the surface of a planet, maybe we are alone. If so, what are the implications of this?

A. For example, if there is just one creature in the universe that resembles a tiger, do we have an added responsibility to make sure it does not go extinct?

B. It seems that we humans are maturing as a culture and are beginning to realize both our power as a geologic force and the responsibility that comes with that power.

1. Einstein once wrote, "A human being is a part of the whole called by us the universe, a part limited in time and space. … Our task must be to free ourselves … by widening our circle of understanding and compassion to embrace all living creatures and the whole of nature in its beauty."
2. Our cultural evolution has been one of continually widening the circle of compassion, from individuals, to families, to extended families, to a clan or pack, to a community or town, a city, a state, a country, and a continent; perhaps eventually the planet, solar system, galaxy, universe, and maybe even multiverse.

C. The philosopher Alfred North Whitehead once equated complexity with beauty and viewed maximizing this beauty as equivalent to reaching God. Perhaps even the Internet can be seen as part of this process; an increase in complexity and therefore a kind of beauty. Perhaps all that we are doing on Earth represents the next stage along the long process that started with the Big Bang and moved from energy, to matter, to life, to mind, and next, maybe to spirit.

D. If any advice can be given from a doctor of geology, it is to get out and enjoy the world.

1. For example, you will see a beautiful and majestic mountain now also as a battleground between the forces of tectonics that made it, and the forces of erosion that are tearing it down.
2. A shoreline will not just be a soothing and relaxing walk in the sand, but a vibrant, pounding struggle as the waves continuously try to make crooked coastlines straight again. You will also see it as a factory for the sedimentary rocks that you will find elsewhere in places like the Grand Canyon.
3. Marcel Proust said that the real voyage of discovery consists not in seeing new landscapes, but in having new eyes. Even better: You will have new eyes with which to see new landscapes.

Recommended Reading:

Davies, *The Goldilocks Enigma*.

Ward and Brownlee, *Rare Earth.*

Webb, *If the Universe Is Teeming with Aliens ... Where Is Everybody?*

Questions to Consider:

1. Imagine a planet slightly larger and hotter than ours. What kind of life do you think would evolve to be the "intelligent" life form on it?
2. Aliens are often portrayed in science fiction as being fairly similar to humans. Given the success of vertebrates on Earth, do you think that the dominant life forms on planets will always evolve to be quadruped vertebrates?

Timeline

Earth History

13.7 billion years ago .... The universe is created during the Big Bang; three minutes later hydrogen begins forming.

13.6 billion years ago .... The Milky Way begins to form; hydrogen and helium begin to come together to form stars.

4.57 billion years ago .... The Solar System forms; the sun, planets, and countless smaller bodies coalesce into a giant rotating disk-shaped nebula.

4.52 billion years ago .... Our moon forms; Earth is likely entirely molten at this point.

More than 4.4 billion years ago ...... Earth's solid crust begins to grow and persist.

More than 4 billion years ago .... The earliest continents form; plate tectonics takes on the same form that is in operation today.

More than 3.5 billion years ago ...... Life begins as simple single-celled prokaryotic organisms.

3.3 billion years ago .... The earliest supercontinent, Vaalbara, forms.

2.5 billion years ago .... The permanent presence of oxygen gas in the atmosphere, paving the way for the evolution of animal life.

Less than 2 billion years ago .... Eukaryotic life evolves.

1.8 billion years ago .... The supercontinent Columbia forms.

1 billion years ago .... The supercontinent Rodinia forms; its pieces come together to form the supercontinent Pannotia.

Less than 1 billion years ago	Multicellular life emerges.
800 million years ago	Short periods of extremely cold climates for the following 200 million years that challenge life.
540 million years ago	The Cambrian explosion; the development of hard shells and bones allows for the regular fossilization of body parts.
300 million years ago	The last great supercontinent, Pangaea, comes together.
245 million years ago	The Permian/Triassic extinction marks the end of the Paleozoic era and the start of the Mesozoic era.
200 million years ago	Pangaea starts to break up, creating the Atlantic Ocean and closing up the Tethys Sea; dinosaurs become the dominant species in many different environmental niches.
65 million years ago	The Cretaceous extinction brings about the end of the Mesozoic era and the start of the Cenozoic era.
Around 60 million years ago	The collision of India into China begins to form the Himalayan Plateau, which is the most impressive mountain range in recent geologic history; global climates continuously cool over the subsequent 60 million years.
2 million years ago	A period of extreme Ice Ages begins.
200 thousand years ago	*Homo sapiens* evolves and becomes the dominant agent of geologic change at Earth's surface.
10 thousand years ago	The most recent warm inter-glacial period.

Geologic History

1556 .... Georgius Agricola publishes *De Re Metallica*, (*Of Things Metal*), which establishes the foundation for exploration geology.

1620 .... Francis Bacon publishes his observation that the continents could have once been attached; sea-going explorers begin to discover the outlines of the continents.

1681 .... Thomas Burnet publishes *Sacred Theory of the Earth*, in which he proposes that Earth began as a homogeneous sphere of dust and rock and then differentiated into three major layers.

1760 .... John Mitchell is the first to publish the suggestion that earthquakes might be the result of layers of rocks rubbing against each other.

1778 .... Compte de Buffon uses experiments on the cooling rate of iron to determine that Earth must be at least 75,000 years than Biblical predictions; he also suggests that climate change is the cause of changes in the appearances of organisms over time, a precursor to the ideas of natural selection and evolution.

1785 .... James Hutton presents the idea that geological processes have repeated themselves over and over in repeating cycles, leading him to suggest that Earth must be very old and "that we find no vestige of a beginning, no prospect of an end."

1815 .... William Smith publishes the first large-scale geologic map covering England

and Wales, observes the correlations between fossils and geologic strata, and develops the principle of faunal succession.

1830 .... Sir Charles Lyell incorporates the ideas of James Hutton into the theory of Uniformitarianism, which he publishes in *Principles of Geology*; Lyell states that the geologic processes that are at work today, such as mountain building and stream erosion, operate the same way they always have in the past.

1837 .... Louis Agassiz publishes his proposition that northern latitudes were once covered with glaciers during an Ice Age.

1859 .... Charles Darwin publishes *The Origin of Species*, which shows that life is intimately dependent upon the environmental conditions within which it exists.

1869 .... Sir William Thomson (also known as Lord Kelvin) publishes "On Geological Dynamics" and other writings, which calculate the age of Earth as 20–100 million years old.

1898 .... Ernest Rutherford begins his work on the demonstration of radioactivity; over the next three and a half decades, many scientists (including George Darwin, John Joly, Frederick Soddy, Bertram Boltwood, and Arthur Holmes) work to develop radiometric dating, eventually determining that Earth is at least several billion years old.

1906 .... Richard Dixon Oldham discovers that Earth has a dense core, demonstrates that P, S, and surface waves can be used to determine the structure and composition of Earth’s interior, and suggests that Earth’s core is liquid.

1909 .... Andrija Mohorovicic uses the arrivals of refracted P and S waves to determine that there is a shallow boundary between Earth’s crust and mantle, later named the Moho.

1912 .... Alfred Wegener puts forward the hypothesis of continental drift.

1928 .... Arthur Holmes lends support to the ideas of continental drift by demonstrating that convection can occur in the mantle, allowing the continents to move as if they were on a conveyor belt.

1936 .... Inge Lehmann determines from reflected P waves that the core is divided into an inner and outer core, and suggests that the inner core is solid.

1949 .... Willard Libby discovers the technique of radiocarbon dating.

1953 .... Maurice Ewing and Bruce Heezen discover a long, continuous rift running down the center of the Mid-Atlantic Ridge.

1957 .... Roger Revelle and Hans Suess demonstrate that human gas emissions are causing an increased greenhouse effect.

1960 .... Harry Hess proposes that ocean seafloor forms at mid-ocean ridges and is destroyed at ocean trenches, opening the door for the rebirth of the continental drift theory in the form of plate tectonics.

1962 .... Robert Coats publishes an article on the mechanism of the subduction of oceanic crust at island arc trenches.

1963 .... Fred Vine and Drummond Matthews show that the reversing polarity of Earth's magnetic field forms parallel bands of magnetic anomalies within the ocean crust, providing a means of remotely determining the ages of oceanic crustal rocks.

1963 .... J. Tuzo Wilson discovers hot spots.

1967 .... W. Jason Morgan and Dan McKenzie develop the details of the theory of plate tectonics from various observations made in several different fields.

1969 .... Neil Armstrong and Buzz Aldrin are the first humans to walk on the moon; analysis of moon rocks proves that Earth and the moon formed from the collision of a Mars-sized body with early Earth.

1980 .... Luis and Walter Alvarez propose that a meteorite impact caused the significant interruption in global climate that lead to the extinction of the dinosaurs 65 million years ago.

1981 .... Adam Dziewonski and Don Anderson publish PREM (Preliminary Reference Earth Model), the first accurate model of the density and seismic properties of Earth, layer by layer, from the surface to the core.

1991 .... The first extra-solar planet is discovered.

1999 .... The world population reaches 6 million people.

2004 .... Mars rovers Spirit and Opportunity begin several years of exploration of the surface of Mars, proving that water once flowed on the surface of Mars and that it might therefore once have supported life.

Glossary

aquifer: Rock or soil through which groundwater moves easily.

asthenosphere: A weak layer of rock beneath the lithosphere that is close to its melting point and flows relatively easily, allowing for the motions of overlying plates.

Big Bang theory: The theory that proposes that the universe originated as a single point of energy that subsequently expanded, pulling space along with it.

biosphere: All life on Earth; the parts of the solid Earth, the hydrosphere, and the atmosphere in which living organisms can be found.

carbon cycle: The combined processes—including photosynthesis, decomposition, and respiration—by which carbon cycles between the major reservoirs of the atmosphere, the oceans, and living organisms.

chemical weathering: The processes by which the internal structure of a mineral is altered by the removal and/or addition of elements.

conduction: The transfer of heat through matter by molecular collisions; this is the dominant way heat is transferred across the core-mantle boundary and across the lithosphere.

convection: The transfer of heat through the movement of material; this is the dominant way that heat is transferred across the outer core, the mantle, the oceans, and the atmosphere.

core: The innermost layer of Earth which is primarily (85%) made of iron and is divided into a solid inner core and liquid outer core.

Coriolis effect: The apparent deflective force of Earth's rotation on all free-moving objects at Earth's surface, which creates the magnetic field in the outer core and drives fluid flow in the oceans and the atmosphere.

covalent bond: A chemical bond formed by the sharing of one or more electrons—especially pairs of electrons—between atoms.

crust: The thin, rocky outermost layer of the solid Earth; it takes the form of either continental or oceanic crust.

earthquake: The sudden slip of rock across a planar fault that releases seismic waves.

electromagnetic spectrum: The range of electromagnetic radiation according to wavelength, which includes radio waves, microwaves, infrared light, visible light, ultraviolet light, X-rays, and gamma rays.

ENSO (El Niño Southern Oscillation): The irregular cyclic swing of warm and cold phases in the tropical Pacific.

erosion: The removal and transportation of rock or soil by water, ice, wind, or gravity.

eukaryote: Complex single-celled organisms that first evolved about 2.5 billion years ago.

fault: A fracture within Earth along which movement occurs.

floodplain: The flat, low-lying portion of a stream valley that is subject to period flooding.

fold: Layer of rock that is bent, usually as the result of plate interactions.

geotherm: The vertical profile of Earth's temperature as a function of depth.

global warming: The increase in average temperature of Earth's atmosphere and surface due in part to the increase in carbon dioxide levels.

greenhouse effect: The heating of Earth's surface and atmosphere from solar radiation that is absorbed and re-emitted by the atmosphere, mainly through water vapor and carbon dioxide.

Hadley cells: Thermally-driven bands of atmospheric circulation symmetric about the equator that was first proposed by George Hadley as an explanation for the trade winds.

hot spot: A region of higher than normal volcanism at the surface that is usually associated with a concentration of heat in the mantle and thought to result from a rising plume of deep mantle rock.

hydrosphere: The water portion of Earth which is found not only at the surface but also within the atmosphere and the solid geosphere.

igneous rock: Rock formed by the crystallization of molten magma.

ion: An atom or molecule that possesses an electric charge through the gain or loss of electrons.

ionic bond: A chemical bond between two ions with opposite charges.

isostasy: The concept that Earth's crust sits at elevations that are laterally balanced gravitationally.

isotope: An atom with the same number of protons but a different number of neutrons for a given element.

Kuiper belt: A disk-shaped region in the outer solar system lying beyond the orbit of Neptune and extending to a distance of about 50 astronomical units; contains thousands of small icy bodies, some of which are on highly elliptical orbits and periodically visit the inner solar system as comets.

lithification: The conversion of newly deposited sediment into solid rock through the pressure of overlying sediment.

lithosphere: The rigid outer layer of Earth containing the crust and the uppermost mantle which is broken into Earth's tectonic plates.

magma: A body of molten rock within Earth that contains dissolved gases and may include solid crystals.

magnetosphere: A region surrounding Earth extending to several thousand kilometers above the surface where charged particles from the sun are trapped and deflected by Earth's magnetic field.

mantle: The rocky layer of Earth above the core and below the crust, containing 83% of Earth's volume and two-thirds of its mass.

mantle convection: The slow cycling movement of rock across the mantle, which is responsible for driving plate tectonics and allowing Earth to cool.

mantle plume: A rising mass of hot rock within the mantle, carrying heat from the deep mantle toward the surface and possibly supplying the source for hot spot volcanoes.

mass movement: The downslope movement of rock, regolith, and soil under the direct influence of gravity.

mechanical weathering: The physical disintegration of rock, resulting in smaller fragments that are subsequently removed as sediment.

metamorphic rock: Rock formed by the alteration of pre-existing rock through the influences of high temperatures, pressures, and/or chemically active fluids.

mid-ocean ridges: A continuous elevated zone on the floor of all major ocean basins with rifts that represent divergent plate boundaries.

Milankovitch cycles: Periodic variations in Earth's orbital parameters (orbit ellipticity, axis tilt, axis precession) that affect the distribution of solar radiation reaching Earth and causing climate changes.

moraine: A ridge of unsorted sediment deposited by a glacier.

nucleosynthesis: The process by which heavier chemical elements are synthesized from hydrogen nuclei in the interiors of stars.

Oort cloud: A swarm of comets orbiting the sun at a distance of one to two light-years, proposed as a source of some comets that pass near the sun.

orogenic belt (orogenesis): A linear region—also called orogen or fold belt—that has undergone folding or other deformation during plate collisions.

ozone layer: A region of the upper atmosphere, between about 15 and 30 kilometers in altitude, containing a relatively high concentration of ozone (a molecule of three atoms of oxygen) that partially absorbs solar ultraviolet radiation.

paleomagnetism: The permanent magnetization acquired by rock that can be used to determine the location of the ancient magnetic poles at the time it became magnetized.

Pangaea: The supercontinent that existed between 350 and 200 million years ago and broke apart to form the current configuration of continents.

permeability: The measure of a material's ability to transmit fluids.

planetesimal: One of millions of small bodies that accreted and orbited the sun during the formation of the planets.

plate: A fragment of Earth's lithosphere that moves laterally across the surface.

plate tectonics: The theory that describes how Earth's plates interact in various ways to produce earthquakes, volcanoes, mountains, and many other features of Earth's geology.

porosity: The percentage of rock or soil that consists of open spaces that could be occupied by fluids.

pressure release: The expansion of rock as the pressure is lowered; the dominant mechanism for melting beneath mid-ocean ridges.

prokaryotes: Simple one-celled organisms that first evolved on Earth more than 3.5 billion years ago.

protoplanetary disk: A rotating accretionary disk of dense gas surrounding a young, newly formed star.

pyroclastic flow: A destructive, burning, dense cloud of gas, ash, and rock that can flow down the side of a volcano during an eruption.

radiation: The transfer of energy through space in the form of electromagnetic waves; this is the way heat escapes from Earth's surface out into space and how the planet cools down over time.

radioactivity: The spontaneous decay of certain unstable atomic nuclei.

radiogenic heat: Heat released inside Earth through the radioactive decay of isotopes of potassium, uranium, and thorium; it is responsible for powering mantle convection and plate tectonics.

radiometric dating: The process of calculating the absolute ages of rocks and minerals by counting the atoms of radioactive isotopes and their byproducts.

rheology: The study of the deformation and flow of matter.

Ring of Fire: An extensive zone of volcanic and seismic activity that coincides roughly with the borders of the Pacific Ocean and is due to the large numbers of subduction zones present there.

rock cycle: The interrelated sequence of events by which rocks are initially formed, altered, destroyed, and reformed as a result of magmatism, crystallization, erosion, sedimentation, metamorphism, and melting.

sediment: Loose particles—created by the weathering and erosion of rock, chemical precipitation from aqueous solution, or from secretions of organisms—which are transported by water, wind, or ice.

sedimentary rock: Rock formed from the lithification of sediment that has been eroded, transported, deposited, compacted, and cemented.

seismic tomography: A method of imaging Earth's interior through the analysis of the paths of seismic waves from earthquakes recorded on seismometers around the world.

shield volcano: A broad, gently sloping volcano built from successive flows of fluid basaltic lavas.

silicate mineral: A mineral formed from the bonding together of silicon/oxygen tetrahedra, usually in combination with other elements. Most minerals, and therefore most rocks, are silicates.

slab pull: The force of gravity acting upon the sheet of subducting oceanic lithosphere, which is the dominant force driving the particular motions of plate tectonics.

solidus: The temperature, at a particular pressure corresponding to a depth within Earth, at which a mineral begins to melt.

stratosphere: The layer of the atmosphere above the troposphere that contains the ozone layer.

stratovolcano: A volcano composed of both lava flows and ashfalls; also called a composite cone volcano.

supercontinent: A continental land mass containing most if not all of the continents; there have been several over the course of Earth's history.

supernova: An exploding star of intense brightness; it is during this final phase of a star's lifetime that elements heavier than hydrogen and helium are formed.

troposphere: The lowermost layer of the atmosphere, which contains Earth's clouds and weather.

unconformity: A boundary within rock layers that represents a break in the rock record, caused by the erosion or the lack of deposition of rock.

volcanic island arc: A chain of volcanic islands generally located about 100 kilometers above a subducting slab of oceanic lithosphere; the magma forms from the entry of subducted ocean water into the mantle.

water cycle: The constant movement of water among the oceans, atmosphere, geosphere, and biosphere.

water table: The upper boundary of the saturated zone of groundwater.

weathering: The disintegration and decomposition of rock at or near Earth's surface.

Wilson cycle: The repeating process, first identified by J. Tuzo Wilson, by which oceans open and close, and supercontinents form and break apart.

Biographical Notes

Louis Agassiz (1807–1873): Swiss-American zoologist and geologist best known for discovering the existence of previous Ice Ages. Trained first as a medical doctor, Agassiz learned zoology from Cuvier and geology from von Humboldt and made great contributions in both areas. Most of Agassiz's career was spent studying fish, but he also spent time studying the glaciers of Switzerland and later figured out that all places that showed evidence of large amounts of loose, unsorted glacial debris had once been under ice (as Greenland was currently). Agassiz later came to America as a professor at Harvard and was revered for many years as America's greatest scientist. Agassiz was one of the last prominent zoologists to reject Darwin and his ideas on evolution, based on religions grounds. He also believed that blacks were inferior to whites, which was used by slave owners as a justification for slavery.

Georgius Agricola (1494–1555): German scientist who laid the foundation of mining and mineralogy through the publication of several famous books. He spent much of his life as a physician but was attracted to geology and laid the foundations for physical geology in 1544 with the book *De Ortu et Causis Subterraneorum*. This was followed in rapid succession over the next six years with books that defined and described the discovery of minerals and ores. His most famous book, *De re Metallica*, set the standards for mining and metallurgy for the next several centuries. It was so popular that it was even republished in 1912 in *Mining Magazine* with an English translation by the American mining engineer Herbert Hoover (better known as the 31st president of the United States!) and his wife, Lou Hoover.

Svante Arrhenius (1859–1927): Swedish chemist who is one of the founders of the field of physical chemistry, which governs the way chemical reactions occur. He was the first to quantify the amount of heat that was needed to be added to chemical materials for a reaction to occur, called the activation energy; the equation describing this relationship is called the Arrhenius equation in his honor. After receiving a Nobel Prize for his physical chemistry work, Arrhenius turned his attention to geology, making contributions to the fields of astronomy, astrophysics, and cosmology. His most significant geological contribution, however, was in predicting the "greenhouse effect" that would be caused by the increased production of carbon dioxide. Arrhenius predicted that a doubling of atmospheric carbon would increase global temperatures by 5°C–6°C, which is remarkably close to recent estimates by the IPCC of 2°C–4.5°C. Because he thought that warmer climates would mean better agriculture, however, he advocated increased CO_2 production.

A. Francis Birch (1903–1992): American geophysicist who intimately understood geophysics at both large scales (seismic waves, mantle structure) and small scales (atomic interactions), and combined both into the first accurate assessment of Earth's interior composition. Birch used observations of seismic wave velocities and laboratory experiments on minerals to approximate the compositions of the mantle and core. He figured out how to extrapolate surface measurements to deep-Earth conditions and how to identify minerals by their seismic properties. Though considered a serious man, Birch allowed himself a bit of humor in a now-famous footnote to his epic (both in importance and length) 1952 paper *Elasticity and Constitution of the Earth's Interior*, where he provided the following sagacious warning to all who study Earth's interior:

> Unwary readers should take warning that ordinary language undergoes modification to a high-pressure form when applied to the interior of the Earth. A few examples of equivalents follow:

High Pressure Form	*Ordinary Meaning*
Certain	Dubious
Undoubtedly	Perhaps
Positive proof	Vague suggestion
Unanswerable argument	Trivial objection
Pure iron	Uncertain mixture of all the elements

Wallace Broecker (b. 1931): American geochemist who laid the foundation for future research in the connections between oceans and climate and the cycling of carbon between different reservoirs. He revealed the intricacies between different environmental systems and used radioisotopes to examine climate change records. Broecker is best known for showing the significant role that ocean circulation plays in changing atmospheric climate and causing abrupt climate change. His research has established the standards for chemical oceanography.

Thomas Burnet (1635–1715): English theologian, cosmogonist, and Royal Chaplain to King William III who published his speculative account of the past formation and future of Earth in the *Telluris Theoria Sacra*, or *Sacred Theory of the Earth*. In it, he described how Earth began as a homogeneous sphere, became layered (the middle layer being water), broken (with the water coming to the surface as Noah's flood), and will eventually become a star during Armageddon. The broken outlines of the continents, he asserted, were the result of Noah's catastrophe. This model was almost entirely based upon Christian theological grounds. Although Burnet dabbled at science (he made sounding measurements of shallow ocean regions to try to estimate the amount of water on Earth), the book is written in a scientific style. Burnet was skeptical in his religion, however, and was forced to leave his court position when he suggested, in the 1692 book *Archaeologiae Philosophicae*, that the six days of Genesis and the Fall of Man were symbolic rather than literal events.

Georges Cuvier (1769–1832): French naturalist and zoologist. No person knew more about animals in his era than Cuvier did, and this had good and bad consequences. Because of Cuvier's reputation and stature (he managed to maintain his position as top scientist in France before, during, and after Napoleon's rule), he was able to gain acceptance of his revolutionary view that most fossils were the remains of organisms that had since gone extinct. Before then, people thought that God would not allow any of his creatures to go extinct, so animals found only as fossils must still be living somewhere around the globe. Cuvier's establishment of extinctions thus set the stage for geologists to determine relative ages of rocks based upon index fossils. Cuvier became a champion of catastrophist theories, proposing that extinct animals must have died in a set of catastrophic events. Catastrophism fell out of favor with the public acclaim of Hutton and Lyell, but, interestingly, with the 20th-century discovery of mass extinctions, Cuvier's views on Catastrophism have been seen in a more positive light. Where Cuvier's influence did harm, however, was in his rejection of the theory of the gradual evolution of species. So sure was Cuvier of the sudden extinction of species that he ridiculed ideas of gradual evolution, and this kept many biologists from considering the ideas of evolution until Darwin published *Origin of the Species* decades after Cuvier's death.

James Dwight Dana (1813–1895): An American, Dana was the most esteemed geologist in the last half of the 19th century, making important contributions concerning volcanoes, mountain-building, and the structure and origin of continents. He was an expert on California geology and provided a great deal of information for would-be gold miners during and after the 1849 Gold Rush. He succeeded the esteemed Professor Benjamin Silliman (who was the first person to distill petroleum) on the geology faculty at Yale University, going so far as to marry his daughter. Dana was an influential writer, and his textbooks on mineralogy are still in use and have been the definitive texts for centuries: *System of Mineralogy*, first written in 1837, had its 8th edition published in 1997, and *Manual of Mineralogy*, first written in 1848, had its 22nd edition published in 2002.

Charles Darwin (1809–1882): English naturalist who was the most influential scientist of the 19th century; his 1859 book *On the Origin of Species* is one of the most influential books ever written. Darwin did not invent the ideas of evolution, which had been around for a while and furthered by scientists like Jean-Baptiste Lamarck, but developed them into a remarkably coherent science. Because of criticism of evolutionary ideas, Darwin waited two decades to publish *On the Origin of Species.* He did so only when Alfred Russel Wallace had arrived at a similar theory and the two published their ideas together in 1858. Darwin was heavily influenced by the Uniformitarian ideas of Lyell as well as his own geologic and paleontologic discoveries as a ship naturalist on the five-year voyage of the HMS *Beagle*. Darwin actually made several important geologic discoveries himself, including the origin of coral atolls, which he published in *The Voyage of the Beagle*. Darwin's theories on evolution and natural selection attracted as much controversy then as they do now but were quickly accepted by the entire scientific community, and he was awarded the Copley Medal of the Royal Society of London in 1864. His ideas were so well thought out that common views of the mechanisms of natural selection have changed only slightly over the past 150 years.

Adam Dziewonski (b. 1936): Polish-American seismologist who was one of the most influential geophysicists in modern times. Dziewonski was one of the founders of the field of seismic tomography, which is the primary means of visualizing the interior of Earth. He showed that subducted lithosphere sank to the base of the mantle and was part of a mantle-wide convection cycle. Dziewonski also pioneered the global categorization of the magnitudes and geographical orientations of all large earthquakes, which has been the foundation for studying and understanding the regional tectonics and interactions between tectonic plates. In 1981, together with Don Anderson, Dziewonski created the best model of Earth's interior, PREM (Preliminary Reference Earth Model). Incorporating many different kinds of data, PREM quantified the density and seismic velocities at all depths within Earth, and—although more than 25 years old—is still the leading global vertical model of the planet's interior.

Walter Elsasser (1904–1991): German-American physicist considered to be the father of geodynamo theory. Elsasser explained how Earth's magnetic field was generated by eddy currents within the liquid iron outer core. Much of his work was done during and after World War II, partly in his spare time while working with the U.S. Signal Corps. Elsasser was a brilliant physicist who came close to winning the Nobel Prize twice; two of his lines of research, concerning the wave aspect of electrons and the binding energies of protons and neutrons in heavy radioactive nuclei, were carried further by other researchers who later received the Nobel Prize.

W. Maurice Ewing (1906–1974): American geophysicist and oceanographer who was one of the most influential investigators of the structure of the ocean and ocean crust, leading more than 50 oceanic expeditions. He is best known for discovering the SOFAR channel, a shallow ocean layer that efficiently carries sound throughout the oceans, and the Mid-Atlantic Rift Zone, which he discovered in 1953 with Bruce Heezen. Ewing was the founder and first director of the Lamont-Doherty Earth Observatory at Columbia University, one of the leading programs of ocean investigations.

Benjamin Franklin (1706–1790): American statesman, inventor, scientist, publisher, and writer who—in addition to everything else this amazing man did—was a pioneer in meteorology and climate change. Franklin showed that lightning was natural electricity and published many other observations of atmospheric phenomena including storms and waterspouts. In 1768 he made the first map of the Gulf Stream. He came remarkably close to predicting plate tectonics, nearly 200 years in advance, when he wrote in 1782 that "The crust of the Earth must be a shell floating on a fluid interior.... Thus the surface of the globe would be capable of being broken and distorted by the violent movements of the fluids on which it rested." In addition, Franklin observed the correlation between eruptions in Iceland in the mid-1780s and the cold weather that followed in the succeeding years. This led to his founding the field of climate change as a result of volcanic eruptions.

Galileo Galileii (1564–1642): Italian physicist who is the "father of modern astronomy" and the first to use a telescope to make inferences about the nature of the solar system. As a result of his discovery that there were four moons that orbited Jupiter, Galileo determined that Earth and the rest of the planets must be orbiting the much larger sun. Galileo used telescopes for many other studies, including charting sunspots, measuring the heights of mountains on the moon, and determining that the Milky Way was not a cloud but a mass of distant stars. Galileo also made tremendous contributions to physics and mathematics and was called the "father of modern science" by Albert Einstein.

Stephen Jay Gould (1942–2002): American paleontologist, evolutionary biologist, and historian of science who, through his colorful and clever essays that ran monthly for years in *Natural History* magazine, taught countless millions of people about paleontology, geology, and evolution. As a scientist, Gould made great contributions in the area of evolutionary biology, advocating the rapid emergence of new species through a process he called "punctuated equilibrium." It was through his writings, collected into many popular books, however, that he was best known, and for many years he was one of the most vocal and staunchest advocates for evolution and the scientific method. Gould was also a renowned baseball fan and was featured in the famous Ken Burns documentary, *Baseball*.

Beno Gutenberg (1889–1960): A German-American seismologist, Gutenberg was born and went to school in Germany and began his career as a professor there. Due to growing anti-Semitic sentiments, however, he was not able to continue his work in Germany and came to America in 1930 where, together with colleague Charles Richter, he turned the California Institute of Technology into the world's leading seismological research institute. Gutenberg was a pioneer in the field of using seismic waves to determine the structure of Earth's interior. The core-mantle boundary, which he was the first to accurately locate, is still often referred to as the Gutenberg discontinuity. Gutenberg also worked with Richter in developing the first earthquake magnitude scales, and together they also developed the Gutenberg-Richter law, which established the probability distribution of earthquakes at different energy levels.

Edmund Halley (1656–1742): English astronomer, geophysicist, mathematician, meteorologist, and physicist, who is best known for the comet named in his honor (because he predicted the year of its next return to the inner solar system). He also made contributions in a wide variety of other earth and planetary sciences. He published works about trade winds and monsoons and was the first to identify solar heating as the cause of atmospheric convection and to document the correlation between barometric pressure and the height of the sea surface. He invented a diving bell and explored the bottom of the Thames River. He even spent two years sailing in the Atlantic Ocean, documenting variations in Earth's magnetic field. One idea he got very wrong was his proposition that Earth was partially hollow, consisting of internal concentric shells separated by atmospheres. This incorrect hypothesis persisted for years and appeared in stories like Jules Verne's *Journey to the Center of the Earth* and Edgar Rice Burroughs's *Tarzan at the Earth's Core*.

Harry Hess (1906–1969): Sometimes chance plays an important role in scientific discovery. American geologist Harry Hess's research was interrupted by World War II, where he served as the captain of the USS *Cape Johnson*; the transport ship, however, was equipped with newly-developed sonar equipment, and Hess used it to map out uncharted regions of the ocean seafloor. He returned to Princeton University after the war and developed his ideas, making some of the most important observations that led to the theory of plate tectonics. His 1962 paper "History of Ocean Basins," which described how ocean seafloor moved away from mid-ocean ridges toward ocean trenches, was for a while the single most cited reference in solid Earth geophysics. Hess made many other discoveries of the ocean seafloor, including the flat-topped underwater seamounts he called guyots, which proved that ocean seafloor sank with age (because the seamounts were once above-surface islands, which is when the tops were eroded and flattened).

Arthur Holmes (1890–1965): British geologist who was involved with the two greatest geologic controversies of his time—he not only made great contributions to them but proved to be right on both counts! Holmes began using radiometric dating of rocks while an undergraduate in 1910 and made the first uranium-lead calculations (on a 370-million-year-old rock from Norway). He strongly advocated an age of Earth in the range of billions of years, decades before such ideas were widely accepted; in fact, his estimate of Earth's age of 4.5 billion years was remarkably close to being correct. Even more importantly, however, Holmes was one of the strongest advocates for continental drift at a time when the idea was widely dismissed. Holmes demonstrated that though the mantle was solid rock it should still be convecting, providing the means of moving continents laterally across Earth's surface.

Alexander von Humboldt (1769–1859): Prussian naturalist and explorer who, like some other geniuses of previous centuries, made significant contributions to many scientific fields; he made the most impact in essentially starting the field of biogeography. Von Humboldt made a long expeditionary journey to South and Central America between 1799 and 1804 and made many important discoveries about the dependence of life upon the physical environments within which it exists. Von Humboldt also made important observations about Earth's magnetic field, meteorology, and the composition of the atmosphere, and even concluded, correctly, that South America and Africa had once been connected.

James Hutton (1726–1797): Few individuals did more to single-handedly change the view of Earth than this Scottish geologist who has aptly been referred to as the "father of modern geology" on many occasions. Hutton determined that Earth's interior was hot, and that this heat converted layers of sedimentary rock into new rock, presenting the first reasonable assessment of the rock cycle. He was the founder of a new school of thought called Plutonism, which described Earth's surface as being subjected to cycles of erosion, deposition, and lithification, creating layers upon layers of rock such as his now-famous "Hutton's unconformity" in Jedburgh, Scotland; this view overturned the Neptunist views presented by Abraham Werner. In addition, Hutton demonstrated that Earth must be very old, and initiated the school of thought called Uniformitarianism. This view ran counter to the biblically based ideas of Catastrophism, which advocated an Earth only thousands of years old. Hutton's big problem was that he was a terrible writer and very verbose; *An Investigation of the Principles of Knowledge and of the Progress of Reason, from Sense to Science and Philosophy,* was 2,138 pages long, so his ideas did not take hold until later, when they were put forth by more literarily capable champions like Charles Lyell.

Thomas Huxley (1825–1895): English biologist who often appeared in the shadow of his friend and colleague, Charles Darwin (and has been referred to as "Darwin's Bulldog"), Huxley was a brilliant anatomist and contributor to the ideas of evolution in his own right. He was initially skeptical about some of Darwin's ideas, such as natural selection and gradual evolution, but became one of Darwin's most powerful advocates and supporters. Huxley himself, an expert on vertebrate anatomy, proposed that humans and apes were similar enough to have a common ancestor and also demonstrated in 1870 that birds had evolved from dinosaurs, which was an idea that did not gain acceptance until 100 years later. Huxley was also vocal on the inadequacy of using religious ideas as the basis of scientific discovery and coined the term "Agnosticism" to describe his own beliefs.

Harold Jeffreys (1891–1989): English mathematician, geophysicist, and astronomer who made contributions to the understanding of Earth's deep interior. His study of seismology helped prove in 1926 that Earth's outer core was liquid. In 1940, Jeffreys, along with geophysicist Keith Bullen, presented a remarkably accurate depth profile of the seismic characteristics of Earth from the surface to the center. Given that they had limited seismic coverage of Earth's surface and no computers to work with, it was an impressive feat. For more than 40 years this "Jeffreys-Bullen model" remained the definitive description of Earth's interior. Despite his deep insights into math and geophysics, however, Jeffreys never accepted the theory of plate tectonics and was an opponent of it until his death.

William Kaula (1926–2000): American geophysicist who made fundamental contributions to two different fields: satellite-based geodesy and comparative planetology. His geodetic work began in the military when he realized that satellites could be used for measuring Earth's surface as well as tracking missiles. His work was vital to the eventual development of the Global Positioning System (GPS) network. Kaula applied the new possibilities of geodesy to satellite studies of other planets and provided the basis for much of our understanding of how planets form and evolve over time.

Wladimir Köppen (1846–1940): Russian-German geographer, meteorologist, climatologist, and botanist. Publishing more than 500 papers in many different fields, Köppen was one of the last of the broad-discipline scientists who made contributions in many different areas. Köppen is best known for his establishment of a classification of climates (the Köppen Classification) which is still used today. He spent a good deal of his career refining this classification but also did important work with his son-in-law Alfred Wegener in providing crucial evidence to support the Milankovitch theory of the cause of Ice Ages.

Inge Lehmann (1888–1993): Danish seismologist who, in 1936, cleverly demonstrated that Earth had a solid iron inner core using seismic P waves that traveled through the inner core, 30 years before seismologic studies that used modern seismographs. Lehmann made contributions to seismology for many decades but did not overstate her findings; her seminal 1936 paper on the inner core was titled *P′* (the name of the seismic phase used in the findings).

Mikhail Vasilievich Lomonosov (1711–1765): Russian scientist and writer whose legendary activities span nearly all areas of human activity and research. One of the most accomplished individuals of the 18th century, his research provided groundwork in the fields of thermodynamics, gravity, the wave property of light, material phase properties, and the theory of gases. He observed Venus's atmosphere, explained the formation of icebergs, determined the organic origin of coal and petroleum, and cataloged more than 3,000 minerals. In addition, he reformed the Russian language, wrote poems, and was an artist who set up the first stained-glass mosaics outside of Italy.

Charles Lyell (1797–1875): The histories of Lyell and James Hutton are forever interlinked. A Scottish geologist, Lyell made significant contributions to the field. He was an excellent writer, however, and his textbooks *Principles of Geology* (1830) and *Elements of Geology* (1838) were the most widely read and influential books on geology in the 19th century. It was in this role of educator that Lyell became an advocate for the earlier work of Hutton and a champion of the philosophy of Uniformitarianism. Lyell wrote that "the present is the key to the past," meaning that the geologic processes that have shaped our world are the same ones in operation today; this suggested that Earth was immensely old. Lyell was also a friend of Charles Darwin and a supporter of his theories on evolution.

Milutin Milankovitch (1879–1958): Serbian civil engineer and geophysicist who, though hindered by both world wars, managed to discover and publicize the connection between fluctuations in Earth's orbital parameters (orbit ellipticity, axis tilt, and axis precession), the distribution of solar radiation, and global climates—providing the explanation for why the recent Ice Ages had occurred. This work was preceded by his computation of the first accurate curve of solar insolation on Earth's surface.

W. Jason Morgan (b. 1935): An American geophysicist, Morgan was a young professor at Princeton University when he published one of the most influential papers ever in the history of earth science: the 1968 paper "Rises, Trenches, Great Faults, and Crustal Blocks," which established the fundamentals of the theory of plate tectonics. The evidence supporting plate tectonics had been around for many years, but it took a totally new way of thinking to put the pieces together, and Morgan was the one to do it (along with Dan McKenzie, working independently in England). Morgan went on a few years later to further the ideas of J. Tuzo Wilson about mantle hot spot plumes, thus providing the means of determining the directions and velocities of the moving tectonic plates. Morgan did not write many papers over his career, but many of the ones he wrote were very influential, and most of Earth science of the past 40 years is built upon his 1968 paper.

Hans Oeschger (1927–1998): German climatologist who revolutionized our ability to document climate change and was one of the first scientists to prove the correlation between temperatures and carbon dioxide concentrations in the atmosphere. Oeschger developed a way to use radioactive isotopes to determine the ages of water in the deep parts of the oceans, quantifying the rates of ocean circulation. He then applied his methods to glacial ice and was able to document atmospheric compositions going back 150,000 years. He found that carbon dioxide levels were 50% lower during Ice Ages than they currently are.

Roger Revelle (1909–1991): American oceanographer who was instrumental in understanding the connection between the compositions of the ocean and the atmosphere. He showed that the oceans would not be able to absorb carbon dioxide at the rate that it was being added to the atmosphere from anthropogenic sources. He was one of the first scientists to accurately quantify increasing atmospheric CO_2 levels and show how the "greenhouse effect" was leading to global warming.

Charles Richter (1900–1985): Before this American seismologist began his studies of the sizes and energies of seismic waves, there was no accurate way to assess the magnitudes of earthquakes. In 1935, working with fellow CalTech professor Beno Gutenberg, Richter developed a logarithmic scale that incorporated both the amplitudes of waves on seismograms with the distance from the earthquake in order to provide an accurate measure of the size of an earthquake. Richter and Gutenberg later went on to relate these earthquake magnitudes to the actual levels of energy released. Richter also published the first major textbook on seismology, *Elementary Seismology*.

A. E. Ringwood (1930–1993): Australian geologist who had an uncanny ability to interpret the composition of Earth's deep mantle based upon a small number of very difficult high-pressure mineral physics experiments. Ringwood was the first person to accurately determine the composition of the mantle, demonstrating how olivine and pyroxene undergo mineral phase changes at depths of 410 and 660 kilometers. He accurately predicted that the upper and lower mantles had mostly the same composition, with most differences in behavior due to the different phases at different pressures. Ringwood was also one of the first people to understand the effects of mantle composition on plate tectonics and the subduction of slabs of ocean lithosphere.

William Smith (1769–1839): English geologist who invented the geologic map through his creation the first geologic map of England. Smith noticed that layers of rock could be identified over large distances and used color coding to map them across the country. Smith also developed the principle of faunal succession, which allowed him to use different fossils as identifying markers for different strata. Unfortunately for Smith—who began his career as a poor surveyor's assistant—his work was never accepted or appreciated by the upper-class geologic establishment and was often plagiarized; he died in debtor's prison.

Nicolaus Steno (Niels Steensen) (1638–1686): Danish anatomist and geologist who established the fundamental principles of stratigraphy, which may seem obvious to us now but were breakthroughs in understanding geology. These fundamentals were the law of superposition (younger layers are deposited on top of older layers), the principle of original horizontality (layers are initially deposited as horizontal sheets), the principle of lateral continuity (layers extend over broad areas), and the principle of cross-cutting (a layer cutting across another layer must be younger). Steno was also one of the earliest paleontologists, observing the similarities between fossils and living organisms.

Harold Urey (1893–1981): An American physical chemist, Urey began his career working with Niels Bohr on atomic structure, receiving a Nobel Prize for his discovery of deuterium. He went on, however, to establish the field of cosmochemistry and made groundbreaking discoveries about the early composition of Earth and the solar system. Urey made the first estimates of the composition of Earth's early atmosphere and with one of his graduate students, Stanley Miller, made inspiring experiments that showed that amino acids, the building blocks of life, would naturally form from simple components. Urey was also a leader in the Manhattan Project during World War II, creating the fissionable uranium-235 used for the nuclear bombs.

James Van Allen (1914–2006): American space scientist who was the pioneer of space physics, using satellites and balloons to increase the world's knowledge of energetic particles, plasmas, and radio waves throughout the solar system. Van Allen began his career with the military and was instrumental in getting satellites up into space, playing a key role in the Cold War space race. After the war, Van Allen and his research program made groundbreaking observations of the upper atmospheres of Earth, Venus, Mars, Jupiter, Saturn, Uranus, and Neptune. Earth's high-atmosphere Van Allen Radiation Belts are named after him.

Charles Walcott (1850–1927): An esteemed American paleontologist who is best known for his discovery of the Cambrian fossils of the Burgess Shale in Alberta, Canada. Walcott had specialized in Cambrian period fossils and identified the most important fossil find in history, revealing the sudden explosion of life forms that occurred 540 million years ago. Walcott was also one of the most influential scientific leaders in the country, directing, at different times, the United States Geologic Survey, the American

Association for the Advancement of Science, and the Smithsonian Institution, as well as helping to found the Carnegie Institute of Washington.

Alfred Russel Wallace (1823–1913): English naturalist, explorer, geographer, anthropologist, and biologist who co-developed the ideas of natural selection, simultaneously and in competition, with Charles Darwin. Wallace was a world expert on the distribution of species in different geographic regions and is considered the "father of bioecology." He was a developer of the ideas of evolution, and also pioneered several environmental fields such as concerns over human impacts on environments, deforestation, and the invasion of foreign species. Public opinion of Wallace was mixed, largely because of his support of several pseudo-spiritual movements such as phrenology and mesmerism, but he is now recognized as one of the most influential scientists establishing the connection between evolution and geographic environments.

Alfred Wegener (1880–1930): A meteorologist, Wegener was trained in astronomy and did most of his research in meteorology, but is known as the author of the theory of continental drift. Wegener traveled on expeditions to Greenland and pioneered the use of balloons to track atmospheric air currents, but became fascinated by the geologic and geographic evidence that the continents were once connected. He put forth his ideas in 1912 and published them in 1915 as *The Origin of Continents and Oceans*. Partly because of his lack of background in geology and partly because the mechanisms he proposed for the continental motions were preposterously unreasonable, his ideas were never broadly accepted within the scientific community. He was right, of course: The continents *do* move and *were* once connected in a supercontinent that he named Pangaea, but only a handful of prominent scientists during his day had the insight and bravery to publicly support him.

Abraham Werner (1749–1817): A German geologist, Werner did not publish much but was renowned as a brilliant teacher and took on a large following of supporters. Werner became the champion of a philosophy of Earth's formation called Neptunism, whereby all of Earth's surface rocks precipitated out of a giant ocean that once entirely covered Earth's surface. This form of Catastrophism, with Earth's rocks forming quickly out of a single geologic event, was in direct conflict with the Uniformitarianism of Hutton and Lyell. Werner received support from biblical supporters because they reconciled his giant ocean with Noah's flood. Werner was not able to reconcile the many inconsistencies of his theory (such as how volcanic rocks like basalt formed) and it eventually fell out of favor, but he was the most influential geologist of his day.

J. Tuzo Wilson (1908–1993): A Canadian geophysicist who, except for the vagaries of publishing, might well be credited as the discoverer of plate tectonics. Several years before Morgan and McKenzie are credited with establishing plate tectonics, J. Tuzo Wilson described how the lithosphere moved over a weaker asthenosphere, and how the Hawaiian Islands formed when the Pacific Plate moved over a mantle hot spot. He also was the first person to accurately describe the mechanisms of transform faults like the San Andreas Fault. Paper reviewers, however, rejected his ideas, and he ended up publishing in a Canadian journal with a small circulation. The Wilson cycle, which describes the process by which oceans open and close over long periods due to plate motions, is named after him.

Bibliography

Alley, Richard. *The Two-Mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future*. Princeton: Princeton University Press, 2002. Ice cores have provided some of the best records of climate change, and a pioneer in the field explains the science behind them and their implications for future climates.

Atwater, Brian. *The Orphan Tsunami of 1700.* Seattle: University of Washington Press, 2005. A description of the stunning discovery of the enormous magnitude 9.0 earthquake that occurred in the Pacific Northwest in 1700.

Aubrecht, Gordon. *Energy: Physical, Environmental and Social Impact*. Boston: Benjamin Cummings, 2005. An excellent text that describes the wide variety of energy sources, including their trends, long-term prospects, and resource supplies.

Benn, Douglas I., and David Evans. *Glaciers and Glaciation.* London: Edward Arnold Publishers, 1998. A premier guide on glaciology, this book looks at the geology and physics of glaciers, the flow of ice, and the erosion that results.

Berner, Elizabeth K., and Robert Berner, *Global Environment: Water, Air, and Geochemical Cycles***.** Upper Saddle River, NJ: Prentice Hall, 1996. Requiring some basic understanding of chemistry, this book provides a good overview of global geochemistry and environmental problems and establishes the fundamental concepts of geology, biogeochemistry, oceanography, meteorology, and limnology.

Bjornerud, Marcia. *Reading the Rocks: The Autobiography of the Earth*. New York: Westview Press, 2005. A nicely written overview of the earth, from its formation to projections of its future.

Bolt, Bruce. *Earthquakes.* New York: W. H. Freeman & Company, 2003. The classic standard introductory discussion of earthquakes and seismology.

Bowen, Mark. *Thin Ice: Unlocking the Secrets of Climate in the World's Highest Mountains*. New York: Holt Paperbacks, 2006. Scientist and expert climber Mark Bowen joins climatologist Lonnie Thompson and his crew on the highest and most remote glaciers along the equator to study the history of climate change.

Breining, Greg. *Super Volcano: The Ticking Time Bomb Beneath Yellowstone National Park*. Osceola, WI: Voyageur Press, 2007. An examination of the volcanic hazard posed by the Yellowstone hot spot that describes the possible results of another enormous eruption in this region.

Bridgeman, Howard A. *Global Climate System*. Cambridge: Cambridge University Press, 2006. A valuable assessment of the world's climate diversity, with each chapter containing an essay by a specialist in that field.

Broecker, Wallace. "Glaciers that Speak in Tongues and Other Tales of Global Warming." *Natural History*, 110 (October 2001): 60–70. One of the world's most influential climatologists gives his account of the climate change and the science behind it.

Brown, Geoffrey C., and Alan Mussett. *The Inaccessible Earth*. London: Chapman and Hall, 1993. An advanced college text that sets the standard for discussions on the composition of Earth's crust and mantle.

Brumbaugh, David. *Earthquakes, Science and Society.* Upper Saddle River, NJ: Prentice Hall, 1998. A very nice and concise overview of the many impacts of earthquakes on humanity.

Bryson, Bill. *A Short History of Nearly Everything.* New York: Broadway Books, 2004. Imagine trying to describe the history of the universe and its discovery (incorporating physics, chemistry, biology, and geology) with engaging and casual prose and succeeding—that is this book.

Bullard, Fred Mason. *Volcanoes of the Earth*. Austin: University of Texas Press, May 1984. This book traces the growth of volcanology with discussions of geothermal energy, the environmental effect of volcanoes on climate, air and soil pollution, and the cyclic nature of volcanic eruptions.

Calvino, Italo. *Cosmicomics.* Orlando, FL: Harvest Books, 1976. A brilliant work of fiction that provides incredible insights to what it might have been like to exist through the creation and formation of our universe. (The essay "All at One Point," which describes hypothetical "life" before the Big Bang in 0 dimensions, is my favorite!)

Carson, Rachel. *The Sea Around Us.* New York: Oxford University, 1951. One of the most influential and widely-read books in the history of science. It is beautifully and simply written.

Clarke, Robin, and Jannet King, *The Atlas of Water: Mapping the World's Most Critical Resource*. New York: New Press, 2004. A good account of the many complex issues surrounding one of Earth's most important and threatened natural resources.

Cone, Joseph. *Fire Under the Sea*. New York: Quill/William Morrow, 1992. The story of the discovery of volcanoes and thermal vents at mid-ocean ridges, and the strange environments that they support.

Cousteau, Jacques-Yves. *The Silent World*. New York: Harper and Row, 1953. The famous memoir by one of the most influential explorers of the unusual worlds beneath the ocean surface.

Cox, John D. *Climate Crash.* Washington, D.C.: Joseph Henry Publisher, 2005. An excellent presentation in very readable language of the many aspects of the complex systems of climate change and the implications for humanity.

Davidson, Jon P., Walter Reed, and Paul Davis. *Exploring Earth: An Introduction to Physical Geology, 2nd ed.,* Upper Saddle River, NJ: Prentice Hall, 2002. An introductory college physical geology text that does a very good job at showing the different components of the rock cycle from a process-oriented viewpoint.

Davies, Geoffrey F. *Dynamic Earth: Plates, Plumes and Mantle Convection*, Cambridge: Cambridge University Press, 1999. An advanced, but mostly qualitative, discussion of the dynamics of mantle convection by one of its founding discoverers.

Davies, Paul. *The Goldilocks Enigma: Why Is the Universe Just Right for Life?* Boston: Mariner Books, 2008. An entertaining book on the multiverse and other surprising theories put forth to answer the question of existence, offering both descriptions of the science behind the theories and the philosophical implications.

De Boer, Jelle Zeilinga, and Donald Sanders. *Earthquakes in Human History*. Princeton, NJ: Princeton University Press, 2004. A good overview of the societal effects of many large historical earthquakes.

———. *Volcanoes in Human History*. Princeton, NJ: Princeton University Press, 2004. Volcanoes have had significant effects on global climates, and the accounts of many such eruptions are presented here.

Decker, Robert, and Barbara Decker. *Volcanoes, 4th ed*. New York: W. H. Freeman, 2005. The classic introductory text to volcanoes and volcanology, widely used in introductory classes throughout the country.

———. *Volcanoes in America's National Parks*. New York: Odyssey Publications, 2001. This book not only talks about the volcanoes that are part of 31 different national parks and monuments but gives travel information on how to actually go and see them for yourselves.

Deffeys, Kenneth. *Beyond Oil: The View from Hubbert's Peak*. New York: Hill and Wang, 2006. An influential assessment by an authoritative geologist on the production futures of petroleum and the implications for the future of energy use.

Diamond, Jared. *Collapse: How Societies Choose to Fail or Succeed*. New York: Penguin, 2005. A dense comparative study of societies that have sometimes fatally undermined their own ecological foundations.

———. *Guns, Germs, and Steel: The Fates of Human Societies*. New York: W. W. Norton & Company, 1999. A brilliant treatise, a bit wordy at times, on the influence of geography and geology on the course of human civilization.

Dietrich, Richard V., and Brian Skinner, *Rocks and Rock Minerals*. New York: John Wiley & Sons, 1979. A visually appealing guide to rocks, explaining the different ways that they form and giving many attractive examples of them.

Emanuel, Kerry. *Divine Wind: The History and Science of Hurricanes*. New York: Oxford University Press, 2005. A good description of heavy weather and storms, including accounts of many important and significant historic hurricanes.

Emiliani, Cesare. *Planet Earth: Cosmology, Geology, and the Evolution of Life and Environment*. Cambridge: Cambridge University Press, 2007. A good overview of the integrated physical and geological systems operating on our planet.

Ferris, Timothy. *The Whole Shebang: A State-of-the-Universe Report*. New York: Simon and Schuster, 1997. Ferris is one of the country's leading science writers, and here he explains the evolution of the universe in a very readable and accessible way.

Fisher, Richard V., Grant Heiken, and Jeffrey Hulen, *Volcanoes: Crucibles of Change*. Princeton, NJ: Princeton University Press, 1998. A description of the different kinds of volcanoes that are found around the world, including firsthand accounts of many eruptions.

Flannery, Tim. *The Weather Makers: How Man Is Changing the Climate and What It Means for Life on Earth.* New York: Grove/Atlantic, 2007. An up-to-date presentation of the ways that human activity continues to alter global climates, including predictions of different possible scenarios for the future.

Flavin, Christopher., and Nicholas Lenssen. *Power Surge: Guide to the Coming Energy Revolution.* New York: W. W. Norton, 1994. A thorough assessment by the Worldwatch Institute on the future potentials of renewable energy sources such as solar energy, wind energy, and biomass energy.

Fortey, Richard. *Earth: An Intimate History*. New York: Knopf, 2004. An elegant account by the renowned paleontologist of the history of plate motions and interactions, including discussions of the pioneers of geology who made these discoveries.

Fradkin, Philip L., *Magnitude 8: Earthquakes and Life Along the San Andreas Fault.* New York: Henry Holt & Company, 1998. A personal and historical account of the San Andreas Fault, combining the science of the fault with the history of the region.

Gillieson, David. *Caves: Processes, Development, Management*. Oxford: Blackwell Publishers, 1996. A discussion of cave evolution and development, emphasizing the delicate nature of cave ecosystems.

Gore, Al. *Earth in the Balance: Ecology and the Human Spirit*. New York: The Penguin Group, 1993. An early call of warning about the future directions of climate change, this book contains an excellent survey of the past effects of climate change on human history.

———. *An Inconvenient Truth.* New York: Rodale Books, 2006. A beautiful combination of photos, figures, and text that is based upon the excellent and influential movie of the same name.

Goudie, Andrew S. *Great Warm Deserts of the World*. New York: Oxford University Press, 2003. An account, region by region, of the world's great warm deserts, describing the geologic and climatic forces that have created them.

Gould, Stephen J. *Time's Arrow, Time's Cycle.* Cambridge, MA: Harvard University Press, 1988. A fascinating examination of the different perceptions of time and the age of Earth, particularly showing the changing and competing views of geologists.

Gross, M. Grant, and Elizabeth Gross. *Oceanography: A View of the Earth*. Upper Saddle River, NJ: Prentice Hall, 1995. A popular introductory text to oceans' complex systems and their impact on our lives and futures.

Gurnis, Michael. "Sculpting the Earth from Inside Out." *Scientific American*, (March 2001): 40–47. One of the world's top geodynamicists explains for a lay audience the connections between mantle convection and tectonic plate motions.

Hambrey, Michael, and Jurg Alean. *Glaciers*. Cambridge: Cambridge University Press, 2004. A nice montage of glaciers, with different themes related to glaciers presented along with the authors' own photographs.

Harris, Stephen L. *Fire Mountains of the West: The Cascade and Mono Lake Volcanoes.* Missoula, MT: Mountain Press Publishing Company,

1988. A great review of the many volcanoes of the Pacific Northwest and an assessment of their eruptive potential.

Hawking, Stephen. *A Brief History of Time.* Toronto: Bantam Books, 1988. The classic discussion of how our universe formed that set the standard for all other discussions of cosmology.

Hinrichs, Roger A., and Merlin Kleinbach. *Energy, its Use and the Environment*. Burgin, KY: Thomson Brooks/Cole Florence, 2005. A well-written college-level text on the many different issues related to energy use from a variety of different sources.

Hoffman, Paul F., and Daniel Schrag, "Snowball Earth." *Scientific American*, 282 (January 2000): 68–75. A description of one of the most fascinating and controversial theories in climate history: the idea that Earth went through a period of repeated deep-freezes that even caused the surfaces of the oceans to freeze.

Hough, Susan. *Earthshaking Science*. Princeton, NJ: Princeton University Press, 2004. An excellently written assessment of earthquake hazards and how they are determined.

Jacobson, Michael, Robert Charlson, Henning Rodhe, and Gordon Oriens. *Earth System Science From Biogeochemical Cycles to Global Changes.* New York: Academic Press, 2000. Earth systems science is the approach to earth science that emerged in the 1990s as an integrated, process-oriented means of study; this book explains how it works and how humans are interconnected with it.

Karato, Shun-Ichiro. *The Dynamic Structure of the Deep Earth.* Princeton, NJ: Princeton University Press, 2003. If you want to dig deeply, this advanced text by one of the world's leading experts provides descriptions of how and why Earth deforms.

Kasting, James F. "The Origins of Water on Earth." *Scientific American* 13.3 (2003): 28–33. An excellent assessment of where our water came from, where it is, and where it is going.

Keary, Philip, and Fred Vine. *Global Tectonics*. Oxford: Blackwell Scientific, 1990. A classic text that focuses on the way the ocean seafloor reveals the motions of the plates.

Keller, Edward A., and Robert Blodgett. *Natural Hazards: Earth's Processes as Hazards, Disasters, and Catastrophes*. Upper Saddle River, NJ: Prentice Hall, 2005. A very good overview of the many and varied types of natural disasters.

Keller, Edward A., and Nicholas Pinter, *Active Tectonics*. Upper Saddle River, NJ: Prentice Hall, 1995. A well-written discussion of folding and faulting and their relationships to plate tectonics, earthquakes, and mountain building.

Kuhn, Thomas S. *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press, 1970. This landmark text on the philosophy of science highlights plate tectonics as an ideal example of a scientific paradigm shift in understanding.

Logan, William B. *Dirt*. New York: W. W. Norton and Company, 2006. A very personal and elegantly written account of a topic (soil) that does not often get a lot of respect.

Longview Publishing Company Staff. *Volcano, The Eruption of Mount St. Helens*. Seattle: Madrona Publishing, 1980. Excellent work by the Pulitzer Prize winning staff of *The Daily News* (Longview, Washington) with the assistance of the *Journal American* staff (Bellevue, Washington).

Lopes, Rosaly. *The Volcano Adventure Guide*. Cambridge: Cambridge University Press, 2005. This book is designed to prepare people to visit a volcano, giving logistical information on visiting 42 different volcanoes.

Macdougall, Douglas. *Frozen Earth: The Once and Future Story of Ice Ages.* San Diego: University of California Press, 2004. An exciting description of the last Ice Age and the significant ways it affected human and other biological life as it melted and receded.

McGregor, Glenn, and Simon Nieuwolt. *Tropical Climatology: An Introduction to the Climates of the Low Latitudes*. New York: John Wiley & Sons, 1998. This book provides a geographical view of physical process in the tropical atmosphere, offers explanations of how a location's climate is a product of these processes, and highlights the implications of tropical atmosphere behavior and climate change.

McPhee, John. *Assembling California*. New York: Farrar, Straus and Giroux, 1994. An intelligent discussion of the complex geologic history of California. Do not miss the stunning final chapter, which traces the damage of the advancing seismic waves from the 1989 Loma Prieta earthquake second by second.

———. "Atchafalaya" in *The Control of Nature*. New York: Farrar, Straus and Giroux, 1989: 3–92. A startling account of the magnitude of the task involved with keeping the Mississippi River in its course and of the inevitability of its eventual escape.

———. *Basin and Range*. New York: Farrar, Straus and Giroux, 1981. The classic story of how the West was formed, both geologically and culturally.

———. "Cooling the Lava" in *The Control of Nature*. New York: Farrar, Straus and Giroux, 1989: 95–179. An elegantly written account of the attempts to stop the flow of lava at two hot spot locations: Iceland and Hawaii.

———. "Los Angeles Against the Mountains" in *The Control of Nature*. New York: Farrar, Straus and Giroux, 1989: 183–272. A fun and entertaining account of Los Angeles' attempts to control the debris flows that continue to damage houses built upon the slopes of the San Gabriel Mountains.

———. *Rising from the Plains*. New York: Farrar, Straus and Giroux, 1986. An engrossing account of the geology of Wyoming, based upon a drive across the state, that weaves in the history of the settlement of this region.

Menard, H. William. *The Ocean of Truth.* Princeton, NJ: Princeton University Press, 1986. A retelling of the discovery of plate tectonics through seafloor observations by one of the early discoverers that makes you feel like you were right there as it happened.

Miller, Russell. *Continents in Collision*. Alexandria, VA: Time-Life Books, 1983. A nicely illustrated popular book that provides the fundamentals of plate tectonics.

Mithen, Steven. *After the Ice: A Global Human History 20,000–5000 BC*. Cambridge, MA: Harvard University Press, 2006. Reading at times like a time-travel novel, this fascinating portrayal of the end of the Ice Ages provides a wonderful sense of what the world was like as the ice was melting and civilization was starting.

Moran, Joseph, and Michael Morgan. *Meteorology: The Atmosphere and the Science of Weathering*. Upper Saddle River, NJ: Prentice Hall, 1996. An introductory text on the atmospheric aspects of environmental concerns with the basics of meteorology and climatology.

Morrison, David, and Tobias Owen. *The Planetary System*. San Francisco: Benjamin Cummings, 2002. A widely used general text on planetary astronomy that includes perspectives on the study of the origin, evolution, and distribution of life within our solar system and other planetary systems.

National Research Council Committee on the Alaska Earthquake. *The Great Alaska Earthquake of 1964*. Washington, DC: National Academy of

Sciences, 1973. Accounts and descriptions of the largest earthquake known to have occurred in the United States.

Nicolas, Adolphe. *The Mid-Oceanic Ridges: Mountains Below Sea Level*, Berlin: Springer Verlag, 1995. A good college-level text on the structure and dynamics of the divergent boundaries between plates.

Officer, Charles B., and Jake Page. *Tales of the Earth*. New York: Oxford University Press, 1994. A nice selection of essays by a geophysicist (Officer) and a science writer (Page) that highlight some of the most interesting stories about the impact of geology on humanity.

Oldroyd, David. *Thinking about the Earth: A History of Ideas in Geology.* Cambridge, MA: Harvard University Press, 1996. A comprehensive overview of how people from ancient times to the present have tried to understand Earth.

Palin, Michael. *Himalaya*. London: Weidenfeld Nicolson Illustrated, 2004. Based on the BBC television series, this gives a wonderful account of a six-month trek around the Himalayan mountain range.

Pearce, Fred. *Deep Jungle*. Cornwall, England: Eden Books, 2005. A fascinating account of jungles, from their early exploration to modern scientific assessments of their diversity and complexity.

Pellant, Helen, ed. *Rocks and Minerals*. New York: DK Publishing, 2002. An attractive presentation of the many and varied types of minerals.

Pimm, Stuart. *The World According to Pimm: A Scientist Audits the Earth*. New York: McGraw-Hill, 2001. An assessment of human impact on Earth's surface, maintaining a sense of optimism in the face of often disturbing data.

Post, Austin, and Edward R. Lachapelle. *Glacier Ice*. Toronto: University of Toronto Press, 2000. The book features aerial and land-based photographs of North American glaciers, with an introductory explanation of glaciology.

Powell, James L. *Grand Canyon: Solving the Earth's Grandest Puzzle*. New York: Pi Press, 2005. An account of the geology of the world's most dramatic stream-erosional feature: the Grand Canyon.

Prager, Ellen, and Sylvia Earle. *The Oceans.* New York: McGraw-Hill, 2001. A wonderful account of the oceans, written to be both entertaining and educational.

Pugh, David. *Changing Sea Levels*. Cambridge: Cambridge University Press, 2004. A thorough discussion of the changes in sea level over short and long time scales, their effects on local geology and biology, and their implications for human society.

Robinson, Kim Stanley. *Red Mars*. New York: Bantam Spectra, 1993. (Also *Green Mars* and *Blue Mars*.) Science fiction, but you would not know it—this trilogy predicts a possible colonization of Mars in remarkably believable ways.

Rosenfeld, Charles, and Robert Cooke. *Earthfire: The Eruption of Mount St. Helens***.** Cambridge, MA: MIT Press, 1982. A description of the events of the violent 1980 eruption, connecting them with the geologic processes that caused it.

Savoy, Lauret E., Eldridge Moores, and Judith Moores, ed. *Bedrock: Writers on the Wonders of Geology*. San Antonio, TX: Trinity University Press, 2006. A fascinating collection of writings, both fiction and non-fiction, that deal with the many aspects of geology.

Schopf, J. William. *Cradle of Life.* Princeton, NJ: Princeton University Press, 2001. A firsthand account of the discovery of some of Earth's earliest fossils and a discussion of what the implications are for the evolution of life in the universe.

Sigurdsson, Haraldur. *Encyclopedia of Volcanoes*.: San Diego, CA: Elsevier Science and Technology Books, 1999. Everything that you ever wanted to know about volcanoes, with plenty of opportunity to ask in these 1,359 pages!

———. *Melting the Earth*. New York: Oxford University Press, 2006. A well-written account of the history of volcanology, showing how our perceptions of melting, magma, and volcanoes have changed over time.

Smith, Keith, and Roy Ward. *Floods: Physical Processes and Human Impacts*. New York: John Wiley & Sons, 1998. A good overview of floods and their impacts, hazards, and assessments, using case examples from historic floods.

Sobel, Dava. *The Planets*. New York: Penguin Books, 2006. A graceful and elegant discussion of the solar system that weaves the science together with popular culture, mythology, and science fiction.

Stacey, Frank D. *Physics of the Earth*, 3rd ed. Brisbane, Australia: Brookfield Press, 1997. Required reading for all geophysicists, this book provides tremendous insights but requires a good foundation in math and physics.

Stein, Seth, and Michael Wysession. *Introduction to Seismology, Earthquakes, and Earth Structure.* Oxford: Blackwell Scientific, 2003. The leading upper-level undergraduate and beginning graduate-level text on earthquakes and seismic waves. It provides the means of imaging our planet's interior, just in case you want to dig deeper.

Sullivan, Walter. *Continents in Motion*. New York: McGraw-Hill, 1974. Walter was the long-time editor of the New York Times' *Science Times*; here he presents the discovery of plate tectonics as it passed across his desk.

Tarbuck, Edward J., and Fred Lutgens. *The Atmosphere: An Introduction to Meteorology*, *10th ed*. Upper Saddle River, NJ: Prentice Hall, 2007. An excellent, solidly written college textbook on weather and the atmosphere.

———. *Earth: An Introduction to Physical Geology*, *9th ed.*, Upper Saddle River, NJ: Prentice Hall, 2008. The most widely used college introductory geology textbook: solid, straightforward, well-written, up-to-date, and with excellent illustrations.

Trujillo, Alan P., and Harold Thurman. *Essentials of Oceanography*, *9th ed*. Upper Saddle River, NJ: Prentice Hall, 2008. An excellent college-level textbook that provides the fundamentals of the study of the oceans.

Tyson, Neil deGrasse. *Death by Black Hole: And Other Cosmic Quandaries.* New York: Norton, 2007. An excellently written collection of essays on cosmology from the world's best-known current spokesman for astronomy and astrophysics.

Uyeda, Seiya. *The New View of the Earth.* New York: W.H. Freeman & Company, 1995. A famous text that gives a very insightful description of the how and why of plate tectonics.

Van Andel, Tjeerd H. *New Views on an Old Planet: Continental Drift and the History of the Earth.* Cambridge: Cambridge University Press, 1994. A classic book, widely read, that weaves together the evolution of the planet, the history of the oceans and atmosphere, and the evolution of life.

Vogel, Shawna. *Naked Earth.* New York: Dutton Adult, 1995. An excellent science writer describes the modern understanding of Earth's interior in highly readable and accessible text.

Vonnegut, Kurt. *Cat's Cradle*. New York: Dell, 1971. A fictional account of the end of the world where a high-pressure form of water ("Ice 9") plays a pivotal role.

Walker, Gabrielle. *An Ocean of Air*. Orlando, FL: Harcourt, 2007. An entertaining account of the scientific study of our atmosphere and the air it contains.

Ward, Peter, and Donald Brownlee. *Rare Earth*. New York: Springer-Verlag, 2003. An extremely influential book that demonstrated that the conditions required for continuous and stable life on the surface of a planet (needed for the evolution of complex life forms) may be exceedingly rare, and that there might not be many planets like Earth in our galaxy.

Webb, Stephen. *If the Universe Is Teeming with Aliens … Where Is Everybody?: Fifty Solutions to the Fermi Paradox and the Problem of Extraterrestrial Life*. New York: Copernicus Books, 2002. Fifty different possible solutions to Fermi's Paradox (Fermi is claimed to have asked, following a discussion of phenomena like flying saucers in 1950, "Where is everybody?"), including the author's favorite—that life may be ubiquitous throughout the galaxy, but the conditions required for the evolution of complex life might be extremely rare.

Westbroek, Peter. *Life as a Geological Force: Dynamics of the Earth*. New York: W. W. Norton & Co., 1992. An interesting presentation of the ways that the geosphere and biosphere are interrelated, each significantly altering the other.

Winchester, Simon. *A Crack in the Edge of the World: America and the Great California Earthquake of 1906*. New York: Harper Collins, 2005. A thorough account of the great earthquake of 1906 and the geology of California and the San Andreas Fault.

———. *Krakatoa*. New York: Harper Perennial, 2005. A detailed description of the geology of Indonesia and the historical events concerning the great eruption of 1883.

Yergin, Daniel. *The Prize: The Epic Quest for Oil, Money and Power*. New York: Simon & Schuster, 1993. The well-known energy consultant provides his assessment of the political, economic, cultural, and environmental issues surrounding petroleum as an energy source.

Zigler, Alan. *Hawaiian Natural History, Ecology, and Evolution*. Honolulu: University of Hawaii Press, 2002. This book traces (with words and pictures) the natural history of Hawaii through such topics as island formation, plant and animal evolution, and the effects of humans and exotic animals on the environment.

Recommended Websites:

http://www.nasa.gov/. The website for NASA (National Aeronautics and Space Administration) has an enormous amount of information, including photographs from every single NASA mission. There are great educational materials and lots of features and stories, but you will be amazed by the number of pictures all those NASA satellites, rovers, and astronauts have taken over the years!

http://www.noaa.gov/. The website of the National Oceanic and Atmospheric Administration (NOAA) is the place to go for all things related to the oceans and atmospheres. As well as having feature stories and materials for teachers, it has an up-to-date weather watch that graphically displays all the problematic weather-related events around the world (e.g., floods, hurricanes, droughts, and forest fires).

http://www.usgs.gov/. The website of the United States Geologic Survey (USGS) has a tremendous amount of information in the areas of geology, geography, hydrology, and biology. It has maps, educational activities, regional science topics, earth science trivia, and a regularly updated natural hazards section that describes the latest earthquakes and volcanoes.