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The World's Greatest Geological Wonders: 36 Spectacular Sites

Course Guidebook

Professor Michael E. Wysession
Washington University in St. Louis

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Corporate Headquarters
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Michael E. Wysession, Ph.D.

Associate Professor of Earth
and Planetary Sciences
Washington University in St. Louis

Michael E. Wysession is Associate Professor of Earth and Planetary Sciences at Washington University in St. Louis. Professor Wysession earned his Sc.B. from Brown University and his Ph.D. from Northwestern University, both in Geophysics.

An established leader in seismology and geophysical education, Professor Wysession is noted for his development of new ways to show how seismic waves propagate through the Earth and the use of these waves to create three-dimensional images of Earth's interior. These images have provided scientists with insights into the makeup of Earth and its evolution throughout history.

Professor Wysession is an author or editor of more than 20 science textbooks, ranging from elementary to graduate school levels. He is chair of the National Science Foundation's Earth Science Literacy Initiative and has represented the earth and space sciences in the creation of the new National Science Education Standards by the National Research Council and Achieve, Inc.

Professor Wysession received a Science and Engineering Fellowship from The David and Lucile Packard Foundation, a National Science Foundation Presidential Faculty Fellowship, and fellowships from the James S. Kemper and Lilly foundations. He has received the Innovation Award given by the Academy of Science of St. Louis and the Distinguished Faculty Award given by Washington University. Professor Wysession has had distinguished lectureships with the Incorporated Research Institutions for Seismology/Seismological Society of America and the National Association of Geoscience Teachers.

Professor Wysession also has taught *How the Earth Works* for The Great Courses. ■

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The World's Greatest Geological Wonders: 36 Spectacular Sites

Scope:

This course takes you to the world's most spectacular geological wonders, explains the forces that have formed them, and tells you the stories that have grown up around them. Our planet remains unique in the galaxy, even after space investigations have found many hundreds of other planets around other stars. Earth is covered with a vast diversity of geological environments that have, for millennia, inspired people with their majesty, beauty, and sometimes their strangeness. Yet certain places stand out above the others and epitomize the different types of amazing geologic phenomena that are found on Earth. These are the geologic wonders of the world, and in 36 lectures, we will travel to and investigate as many of them as we can. Each of the lectures focuses on one particular geographical location but touches on other examples, as well. Some of these wonders are well known, and you may already have traveled to them. Others you may never have heard of but will likely want to visit once you have learned of them.

There is no agreed-upon list of the 30 or 40 top geological wonders of the world, the way there was once a list of the Seven Ancient Wonders of the World. There is not even a single set of criteria by which to obtain such a list. If you asked 100 different geoscientists, you would undoubtedly get 100 different lists. Each lecture in this course is devoted to a particular geologic formation or process; the lecture then explores those wonders that most epitomize that topic. For instance, in the lecture on waterfalls, we will visit the Iguazu Falls in Argentina as the most spectacular example of these formations on Earth. Each lecture also highlights the remaining wonders that might appear on a "best of" list. For waterfalls, that list would include Victoria Falls, Angel Falls, and Niagara Falls. In addition, we will dedicate one lecture to an array of unique and unusual wonders (a "rogue's gallery" of sorts) that don't warrant a full lecture but deserve mention. Some of the geologic wonders we'll explore are obvious choices because of their sheer size and spectacle, such as the Grand Canyon or the Himalayas. Others, such as the Blue Hole off the coast of Belize, are chosen because they are perfect examples of a given topic in geology (in this case, sinkholes).

The goal of this course is to heighten your sense of wonder, awe, and respect for our planet. Many people find mountains aesthetically beautiful, but when you learn about their half-billion-year history, their formation through multiple collisions of ancient continents, and their experience of powerful erosion by glaciation, you begin to see something more than just a pretty vista. You view the surface of a mountain as a great battlefield—the site of a clash between Earth's internal forces pushing up the mountain and the Sun-driven forces of erosion relentlessly tearing it down. Rather than diminish their beauty, this added knowledge makes the mountain even more beautiful. The more you know and understand the natural world, the greater will be your love and appreciation for it. As you watch these lectures, you will begin to notice countless new features of the geologic world around you, and your growing interest and fascination will add a new dimension to your appreciation for the world in which you live. ■

Santorini—Impact of Volcanic Eruptions

Lecture 1

In this course, we will travel around the Earth to visit some of our planet's most spectacular geologic wonders. Our premise is that when you look at something with added knowledge about it, it becomes more interesting. Consider a picture of a mountain. It may be beautiful, but it's just another mountain if you don't know its history. However, once you understand its formation in the crucible of a massive collision between ancient continents, you begin to see that mountain with the eyes of a geologist, and it evokes a deeper response. The goal of this course is to help you develop that understanding and a sense of wonder when you look at the spectacular world that has formed around us.

Introduction to the Course

- Let's begin with a definition of the word "wonder" in the phrase "geologic wonder." We'll use this word to mean something that stands apart from the things we normally see in our daily lives, something that is often rare or, at least, infrequent. A geologic wonder is something that creates a lasting impression. It's more than just beautiful; it makes us curious about its origins or formation.

- How can we choose these geologic wonders? In this course, we'll devote just one or two lectures to each type of geologic feature or phenomenon, such as waterfalls, glaciers, and so on. Although each lecture discusses a specific location, at the end of each lecture, we'll also look at additional sites that fall into the same category.

- Another motivation for this course is for us to develop a respect and appreciation for our incredible planet. We as humans are intimately connected with the Earth in all ways. We get our resources from it; we're affected by natural hazards; and now, with more than 7 billion humans on the planet, we have become the greatest geologic force on Earth's surface. We actually affect Earth's systems sometimes more than other geologic forces. We need to learn our strength and be mindful of it.

- The geologic wonders we'll see have also been chosen because they tell interesting stories, and stories are one of the best ways that human beings learn. We'll begin with the story of the eruption of a volcano on the island of Santorini in Greece.

The Island of Santorini

- Santorini is located among the Cyclades islands in the Aegean Sea in the eastern Mediterranean. Some 4000 years ago, this region was ruled by the Minoan civilization on Crete. The largest city outside of the mainland of Crete was Akrotiri, which was on the south side of the small island of Thira, now called Santorini.

- Santorini was born as a volcano several million years ago, and in the time since, it has gone through several cycles in which a volcanic cone builds up and then explodes away violently, ejecting much of the interior rock of the island. Following these large eruptions, the magma underneath drains back downward into the Earth, which causes the bottom of the volcano to collapse and adds to the formation of a caldera. A caldera is usually formed when the bottom of a volcano has dropped out because of the draining of the magma, and it results in a large empty area in the middle.

- On Santorini, this cycle happened about 21,000 years ago. A large eruption occurred then that would have blown out much of the interior and given the island its ring shape. It stayed that way until roughly 3600 years ago, when there was the most recent large eruption. At that time, a cataclysmic explosion would have thrown ash and rock throughout the Mediterranean area and would have blown away much of the north side of the island.

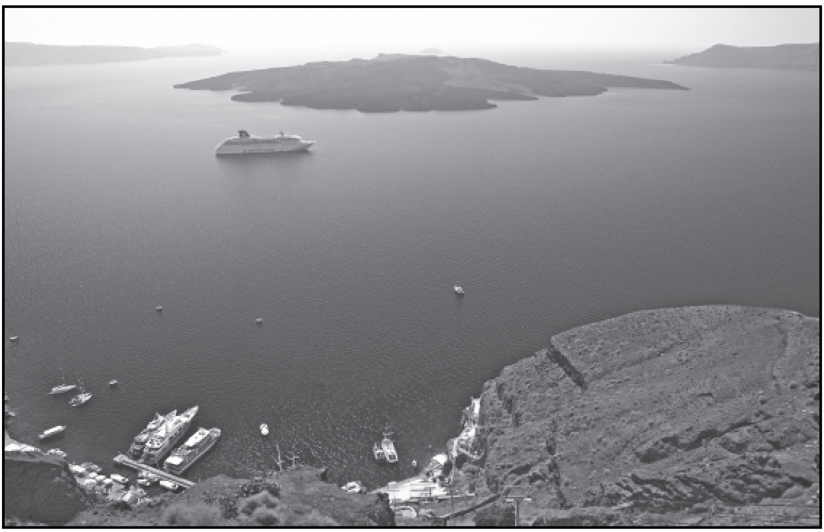
- If you visit Santorini now, you'll notice that there is a small island in the middle of the ring. This island is being formed by the buildup of magma. It may eventually become another large volcano that will once again go through this cycle.

- The walls of the caldera are beautiful. They are filled with alternating layers of red, white, and orange ash and lava that have come out over time in the process of building up this volcano. The geologic record from Santorini tells a particularly remarkable story for the eruption that occurred in about 1628 B.C.E., a date derived from climate records around the globe.

Ancient Destruction

- Geologic excavations on Santorini have revealed a thin layer of ash from around 1628 B.C.E. with footprints in it, covered by about 200 feet of volcanic ash. The blast at that time ejected about 60 cubic kilometers of shattered rock and ash—solid material called tephra.

- Akrotiri, which had been an advanced city, was destroyed, buried under 200 feet of ash. Remarkably, archaeologists have found no bodies from the time of the eruption, unlike excavations in Pompeii and Herculaneum, where casts of the bodies of more than 1000 people have been uncovered, buried by the eruption of Vesuvius in 79 C.E. It seems as though the people of Akrotiri had time to escape.



Visitors to Santorini by boat sail right into the caldera of a giant volcano.

- Interestingly, there is evidence at this time of widespread destruction throughout the Mediterranean but particularly in Crete. We find evidence of widespread fires and, perhaps, a large tsunami that was caused by the eruption.
    - Again, Santorini is very close to Crete, and the massive tsunami from this eruption would have been devastating to the seafaring culture of Crete. It may have wiped away the entire fleet on the north side of the island.

    - Although the Minoans rebuilt their cities, they seem to have been severely weakened, and within 100 to 150 years, they had been overrun by the Mycenaeans from what is now Greece.

    - Incidentally, the Mycenaeans took the Minoan language, known as Linear B. This became the first form of the Greek language, which then influenced many other languages. The predecessor to Linear B, Linear A, remains undeciphered; some of the remains at Santorini show inscriptions written in Linear A.

- More than 1000 years after the eruption, Plato wrote in his dialogues *Timaeus* and *Critias* of the destruction of Atlantis. According to Plato, "At a later time there occurred portentous earthquakes and floods, and one grievous day and night befell them, when the whole body of your warriors was swallowed up by the Earth, and the island of Atlantis in like manner was swallowed up by the sea and vanished." Some scholars think this refers to the eruption of Santorini and the destruction of the city of Akrotiri and much of Minoan culture.

- In its description of the Exodus, the Old Testament tells us that the Israelites followed a pillar of smoke by day and of fire by night, that darkness occurred during the day, debris fell from the sky, and the sea opened up, pulling back and rushing forward. This description sounds similar to a volcano and an associated tsunami, although the Exodus seems to have occurred later than the eruption on Santorini.

Causes of Volcanic Eruptions

- As most of us know, the Earth's surface is broken into pieces called tectonic plates; there are about a dozen large plates and another dozen or so minor plates. They form the lithosphere, the top 60 miles of the Earth's surface. When these pieces of the Earth either collide or pull apart and slide past each other, the result is exciting geology.

- The region where Santorini is located is in the boundary between the African and the Eurasian plates. Such a boundary is called a subduction zone; it works as follows: A portion of the ocean seafloor sinks beneath the edge of another plate, generating magma, which rises up to form a volcano. There are volcanoes throughout the Greek islands that have formed from this process of subduction.

- The tectonics of the region tells us why this is happening: The African Plate is rotating up into Eurasia. As part of that process, the Arabian Plate has actually broken away and is sliding northward, crashing into Eurasia. In response, the whole peninsula of what is now Turkey is being pushed westward and colliding into Greece, which pushes the whole region south, bringing it into contact with the African Plate, rising northward.

- Santorini and all the rest of the volcanoes in this region are the result of this tectonic collision between Africa and Eurasia. In the process, the Mediterranean Sea is being destroyed; if you were to come to this region in a few tens of millions of years, there will be nothing here. Africa will be directly connected with the rest of Eurasia.

- Santorini serves as a forcible and dramatic demonstration of the influence of Earth's geology on society. These Greek islands are beautiful, but they exist only because of the plate tectonics of the region: Africa crashing into Europe and closing up the Mediterranean. And the same forces that made these beautiful islands can also destroy them.

Top Volcanic Eruptions

- Mount Vesuvius in Italy represents the birth of modern geophysics because its eruption in 79 C.E. was described in great detail by Pliny the Younger. In fact, this kind of eruption, with ash being ejected tens of thousands of feet into the atmosphere, has come to be called a Plinian eruption in honor of his description.

- Mount Tambora, on the island of Sumbawa in Indonesia, had an enormous eruption in the year 1815. It ejected about 160 cubic kilometers of ash and rock and is, in fact, the largest eruption in recorded history. This eruption greatly changed the climate of the world, blocking out sunlight and causing a drop in global temperatures.

- Krakatau is also in Indonesia, but it exists as a lone island between Sumatra and Java. This volcano is actually in the process of filling in the space between the islands and will eventually connect them. The massive eruption of Krakatau in 1883 caused the largest tsunami in the Indian Ocean until the earthquake in Sumatra in 2004. The island of Krakatau has a similar appearance to Santorini and is, in fact, undergoing a similar cycle of building up a cone and then blowing it out.

- The volcano Laki in Iceland had an extended eruption that began in 1783. This eruption released an enormous amount of sulfur dioxide aerosols, causing another significant drop in temperature and crop failures in Europe.

Suggested Reading

Friedrich, *Santorini*.

Scarth and Tanguy, *Volcanoes of Europe*.

Questions to Consider

1. The Greek islands are currently the location of volcanoes. Given that Africa is rotating up into Europe at the rate of about a centimeter per year, what do you think will be in the location of Santorini in about 50 million years?

2. What is the difference between the processes by which the famous eruptions at Santorini and Vesuvius occurred? What were the results for the people living nearby?

Mount Fuji—Sleeping Power

Lecture 2

In the last lecture, we talked about the island of Santorini and its formation during a cataclysmic eruption 3,600 years ago that shaped the dynamics of the Mediterranean. In this lecture, we'll focus on volcanoes themselves, with a visit to Mount Fuji in Japan, also known as Fuji-san. Fuji's dimensions are impressive: It's more than 12,000 feet high, 78 miles in circumference around the base, and 25 to 30 miles in diameter. What makes Fuji remarkable is its nearly perfect cone shape.

Significance of Fuji in Japan

- Mount Fuji is a popular subject in Japanese art and landscape photography. Well-known artists, such as Hiroshige, Hokusai, and others, have made Fuji internationally recognizable.

- Fuji is also important for local religious reasons, as are many other geologic wonders around the world.
    - The Ainu people, early Aboriginal inhabitants of Japan, considered Fuji to be sacred.

    - For modern practitioners of the Shinto religion, Fuji is related to the goddess Sengen-sama, who is an embodiment of the spirit of nature. Fuji is also associated with the Shinto goddess Koyasu-sama, who is revered as a goddess of fertility. The Shinto Fujiko sect believes that the mountain itself is a sacred being with its own soul.

- The name Fuji comes from the name of the Buddhist fire goddess, Fuchi. According to the Buddhist tradition, Fuji rose from the Earth in 286 B.C.E. after a large earthquake. Buddhists revere the mountain as a gateway to the next world.

- Every summer, more than 200,000 pilgrims and tourists climb Mount Fuji. In fact, the ascent to the summit is an important religious pilgrimage. Ten religious stations are on the mountain—huts and shrines that offer places to rest.

Formation of Mount Fuji

- A map of the global distribution of volcanoes reveals an uneven distribution around the world. Notice that a number of volcanoes occur in the western Pacific, in the area around Japan. Another map of earthquakes around the world also shows an uneven distribution. Earthquakes tend to occur along linear trends and line up very much with volcanoes.

- A map of the tectonic plates shows that volcanoes and earthquakes occur almost entirely on the boundaries between plates. In other words, it's the interactions between plates that cause interesting geology.
    - o Scientists have created maps showing the locations of the plates hundreds of millions of years ago and are able to track how the continents have moved.

The interactions of the Earth's tectonic plates bring us interesting geology, such as the formation of the volcano Mount Fuji.

- We see how the continents were distributed 540 million years ago, when the supercontinent Rodinia had only recently broken apart. The eastern part of North America hadn't even formed at that time.

- About 270 million years ago, nearly all the continents came together to form the supercontinent Pangaea, but it began to break up about 200 million years ago.

- As we approach modern times, we have to realize that the story isn't over. If we run the clock forward 10 or 20 million years into the future, the plates will continue to move. The Atlantic Ocean will continue to open up, Africa will close up into Eurasia, and Australia will become a part of the Asian continent.

- In this context, it's important to note that many of the geologic wonders we'll look at in this course took a staggeringly long time to form—millions or even billions of years.

- Japan sits above a subduction zone, which is what generates its earthquakes. A subduction zone works as follows:
  - The ocean seafloor approaching the edge of a continent is much heavier and colder than the rock underneath it, and given the opportunity, it will sink down into the Earth.

  - Part of that subduction process results in earthquakes and volcanoes, where magma travels upward and reaches the surface as individual volcanoes. Rock is melting all along the subduction zone, but it tends to channel together into single conduits, the same way tributaries of a river come together to make a single trunk.

  - In this case, magma may come up all along the zone, but we end up with a few distinct volcanoes. Over time, volcanoes may pop up in numerous places; thus, we can view Japan as one massive connection of volcanoes that have erupted over tens of millions of years.

- Japan sits at the juncture of four tectonic plates: the Pacific, North American, Eurasian, and Philippine plates. Surprisingly, the north island of Japan is technically part of North America. This kind of convergence happens in only one other place in the world, on the other side of the Philippine Plate.

- A map of the bathymetry of Japan shows multiple subduction zones. We see the subduction zone of the Pacific Plate beneath the northern part of Japan, but it's also subducting beneath the Philippine Plate, which is subducting beneath Japan. This region is tectonically complex, resulting in tremendously complicated geology with active volcanoes and earthquakes.

Separation of Japan from Asia

- On a map of the bathymetry of the area around Japan, notice that the deepest parts of the ocean seafloor are not in the middle of the Pacific Ocean but right at the edges of the continents. These deep oceanic trenches are places where the Pacific Ocean seafloor is actually sinking down into the Earth. The deepest place anywhere around the world is just south of Japan, the Mariana Trench.

- Here, through the subduction process, Japan has been pulled away from the Asian continent. In other words, Japan was once connected to Asia. How can it happen that in a zone where the plates are colliding, Japan would be pulled away?

- As the Pacific Ocean seafloor is subducted, even though it bends and heads under Japan, the force of gravity is still pulling it downward. That creates a low-pressure zone right in the area of the trench with a suction force that actually pulls Japan toward it. The Japan Sea has opened up as this subduction suction process has pulled the whole island away from Asia.

The Puzzle of Melting Rock

- We know that the rock underneath Japan is hot, but it's not melting. How can it be, then, that the cold rock that has been sitting underneath the Pacific Ocean melts when it moves under Japan? We would think the opposite would take place. If we cool something off, it doesn't usually melt.

- At about 60 miles beneath Japan, the temperature is about 1500°C, or 3000°F. At the center of the Earth, the temperature is about 6000°C—more than 10,000°F. Why doesn't the rock underneath Japan melt? The answer is that intense pressure on top of the rock squeezes it down, holding it in place. If it were to melt, it would have to expand, but the pressure doesn't give it any room to expand into. For this reason, the rock of the mantle is entirely solid, even though it's quite hot.

- But when the ocean seafloor sinks under Japan, it brings both cold rock and water. Water has the property of allowing most things to melt more easily; thus, the hot rock underneath Japan that is normally solid melts with the addition of cold rock and water. The results are magma and volcanoes.

Fuji's Conical Shape

- Lava erupting out of the surface of the Earth results in broad, flat volcanoes, such as the shield volcanoes of Hawaii. Ash erupting out of the surface results in cone-shaped volcanoes, but ash volcanoes wash or erode away quickly. How do we build up a 15,000-foot-high cone-shaped volcano?

- Mount Fuji is called a stratovolcano. *Strato* comes from a Greek word meaning "layered," and these volcanoes actually build up from multiple layers of both ash and lava.
  - The type of eruption from a volcano—lava or ash—depends on a variety of factors, such as the amount of water in the magma, its composition, and temperature.

  - A good bit of water in the magma results in a very explosive eruption, such as those at Santorini. If the magma is too cold or there is too little water, it has a thick, sluggish consistency that can build up great pressure before it is released, also resulting in a large explosion.

    - If the magma is “just right,” the water inside it has a lubricating effect that causes it to flow out, covering layers of ash and building up a large stratovolcano cone.

Earthquakes in Japan

- The fact that Japan is in a zone where two plates are rubbing against each other also explains why it frequently experiences earthquakes. In fact, Japan is one of the most seismically active places in the world. In the earthquake that occurred there in March of 2011, a whole portion of the Pacific Ocean seafloor slid beneath the north island of Japan in a matter of minutes.

- Perhaps the worst hazard resulting from an earthquake is a tsunami, which can occur whenever there is a change in the elevation of the seafloor. Don’t think of a tsunami as a wave, which has a crest and a trough behind it. A tsunami is the equivalent of a new sea level in the minutes after it occurs.

- One region of Japan may yet experience something called the Tokai earthquake. The place where the Philippine Plate is subducting beneath Japan is called the Nankai Trough, and earthquakes there seem to occur in separate gaps—sometimes together, sometimes individually; a map shows four gaps that have ruptured as earthquakes in recent times. A fifth gap is directly beneath Tokyo, which may be the location for Japan’s next catastrophic earthquake.

Top Stratovolcanoes

- There are 1,500 active or potentially active aboveground volcanoes in the world; 700 of those are stratovolcanoes and are located around the Ring of Fire in the Pacific. The tremendous volcanic activity in the Ring of Fire is caused by the fact that the Pacific Ocean floor is sinking beneath continents almost all the way around the Pacific basin.

- Mount Rabaul, on the east end of New Britain in Papua New Guinea, is the other place on Earth where four major tectonic plates meet. This site has experienced significant eruptions over the past few thousand years.

- Mount Rainier, close to Seattle and Tacoma in the United States, it is considered to be one of the most dangerous volcanoes in the world.

- Cotopaxi and Chimborazo are both in the Andes in Ecuador and are both incredibly high in elevation. Cotopaxi has erupted more than 50 times since 1738. Chimborazo is more than 20,000 feet above sea level and is the farthest point on land anywhere from Earth's center.

Suggested Reading

Francis and Oppenheimer, *Volcanoes*.

O'Meara and Manning, *Volcano: A Visual Guide*.

Questions to Consider

1. What is the connection between the geologic setting of this lecture and the setting of the previous lecture?

2. If lava keeps coming out of such volcanoes as Mount Fuji, why don't they eventually become incredibly tall, like Mount Everest?

Galapagos Rift—Wonders of Mid-Ocean Ridges
Lecture 3

In the previous lecture, we saw the kind of feature that occurs at the boundary where tectonic plates collide: a subduction zone with giant volcanoes, where ocean seafloor is destroyed by sinking back down into the mantle. In this lecture, we'll look at the kinds of places where ocean seafloor is created—at mid-ocean ridges—starting in the spectacular Galapagos Islands. We'll also see some of the unfortunate effects that humans and human activities can have on the Earth's surface, including some of our geologic wonders.

Galapagos Islands

- If you start at the west coast of South America at about the equator and head straight west into the Pacific Ocean, after a stretch of empty ocean, you reach a cluster of islands. The largest of these, Isabela, is actually a combination of six separate volcanoes. Other islands in the cluster include Santa Cruz and Fernandina.

- The fact that islands exist in the middle of the Pacific Ocean is quite remarkable. The ocean here is very deep; thus, for even a small rock to poke out above the surface means that a very tall mountain must be under the water beneath it.

- The Galapagos Islands were discovered by accident in 1535 by Tomás de Berlanga, the bishop of Panama, aboard a Spanish ship. He and his crew stumbled upon the islands looking for food and water; unfortunately, they didn't find much of either. Berlanga named the island after the gigantic tortoises he saw there.

- The islands soon became a haven for English pirates, preying on Spanish ships in the Pacific. By the late 1700s, the pirates had been largely replaced by whalers. During the 1800s, whaling ships took as many as 200,000 of the giant tortoises for food and drove them to extinction on many of the islands. The whalers also introduced new species to the islands, such as goats; goat populations devastated native plants and assisted in driving the tortoises to extinction.

- Charles Darwin visited the Galapagos Islands in 1835 and immediately recognized their geologic wonder. Darwin had recently spent several years at Cambridge, studying with the famous geologist Charles Lyell, the father of modern geology. Of course, Darwin's geological observations have long since been overshadowed by his biological discoveries.

Volcanic Activity in the Galapagos

- The Galapagos Islands exist because of the presence of a hotspot within the mantle that causes magma to rise to the surface in the middle of a plate, not at a plate boundary.
  - o Hotspots are a controversial and much-debated topic in geology. They don't fit nicely into our model of plate tectonics,

Just to the north of the Galapagos Islands is a segment of the ocean ridge system, a network of ridges that reaches up into the Indian Ocean, connecting with the Red Sea and continuing out into both the Atlantic and the Pacific oceans.

which would have volcanoes occurring either at subduction zones, where plates come together, or as we will see, at ridges, where plates pull apart.

  - Hotspots result in volcanism in the middle of a plate, though it turns out that hotspots, such as those in the Galapagos and others we will see in Iceland, often occur near mid-ocean ridges.

- Many active volcanoes are present in the Galapagos, and some of them have unusual shapes, different than the cone-shaped stratovolcano we saw in Mount Fuji. Some of the volcanoes here look like upside-down soup bowls. It is, however, the proximity of the Galapagos Islands to a mid-ocean rift that enhances the volcanic activity of the islands.

- Just to the north of the Galapagos Islands is a segment of the ocean ridge system. The islands occur at the boundary between two plates: the Cocos Plate and the Nazca Plate, which are part of the Pacific seafloor. The Pacific seafloor is actually broken into several plates. Most of it is the large Pacific Plate, but these smaller plates, the Cocos and Nazca plates, are moving in the opposite direction from the Pacific Plate. They are subducting beneath Central America and South America, and that's the location of the Galapagos Ridge.

- The bathymetry around the Galapagos Islands shows an unusual pattern. Extending both eastward and northeastward from the Galapagos Islands are two underwater mountain ridges that seem to come together at the Galapagos. How could something like this form?
  - The Cocos Plate to the north and the Nazca Plate to the south are actually moving north and south, separating away from each other.

  - However, both of these plates are also moving eastward relative to the rock underneath, and the Galapagos Islands are adding volcanic material onto both of them. We have two ridges developing under the surface as a result of the volcanism there.

Mid-Ocean Ridges

- Mid-ocean ridges are factories for making ocean seafloor. Essentially, as plates move apart, a gap forms in between that is quickly filled by magma. If we drill down, the ocean seafloor looks the same everywhere: There is a layer of lava on top that erupts. There are often vertical sheets of lava that have squirted up in the gap between plates as they separate. And there is crystallized rock that develops underneath, called gabbro.

- A map of the ocean seafloor shows that the mid-ocean ridge system resembles the seams that encircle a baseball. The system is nearly 70,000 kilometers long, entirely connected, and runs through the Indian Ocean, the Atlantic Ocean, and the Pacific Ocean.

- Mid-ocean ridges are remarkable places. About 20 cubic kilometers of basaltic ocean crust comes out at ridges every year. As we saw in the last lecture, the deepest places in oceans—the mid-ocean trenches—are along the edges. Often, the most elevated places of the ocean seafloor are in the middle of the oceans; these are the mid-ocean ridges.

- When the Galapagos Rift began to be investigated, many puzzles emerged, one of which was that the temperature of the rock didn't seem to fit with scientists' idea of a mid-ocean ridge. The temperature of the rock as it moves away from the ridge should gradually drop, but it was found to be much cooler than expected.

- In 1977, a manned submersible named Alvin visited the area and made incredible discoveries. As the marine scientist Richard Lutz wrote, "Literally every organism that came up was something that was unknown to science up until that time. It made it terribly exciting. Anything that came up in that basket was a new discovery."
    - Thermal vents and all sorts of incredibly diverse, bizarre biological communities were found around the Galapagos Rift.

Since that time, similar communities have been found along other mid-ocean ridge segments.

- In this bizarre world are huge towers, like enormous chimneys—more than 50 feet high—belching large amounts of black water. The water is about 400°C and contains all sorts of minerals. The seafloor is covered by formations called pillow basalts and populated by strange creatures.

- The heat-flow problem is now understood. The heat from the magma chamber causes the surrounding water to expand and become more buoyant. It then rises up out of thermal vents. As the water heats up, it dissolves minerals and metals out of the rock, but the moment it hits the chilly temperatures of the ocean, the minerals and metals precipitate right back out, building up chimneys and depositing sediment along the ocean floor.

Significance of Mid-Ocean Ridges

- Mid-ocean ridges may represent the kind of place on Earth where life originated more than 3.5 billion years ago. At that time, there was no oxygen in the atmosphere and, thus, no ozone; the Earth's surface would have been an incredibly hostile environment. A region with available energy, food, and water that was far removed from the surface would have been more hospitable to life.

- We may eventually need the minerals that are coming out of these thermal vents. The estimated resource lifetimes for many minerals and metals are on the order of hundreds of years. For zinc, for example, the estimated lifetime is 200 years; for nickel, it's 100 years; and so on.
    - Mineral deposits are economically viable only if they are concentrated by natural geologic processes above a certain level. The plate tectonic process has been cooperative in concentrating these resources for us, and the mid-ocean ridges are among the places where these concentrations can be found.

- As minerals become increasingly expensive and we have to keep digging deeper to get them, it may one day be economically feasible to go down to these mid-ocean ridge thermal vents and vacuum the minerals up with large hoses.

Top Ophiolite Sites

- With the exception of a location in Iceland, the mid-ocean ridge chain is underwater. But if most of us can't go to the rifts, then there are at least some places where the rifts have come to us. For example, there are sequences of rock known as ophiolites. Essentially, these are bits of the ocean seafloor that have been thrust up on land during the collision between tectonic plates; these sequences show all the layers of the ocean crust.

- The Troodos Ophiolite from the island of Cyprus consists of former ocean seafloor from the Tethys Sea that was pushed up during the ongoing collision of Africa into Eurasia. The mountains there, the Troodos Mountains, are the largest mountain range in the area and have long been mined, particularly for copper. These mountains show the full sequence of ocean crust exposed along their sides; study of these mountains helped in the original discovery of the process of plate tectonics.

- The Semail Ophiolite is located along the Gulf of Oman, at the entrance of the Persian Gulf. This is also ocean crust pushed up onto land during the closing of the Tethys Sea about 70 million years ago.

- The Lizard Complex Ophiolite is found along the scenic rocky coast of Cornwall in southern England.

- Ophiolites in the beautiful Gros Morne National Park, in the Bay of Islands area of Newfoundland, are about 1.2 billion years old. These examples confirm that the process of making ocean plates has been the same for more than a billion years.

Suggested Reading

Condie, *Plate Tectonics*.

De Roy, *Galapagos*.

Questions to Consider

1. Life that exists at mid-ocean ridges rarely survives when it is brought up to the surface. Why do you think this might be?

2. The basaltic rock covering the surface at mid-ocean ridges is often in the form of pillowy shapes. Why don't we see these on the seafloor in older rocks, away from the ridge?

African Rift Valley—Cracks into the Earth

Lecture 4

In the last lecture, we visited the Galapagos Rift and looked at mid-ocean ridges. In this lecture, we'll go to Africa to look at rifting within continents and the process of ocean formation. In Tanzania, Kenya, and the surrounding countries, we are witnessing something that we don't see happening actively anywhere else on the surface of the planet, at least not to this degree: We're watching a continent splitting into pieces.

Kilimanjaro

- Kilimanjaro is the tallest mountain in Africa—almost 6 kilometers, or 20,000 feet, high. It is a massive stratovolcano with alternating layers of lava and ash. Kilimanjaro is currently dormant, but it could become active at any time. The last large eruption was 360,000 years ago, but there was volcanic activity as recently as 200 years ago, and geological investigations have found molten magma just 400 meters below the summit.

- Kilimanjaro is so tall compared to the surrounding planes that it acts as a sky island. It has climates that are not seen nearby and, therefore, unique environments for vegetation and animals. These environments are entirely cut off, and many endemic species are present that don't exist elsewhere. Even though it's near the equator, Kilimanjaro has snow and glaciers at its top all year long.

- Other stratovolcanoes we've seen, such as Fuji and Rainier, have been at well-established subduction zones. Given that there's no subduction zone in Tanzania, how did Kilimanjaro form? In fact, many other volcanoes are in the middle of the African continent. What's going on here?

The Splitting of a Continent

- As we discussed in Lecture 2, about 200 million years ago, the supercontinent Pangaea started to break up. In a sense, what we find in Africa is the continuing breakup of Pangaea. Africa used to include Arabia, but that broke away. The mainland of Africa is now splitting in two.

- The Arabian Peninsula fits nicely into the corner of Africa. Thirty million years ago, the Gulf of Aden and the Red Sea didn't exist. Africa was one large continent, but it began to experience volcanic activity, and about 12 million years ago, Arabia broke away enough that the Red Sea began to form as its own small ocean.

- That rifting has since continued in the south, with the Ethiopian Rift and the East African Rift system, with an eastern and a western arm. It's almost as if something is pushing these pieces of the continent apart.

- As you can imagine, rifting isn't easy; it's like trying to tear a rock in half. As a consequence, the rifts run crooked and break into several pieces. In fact, the rift system actually surrounds an independent piece of very ancient crust, the Tanzania Craton, which contains within it Lake Victoria.

- The reason for this rifting in Africa is not fully understood and is the subject of current debate in geology. The plates don't seem to be in the process of being pulled apart—there are no subduction zones anywhere along the sides of the plates—but it seems likely that this is happening.

- One bit of evidence of this plate movement is the presence of two large topographic domes, one around the Afar region of Ethiopia and another farther south, known as the Kenya dome. It looks as if these are being lifted up from below.
  - Geologists believe that a mantle hotspot underneath this region is physically pushing up the surface, with the presence of warm rock rising up underneath the plate.

  - Whether there is one hotspot or more has not been determined, but it is known that the presence of active volcanic rifts running through the continent must be somehow related to the deep Earth and gives rise to a variety of fascinating and dramatic features.

Landscape Features Caused by Volcanism

- The volcanism that occurs in Africa is an ocean crust–type, basalt volcanism, which is not normally found on a continent. That's a sign that the rift is on its way to becoming an ocean. Basaltic lava tends to be much more fluid than other kinds of lava and can spread across great distances.
  - In some cases, the lava forms rivers that may actually close over on the top. The result is long lava tubes that may extend great distances.
  - The longest lava tube in the world is in Kenya, the Leviathan lava tube, which is more than 9 kilometers long. The magma has drained out, and visitors can actually walk through this tunnel.

- The ash from volcanic eruptions in Africa makes it difficult for trees to grow and has allowed rich grasslands to develop. The volcanic areas of the African Rift system also produce hot springs, lava lakes, and other geologic features.

- The pulling apart of a continent results in landscape features called grabens, flat valleys separated by high ridges. In the case of the African Rift system, these valleys can sometimes be a mile below the surrounding highlands and run for hundreds or thousands of kilometers. This feature of the landscape is another sign that the continental region is being stretched apart.

- In some places, as in Kenya, we find multiple graben structures, alternating blocks that have dropped down and are surrounded by regions on either side that have lifted up. These grabens are often filled with water to make long lakes. Lake Tanganyika, for example, is the longest lake in the world; it fills in a huge part of the western rift valley for almost 700 kilometers.

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The Serengeti hosts the largest annual migration of mammals anywhere in the world, thanks to the volcanic ash that makes it difficult for trees to grow in the grasslands.

- Lake Kivu in the Congo in Rwanda is one of just three lakes in the world that is known to undergo catastrophic overturns due to the release of gases trapped within the water. The other two are also in Africa, on the west side in Cameroon, Lake Nyos and Lake Monoun.

- Because of volcanic activity under these lakes, carbon dioxide builds up within the lake waters. But the fact that the lakes are very salty keeps the water stratified; the surface and deep waters don’t mix, which allows the carbon dioxide buildup.

- Lake Kivu contains more than 250 cubic kilometers of dissolved carbon dioxide. Such concentrations are dangerous because carbon dioxide is heavier than air; if it is emitted, it stays low to the ground and can suffocate animals.

- In 1984, carbon dioxide erupted from Lake Monoun when its normally layered waters overturned. About 40 people died. In 1986, a larger eruption occurred in nearby Lake Nyos, killing nearly 1,800 people, as well as cattle, birds, other wildlife, and insects.

- Lake Kivu presents an added danger in that methane is also building up in the lake from underground volcanic activity. The lake now holds 65 cubic kilometers of methane. If it were suddenly released, it could ignite and explode, presenting a danger to the many people living along the lake shores.

- The rifting in Africa creates other landforms, such as very tall mountains. Rifting has uplifted mountains on either side of the rift valley in Uganda, creating the spectacular Rwenzori Mountains ("Mountains of the Moon") that separate the rift valley lakes on either side.

African Megapile

- Tectonic plates move about because of large-scale motions connected with convection within the Earth's mantle. This mantle-wide process of convection creates some large variations in composition and temperatures at the base of the mantle—the core-mantle boundary. By far, the largest region of variation anywhere within the planet is the African Megapile.

- The megapile is a massive cone-shaped region of hot and heavy rock that bends upward from the bottom of the mantle—more than 1,500 kilometers up—right underneath Africa. It may be the underlying reason for the Afar hotspot and all the other volcanoes in East Africa.

- Much research is going on to determine whether or not such volcanoes as Kilimanjaro have their origins at the very base of the mantle, but some questions remain.

- Some scientists have put forth the megaplume hypothesis: that a massive plume is rising up and lifting Africa, causing the domes and volcanoes.

- Others believe that heavy, iron-rich material is being swept upward into a cone by the circulation of rock within the mantle. This material whisks heat out of the core and is so hot that it generates smaller plumes along the flanks. This activity would explain hotspots in the Canary Islands, the Cape Verde Islands, Cameroon, Afar, and elsewhere.

- It's possible that our understanding of rifting will be enhanced by three-dimensional maps of the Earth's interior made using the waves from earthquakes to trace the possible flow of magma.

Human Origins

- Another reason scientists are fascinated with the East African Rift Valley system is that modern humans evolved from hominid species that lived primarily in Africa. Large numbers of significant fossil finds have been made in and around the African Rift valleys.

- The rift valleys not only provided sheltered areas to live in terms of weather, but they are also, because of volcanic activity, quite fertile. These lands had abundant vegetation and animal life. Recent anthropological research has looked at rifted topography as providing other benefits, as well. The faults there allow water to rise to the surface, creating wetlands at the surface, even in periods when climates are dry.

- The high sedimentation rates make great conditions for preserving the bones of our ancestors. Many important fossil finds have been made throughout Africa, starting from 10 million years ago and including the oldest known *Homo sapiens*, from 200,000 years ago in Ethiopia.

Top Continental Rifts

- Lake Baikal in eastern Russian is by far the deepest and oldest lake in the world, as well as the world's largest freshwater lake. It is formed by an active rift, just like the rift zones in Africa. Lake Baikal is considered part of the plate boundary between Eurasia and the Amur Plate, although it may qualify as its own plate boundary.

- The Rio Grande Rift is a north-south trending rift zone. It's about 50 kilometers wide, extending from Colorado down through New Mexico and into Mexico. The rifting began here about 35 million years ago and caused the crust to be stretched very thin and then to fracture and form grabens. The rifting here has been accompanied in the past by enormous amounts of volcanism.

- Rifting in the Rhine Graben in Germany is the result of the uplift of the Alps. The Rhine Graben is a down-drop rift valley that began forming about 100 million years ago.

- The Midcontinent Rift Valley in the United States is about 1.2 billion years old. It runs from Oklahoma through Kansas, Iowa, and Minnesota and up into Canada. It may be hard to imagine, but 1.2 billion years ago, North America saw the same kinds of volcanic activity as East Africa.

Suggested Reading

Oreskes, *Plate Tectonics*.

Pavitt, *Africa's Great Rift Valley*.

Questions to Consider

1. What will happen to the African Rift system when spreading occurs to the point that a new ocean is formed?

2. Why is Kilimanjaro, not in the rift valley, a stratovolcano, while volcanoes in the rift valleys are more basaltic (that is, more like ocean crust)?

Erta Ale—Compact Fury of Lava Lakes

Lecture 5

In the last lecture, we looked at the complex African Rift Valley system, and in this lecture, we'll visit one particular feature of the rift valley, a kind of volcanic geologic wonder that forms only in unique situations: the lava lake. In earlier lectures, we've seen volcanoes that occur at subduction zones, which tend to be quite explosive and emit stiff, somewhat gummy lava. We've also seen basaltic volcanism, in which the lava is more fluid. In rare cases, the lava slowly and continuously feeds into the crater of a volcano and bubbles away, like a seething caldron. Among the five active lava lakes on Earth, the oldest and longest running is at Erta Ale in Ethiopia.

Location and Description of Erta Ale

- Erta Ale is located near the southern end of the Red Sea in northern Ethiopia, a region that sees an enormous amount of volcanic activity associated with the Afar hotspot. This volcano sits within the Ethiopian Rift Valley. Erta Ale is the name of both a range of volcanoes that occurs along a line there and the single most active volcano in the range.

- Erta Ale sits in the Danakil Depression, which is below sea level in some places by more than 100 meters. As a result, even though Erta Ale is a fairly large volcano, it reaches a height of only 600 meters, just 2000 feet above sea level. It is 50 kilometers wide and is a shield volcano. Its low-viscosity lava can flow outward for great distances.

- The volcano has an elliptical summit caldera that's about a mile wide and contains many smaller pit craters; it's in one of these pit craters that the bubbling lava lake can currently be found.

- Lava lakes are rare because it's difficult for them to maintain their volcanic activity for long periods of time. The lava drains out of the caldera at the top or cools and hardens over time. At Erta Ale, a continuous lava lake has been bubbling in the crater for more than a century.

- From 2005 to 2007, there was a significant increase in activity at Erta Ale. Several new fissures opened up, some of them meters wide. The lava eruptions out of these fissures spread out more than 300 square kilometers. The lava filled the crater to its rim by the year 2010 and overflowed the lava lake onto the flanks of the volcano.

Dallol Hot Springs

- Nearby Erta Ale are the spectacular hot springs of the Dallol volcano. These strangely colored formations are mostly caused by the presence of salts, including potassium, magnesium, and sulfur salts. The hot water dissolves the salts out of the ground in a process similar to the hydrothermal circulation we saw in Lecture 3 on the Galapagos Rift.

- The Dallol region consists of a wide plain of 1000-foot-thick salt flats in many successive layers. The Dallol mountain has large cliffs and towers that are made entirely from salt. Where does all this salt come from?
    - Part of the explanation comes from the fact that the Danakil Depression is below sea level. Global sea levels fluctuate by many hundreds of feet; thus, at times of high sea level, the seawater rushes into the rift valley and floods the entire Dallol region. When global sea levels drop again, this water is cut off; it evaporates away, but the salts remain.

    - This explanation, however, is only a partial one because the salts here are not typical sea salts. They contain large amounts of a useful material called potash, which is potassium chloride and potassium and magnesium salts. This mix results from the interaction of hot fluids with magma not far beneath the surface.

    - Water, heated by the magma, dissolves the potassium, magnesium, and other materials out of the underground rocks and brings it up to the surface. The water then bubbles out of the ground as dramatic and colorful hot springs. Iron leached out of the volcanic rocks underneath the ground also contributes to the wide range of colors seen.

Lava Lake Activity

- The lava lake at Erta Ale consists of liquid rock that is constantly churning because the top part of the lava lake keeps cooling, hardening, sinking, and remelting. The lava here in general is about 1100°C (2000°F). The lava lake is not constant in its behavior, and the process of convection within the crater varies greatly over time.

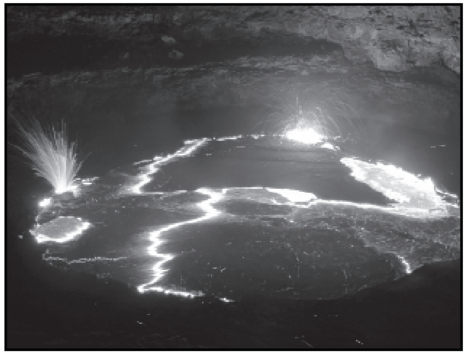
- Two modes of convection, a fast and a slow mode, are in operation in the lake at Erta Ale. During slow convection periods, a thick crust begins to develop and move across the surface. Pieces of the surface move slowly, perhaps 10 centimeters a second, and begin to thicken as they move.
    - Within 7 minutes of coming to the surface, the lava develops into a solid crust about an inch thick. After about 70 minutes, the crust grows to about 3 inches and becomes heavier than the liquid rock underneath.

    - The solid rock of the crust is also insulating, and the surface temperature can drop to below 200°, making the rock colder and heavier. At some point, the crust becomes too heavy and begins to crack and sink; the lava lake then switches into its fast mode.

    - The hardened crust moves at up to 40 centimeters a second and is rapidly consumed back into the lava lake, where it melts again. The surface is re-covered with a new layer of hot, glowing magma. Even during the fast phase, convection doesn’t occur steadily; the sites of active convection move about the surface.

- The lava lake often experiences periods of higher activity, when more convective overturning occurs. When the lake was studied in 2002, these cycles took about 10 hours to repeat.

- The lava lake also goes through cycles of changing its height. The lava level in the pit may drop when lava drains back into the magma chamber or when it finds a conduit or crack and flows out the sides of the lake. At other times, the lava pit fills up so high that it overflows and spills down the flanks of the volcano.



Gases that have accumulated beneath the crust of the lake at Erta Ale sometimes burst out of the surface, triggering large lava fountains.

- Another unusual feature that sometimes forms at Erta Ale is a hornito, a solid tower or chimney of lava that pushes its way out of the surface at a particular point along the flank of the volcano. Points where the lava stops flowing out and rains back down often become the sites of fumaroles, where hot gases jet out from underneath the towers.

A Microcosm of Plate Tectonics

- Perhaps the most remarkable aspect of the lava lake is how closely it resembles the process of plate tectonics. We see everything here: subduction, ocean rifting, transform faults, and even hotspots.

- As the surface crust of the lava lake begins to cool and harden, it becomes heavier than the liquid below; it then bends, cracks, turns sideways, and sinks down into the boiling vat of the lake. This is just like the process of subduction that we saw beneath Japan in Lecture 2.

- As this subduction takes place, the crust is pulled apart in places and new lava comes up from below to form new crust, similar to the process we saw in Lecture 3 at the mid-ocean ridges.

- There are even places in the lake where two pieces of crust slide past each other, forming a transform fault, similar to the San Andreas Fault that we will discuss later.

A Microcosm of the Early Earth

- Lava lakes are important for another geologic reason: They are as close as we get to seeing what the earliest period of Earth's history was like.

- The Danakil Depression is one of the driest and hottest places on Earth, regularly reaching temperatures of more than 115°F for extended periods, with no rainfall.
    - The earliest Earth was also extremely hot. With no water, it was too hot for water vapor to condense to form oceans.

    - This heat from the early Earth had many sources, and the Earth went through an active period of heating up and eventually melting.

    - The early Earth experienced impacts of small protoplanets as the solar system was developing. Large amounts of highly radioactive elements, most of which have decayed away, contributed to the heat.

    - The early Earth also experienced the impact of a Mars-sized planet; this impact ejected material that circled the Earth and came together to form our Moon. Following this impact, about 40 to 90 million years after the start of the solar system, Earth's mantle would have been mostly molten, making it just like the lava lake on a much larger scale.

- The surface of the Earth at that time would have been violently volcanic, with huge pieces of Earth's crust continuously cracking, sinking back into the molten mantle, and remelting.

- Our mantle is currently nearly entirely solid, but this process actually began from the bottom of the mantle up. The pressures are so great deep within the Earth that the rock at the base of the mantle, even though it is hotter, is much more easily solidified. As the whole mantle cooled, the mantle would have crystallized from the bottom up. Thus, the top part of Earth's mantle would have remained molten, like the lava lake, for many tens or even hundreds of millions of years.

- Even now, there is a layer of rock within Earth's mantle, the asthenosphere, about 200 to 300 kilometers beneath the surface, that is close to its melting temperature. This layer represents the last process of Earth cooling off.

- Eventually, Earth's surface cooled enough to allow water to condense and rain out of the atmosphere to form the ocean; this process, too, has an analog at Erta Ale in the fumaroles and steam vents around the pit.

Top Lava Lakes

- Nyiragongo in the Democratic Republic of Congo had a huge lava lake—600 meters deep—up until 1977. During a large eruption, however, this lava lake drained entirely in 1 hour. Since then, Nyiragongo has filled up again.

- Kilauea in Hawaii is the longest continuously erupting volcano in the world and has two separate lava lakes: Halemaʻumaʻu and Puʻu ʻŌʻō.

- On Ambrym Island, part of the country of Vanuatu in the southwest Pacific Ocean, is the Marum crater, an active lava lake that sits within a large caldera.

- Finally, the southernmost volcano in the world is Erebus in Antarctica. Persistent low-level activity takes place in a lava lake right at the top of this volcano.

Suggested Reading

Mackley, *In Extreme Danger*.

Rosi, Papale, Lupi, and Stoppato, *Volcanoes*.

Questions to Consider

1. Why do most volcanoes not have associated lava lakes?

2. If no new magma is added, a lava lake can take tens or even hundreds of years to completely solidify. Why does this process take so long?

Burgess Shale—Rocks and the Keys to Life

Lecture 6

In the past few lectures, we've discussed volcanic activity and how volcanic processes have shaped the surface of the Earth. In this lecture, we'll look at the evolution of hard-shelled, multicellular life on our planet. For this topic, we'll travel to Yoho National Park in the Canadian Rockies, along the border between Alberta and British Columbia, to visit a layer of rock called the Burgess Shale. This outcropping contains one of the most spectacular displays of fossils found anywhere in the world, including full imprints of the soft body parts of creatures that lived about 500 million years ago.

The Canadian Rockies

- The Canadian Rockies are a continuation of the Continental Divide up from the American Rockies. The Continental Divide is the boundary between major watersheds. Any rain that falls east of the divide in Canada ends up either in Hudson Bay or in the Arctic Sea and, therefore, in the Atlantic Ocean. Any rain that falls on the west side of the Canadian Rockies winds its way down into the Pacific Ocean.

- The Canadian Rockies are different from their American counterparts in a couple of ways. The American Rockies are taller, but the Canadian Rockies are much steeper. The Canadian Rockies also tend to be more jagged from the greater degree of glaciations they've undergone. Because the Canadian mountains are at a higher latitude, their tree line is lower.

- The American Rockies were pushed up from below, while the Canadian Rockies formed from horizontal compression from the West Coast during an episode of subduction. The American Rockies are mostly igneous and metamorphic rock, which form deep beneath the surface. The Canadian Rockies are mostly ancient sedimentary rock, such as limestone and shale, that formed at and beneath the floors of ancient shallow seas; thus, they contain many fossils.

The Fossil Record

- The fossil record in general tells a remarkable story about life on our planet. Single-celled life—a simple form called a prokaryote—existed perhaps as long as 3.5 billion years ago, and it ruled from 3.5 billion to 2 billion years ago. Prokaryotes took two different forms: archaea and bacteria.

- Sometime around 2.7 billion years ago, a more complex form of single-celled life—the eukaryote—emerged. Around 2 billion years ago, multicellular life—such as sponges and corals—probably evolved independently from colonies of single-celled organisms.

- By 1 billion years ago, eukaryotes had spines, and their fossils may reveal some evidence of predation. Predator/prey relationships tend to drive evolution much more quickly. Essentially, the prey evolves not to be eaten and the predators evolve to eat the prey.

- Some 800 million years ago, our planet experienced what is called the Snowball Earth scenario. All of Earth froze over, even the surfaces of most of the oceans. Between 800 million and 630 million years ago, the planet may have alternated between Snowball Earth conditions and a runaway greenhouse effect, making it difficult for life to take hold.

- As soon as this period ended, life bloomed. We see evidence for the first time of worms, strange jellyfish-like organisms, and frog-like seafloor creatures. These creatures are known collectively as Ediacaran life after a fossil find in the Ediacara Hills in Australia.

- Most of the Ediacaran life forms died out in a mass extinction before the start of the Cambrian period, 540 million years ago. The fossils found in the Burgess Shale are from the Middle Cambrian.

Fossil Formation

- After they die, most living things decay or are broken down, but in some rare cases, an environment is buried rapidly and gently enough so that the organisms in that environment are preserved nearly unchanged.

- Fossils are found in many forms, including footprints, teeth, bones, and shells. Plants are often difficult to preserve, but they can be fossilized. The flesh of animals is also difficult to preserve, but under the right conditions, even feathers and fur can be preserved.

- Sometimes, the right conditions are created by a layer of volcanic ash or an underwater mudslide, which is probably what happened at the Burgess Shale. Essentially, the sediment along the slope off the shore rushes down the slope, much like an avalanche on land, instantly burying all life forms in its path.

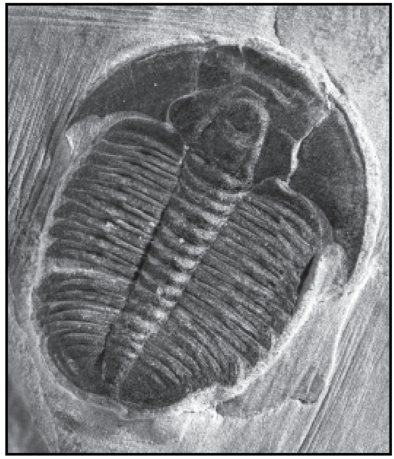
- For ocean-living organisms, worms burrowing in the sediments often prevent the formation of fossils. There are very few *Lagerstätten* ("storage places") finds after 500 million years ago, because that's the time when worms began to proliferate on the ocean seafloor.

- For the animals of the Burgess Shale, additional burial occurred over the years, slightly metamorphosing the rock and altering it chemically. The layer of sediment got compressed vertically by a factor of about 8. It then got caught up in the ancient plate collision that made the Canadian Rockies, starting 175 million years ago. When the mountains stopped growing and erosion took over, these spectacular fossils were exposed.

The Burgess Shale Fossils

- The Burgess Shale fossils were discovered in 1909 by Charles Walcott, a remarkable scientist and administrator. After his initial discovery, Walcott returned to the Burgess Shale many times, collecting more than 65,000 fossil specimens. Subsequent research found that Walcott's fossils showed many organisms that were not like any modern counterparts.

- Among the specimens found in the Burgess Shale are trilobites; *Marrella*, a creature about 1 centimeter long with two sets of spines curving around its body; *Opabinia*, a soft-bodied creature with five eyes; and *Hallucigenia*, which had no distinguishable head.



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Trilobites dominated ocean seafloors during the Cambrian period.

- Predators at the time included *Nectocaris*, an early relative of the squid, and *Anomalocaris*, a creature that grew up to about 1 meter long and had two long, curved feeding appendages.

- Very soon after the development of multicellular life, an incredible diversity of hard-shelled creatures emerged. One of the most important from the Cambrian period was the small wormlike creature called *Pikaia*. It's one of the oldest creatures with a notochord, essentially a primitive spinal cord. It's quite likely that all mammals evolved from a creature like *Pikaia*.

Variations in Diversity

- The paleontologist Stephen Jay Gould put forth an interesting hypothesis related to diversity of life forms: Early life might have been extremely diverse, with little competition for resources. But as populations increased, so did competition, both in terms of predator/prey relationships and use of resources. Only the most efficient life forms persisted, with many forms going extinct. The species that evolved later seem to be variations of a fairly small number of successful life forms. In a sense, the diversity of life has decreased over time.

- We see this pattern happening at many levels. Biologists often classify life forms according to their genetic differences. If we look at a tree of the different life forms, we see only three major branches: single-celled bacteria, single-celled archaea, and single-celled eukarya. All animals, plants, and fungi are small branches off of one end of the eukarya branch. In other words, we are all variations of one particular biochemistry that works very well.

- Diversity of life has not changed continuously. In fact, from about 450 million years ago to 200 million years ago, there was a fairly steady decrease in the number of genera (groups of species). Such events as meteorite impacts or volcanic eruptions may have driven many species to extinction rapidly, but each such event opened up many more environments for a new round of increased diversity.

- As Gould has pointed out, early on, as the newest multicellular life forms were developing, even a slight change in one environment that might have favored one species over another could have led to a totally different history of life. Humans might never have evolved.

- Other *Lagerstätten* around the world have shown that the Burgess Shale wasn't geographically anomalous. These other sites have also revealed that the process of diversification was more gradual than previously thought—not quite the "Cambrian explosion" we often hear about.

- As mentioned earlier, primitive life forms of the Ediacaran era died out in a mass extinction that allowed Cambrian life to expand. This fact points to a pattern in our planet's history: Each bloom of life forms has followed a period of mass extinction. Since the Ediacaran extinction, Earth has experienced five other major extinctions: at 440 million years ago, 360 million years, 251 million years, 205 million years, and 65 million years. In each case, the massive dying off of life opened up new environments and allowed for new bursts of life.

Top Fossil Sites

- The Jehol fossil beds in Liaoning, China, yield finds from a period 164 million to 158 million years ago. This was a wetlands area, with numerous lakes that were interrupted periodically by ash eruptions from volcanoes farther to the west. Amazing soft-bodied fossils of incredible diversity have been found here, including the earliest known examples of tyrannosaurs, triceratops, and raptors.

- What's called the Morrison Formation is often found in such places as Colorado, Utah, and Wyoming. Fossils found in these deposits represent the period just after the Jehol fossil bed, 156 million to 147 million years ago. These fossil finds reveal a variety of climates, from swamps to deserts. The Morrison Formation is most well known for its dinosaur fossils, which include allosaurs, stegosaurs, and brachiosaurs.

- The Messel Pit in Germany dates from 47 million years ago. This area was a series of lakes at that time, surrounded by lush subtropical forests; the Messel lake bed was probably a center point for drainage from nearby rivers and creeks. It's thought that a release of carbon dioxide from that lake killed off organisms in mass numbers. The result was the preservation of fossils with feathers, fur, and skin, even some very early anthropoid creatures.

- The Cradle of Humankind in South Africa is just south of the African Rift Valley. One particular region here, the Sterkfontein Caves, is where the first *Australopithecus africanus* was found in 1947. This was a 2.3-million-year-old human ancestor. In fact, one-third of all hominid fossils ever found are from this one cave alone.

Suggested Reading

Conway-Morris, *The Crucible of Creation*.

Gould, *Wonderful Life*.

Questions to Consider

1. Geologic conditions that do a good job of preserving fossils are often "anoxic," meaning that not much oxygen is present. Why do you think this might be important for preserving fossils?

2. Different species of trilobites are often used as markers, "index fossils," for identifying rocks around the world that formed at particular times. What characteristics of these organisms might aid in this identification?

The Grand Canyon—Earth's Layers

Lecture 7

In the last lecture, we visited the Burgess Shale in the Canadian Rockies. In this lecture, we'll head south, down the spine of the Rockies, until we reach the Colorado Plateau, to visit the Grand Canyon, which is in Utah and Arizona. Grand Canyon National Park became the 15th national park of the United States thanks to the support of two presidents, Teddy Roosevelt and Woodrow Wilson. Just as Mount Fuji defines and symbolizes the landscape of Japan, the Grand Canyon, with its immense size and stunning appearance, serves the same role for America.

History of the Grand Canyon

- Native Americans have lived in the area of the Grand Canyon for about 4000 years, but it wasn't seen by Europeans until 1540, when the Spanish explorer Coronado and his men traveled through the southwest looking for the fabled Seven Golden Cities of Cibola.

- After Coronado, the Grand Canyon was rediscovered by Europeans in the mid-1800s. In 1869, Major John Wesley Powell led the first expedition into the canyon. Powell was amazed by the tall carved walls, incredible arches, deep glens, alcoves, gulches, mounds, and monuments he saw. He returned in 1871–1872 with another expedition to map and photograph the canyon.

- Today, the Grand Canyon is one of the most visited landscapes anywhere in the world, with as many as 5 million visitors a year.

Rock Layers

- Other canyons around the world are much deeper than a mile, and some are even wider and longer than the Grand Canyon, but none of them has its visual impact. Part of this impact stems from the sudden depth and width of the canyon in a plateau that is otherwise flat. Further, the rocks of the canyon are exposed in an amazing display of colors: reds, yellows, oranges, and browns.

- The rocks along the sides of the Grand Canyon display layers that are exceedingly flat. In most other mountain canyons, the rocks show extensive folding of the layers as a result of the mountain-building process.

- In the Grand Canyon, we find little evidence of folding and just a small amount of faulting. The rocks here have lain underground, essentially unchanged, for hundreds of millions of years.

- In fact, the rocks at the top of the canyon—the youngest rocks—are 240 million years old. Near the bottom, the rocks are more than 500 million years old, the time of the Cambrian period.

- At the very bottom of the canyon, by the Colorado River, is a major unconformity, a feature that represents a gap in time. An unconformity occurs when many layers of rock are deposited on top of one another, but the deposits are interrupted by a period when the younger layer is eroded away and new deposits are added later.
  - We see such a gap between rocks that are 540 million years old and those that are about 825 million years old at the bottom of the Grand Canyon.

  - As we go deeper, we reach the Nankoweap Formation, with layers that are 1 billion years old, and the Unkar Group, with layers that are 1.25 billion years old.

  - The very deepest rock layer in the canyon, the Vishnu Schist, is 2 billion years old.

- Each layer in the Grand Canyon is a different kind of sedimentary rock that formed from different materials in different environments. The rocks are principally limestone, sandstone, and shale, most of them formed in marine settings.

- The rocks also have different strengths, which gives the canyon is layered-cake appearance. The shallow slopes are formed from rocks that weather easily, usually shales. The slopes that have a more vertical appearance are made of the tougher sandstones and limestones. The whole canyon consists of an alternating set of these layers, which is what gives it a dramatic appearance.

Structure of the Grand Canyon

- The Grand Canyon is a deep canyon that cuts through flat layers of rocks. Again, big valleys usually form when mountains are pushed up, but there are no mountains here. Why is there such a deep valley here in the first place?

- Part of the answer comes through an understanding of how streams behave. A stream usually maintains a particular profile in terms of its elevation. It has a downward slope that gradually flattens from its start at the headwaters to the finish at a delta, usually the ocean.
    - The shape of this profile is like a hyperbola: steep on one side and then gradually flattening out. The tendency of a stream is to maintain this profile. Thus, if there's a bend in the stream, the water will speed up (and hold more sediment) or slow down (and deposit more sediment) to return to the hyperbola.

    - If the end of a stream or a river is suddenly dropped, the whole rest of it will cut down in order to maintain the hyperbola.

- This behavior of streams tells us that we need to be on the lookout for something in the history of the Grand Canyon region that might have changed the height of either the sea level or the surface of the land or changed the length of the Colorado River.

- We get one clue about this change in the very rocks of the canyon themselves. They're mostly ocean sediments—mud, sand, and lime that were fossilized into limestone, shale, and sandstone. They were formed at or below sea level. Why are they now more than a mile high? The Colorado Plateau is a broad area in the southwestern United States that is, in some places, 7000 to 8000 feet above sea level. We need to find some mechanism that lifted up the Colorado Plateau; the river would then carve down through the plateau to maintain its hyperbolic shape.

- The question of how the Colorado Plateau got lifted so high involves the plate tectonic history of California.
  - More than 50 million years ago, there was no San Andreas Fault. That part of the world was a subduction zone. A large part of the Pacific Ocean seafloor—the Farallon slab—was separating from the Pacific Plate along a mid-ocean ridge that headed down the middle of the Pacific. But North America has been moving westward for 200 million years; we approached that mid-ocean ridge and finally began to go over it.

  - If we go back to a time 30 million years ago, the North American Plate was not in contact with the Pacific Plate. There was still subduction along the entire Pacific West Coast, from Alaska down to Mexico. Then, as North America continued to move westward, it came in contact with the Pacific Plate, and the San Andreas Fault was born.

  - As the motion continued, eventually, the little bit of the Farallon slab in the north closed up, so that only the smaller Juan de Fuca Plate remained, and the San Andreas Fault began to grow longer. Now, the San Andreas Fault stretches more than 1300 kilometers; eventually, the Juan de Fuca Plate will entirely subduct, and the San Andreas Fault will run from California far up north.

  - As the plates came into contact, North America had to ride over hot, buoyant, young ocean seafloor forming at this mid-ocean ridge. This is largely the reason that features of Colorado, such as the Rocky Mountains, were pushed up. The Farallon slab, right underneath North America, pushed up many of the mountains in the west and lifted the Colorado Plateau.

- This plate tectonic activity gives us an explanation of how the Grand Canyon formed: The Colorado Plateau was lifted up from below. The Colorado River sought to maintain its stream profile and cut down through the layers of rock. The problem with this explanation is that plate tectonics moves slowly. It took 70 million years to lift up the Colorado Plateau, but the canyon formed in just 5 million years. There must be some other factor that could affect the stream profile of the river.

- It turns out that the Colorado River used to be longer than it is now. In fact, it used to empty into the Pacific Ocean, although it now empties into the Gulf of Mexico. Baja used to be directly connected to Mexico but is now part of the mid-ocean ridge system and is opening up. The river initially wound its way out to the Pacific Ocean, but when the Baja Peninsula broke far enough north, it suddenly found a shorter path to the sea and jumped down into the Gulf of Mexico. The moment that happened, the river began to cut down through the canyon.

Descent into the Canyon

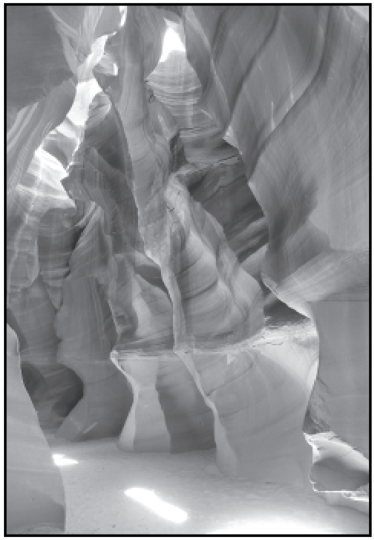
- Descending into the Grand Canyon is almost like visiting another world. The temperature changes drastically from the Colorado Plateau down to the bottom of the canyon. At night, you can hear the cold air rushing down the sides of the canyon, replacing the warm air at its base.

- There are incredible erosional features at the bottom of the canyon and giant boulders brought by floods. The canyon is also a beautiful desert environment, with incredible desert flowers and occasional rattlesnakes.

- The Grand Canyon presents some remarkable vistas from the rim. Imperial Point is the highest point along the canyon rim, and at Guano Point, some of the rock juts far out into the canyon, allowing spectacular views.

- Nearby the Grand Canyon is Antelope Canyon, one of the most photographed features in the western United States. Antelope is a classic example of a slot canyon, a narrow canyon through which water flows during flash floods.

- Another spectacular location just north of the Grand Canyon is Wave Rock. Here, the various sandstones have weathered and eroded into wavy, undulating shapes that almost look as if they have been carved by an artist.



From the surface, Antelope Canyon is almost unnoticeable, but inside, the curving, colorful walls are stunning.

Top Canyons

- Fish River Canyon in Namibia is more than 160 kilometers long and up to 27 kilometers wide. It's the most similar to Grand Canyon, probably of any canyon in the world, in its appearance.

- Copper Canyon in Mexico is deeper in places than the Grand Canyon, and overall, it's longer. It consists of six separate canyons in various parts of the Sierra Madre Mountains from six different rivers in the southwestern part of Chihuahua, Mexico.

- The Yarlung Zangbo Canyon in Tibet drains the northern part of the Himalayas. At 15,000 feet, it's three times deeper than the Grand Canyon and slightly longer.

- Measured peak to valley, Kali Gandaki in Nepal is even deeper than the Yarlung Zangbo. This canyon, the deepest anywhere, cuts through the majestic southern Himalayas and drains into the Ganges River.

Suggested Reading

Grubbs, *Grand Canyon Guide*.

Kaiser, *Grand Canyon*.

Questions to Consider

1. What will happen to the Colorado River if the sediment no longer makes it to the ocean because all the water is being removed?

2. Knowing that the canyon continues to widen over time and side canyons continue to grow, what do you think the Grand Canyon will look like in 50 million years?

The Himalayas—Mountains at Earth's Roof

Lecture 8

In the last lecture, we toured the Grand Canyon in Arizona. In this lecture, we'll travel around the world to visit a place with many big canyons, big mountains, and other big features: the Tibetan Plateau, including the Himalayan Mountains. When viewed from space, it is likely that there is no more impressive geologic wonder than the Tibetan Plateau. It's 2.5 million square kilometers of land. At approximately 5 kilometers above sea level, the plateau is called the Roof of the World.

Defining the Size of Mountains

- The Tibetan Plateau contains the world's highest mountain range, the Himalayas, and the world's highest mountain, Mount Everest, at more than 29,000 feet. But in the realm of mountains, there are multiple ways to define "high" or "big."

- The Andes in South America is by far the longest mountain range in the world, more than 7000 kilometers. In comparison, the Himalayas are only 2400 kilometers. The Andes Mountains are currently growing by the subduction of the Nazca Plate, occurring beneath the whole extent of the west coast of South America. It's the longest continuous subduction zone in the world and, therefore, has the longest mountain range.

- Mount McKinley, or Denali, in Alaska rises farther from the surrounding valley than any other mountain on land. It is 18,000 feet above the surrounding plains. Mount Everest is only 12,000 to 15,000 feet above the plain.

- As a single mountain, nothing compares to Mauna Kea on Hawaii, which rises more than 33,000 feet off the seafloor.

- Still, it's impossible for anything to compare with the Tibetan Plateau in terms of sheer size. There are about 450 mountains in the world that are more than 7 kilometers above sea level, and every one of them is part of the Tibetan Plateau. Unlike other parts of the world, the Tibetan Plateau doesn't contain a single mountain range but many of them, including the Kunlun Mountains, Qilian Mountains, Hengduan Mountains, Karakoram Range, and Himalayan Range.

Water in the Tibetan Plateau

- The Tibetan Plateau also contains an enormous amount of water, mostly in frozen form. The Himalayas alone have about 15,000 glaciers that carry as much as 12,000 cubic kilometers of ice down out of the mountains. In fact, almost half the people in the world get their water from sources that start in the Tibetan Plateau. The major rivers that originate here include the Indus, Ganges, Brahmaputra, Mekong, Yangtze, and Huang He (Yellow).

- The Tibetan Plateau acts as a huge barrier to monsoon air patterns. India has a monsoon-type climate, which means that for part of the year, a massive moist, warm airflow comes off the Indian Ocean and heads north, up across the Indian subcontinent. As it does, rain falls out, but as the air begins to hit the Himalayas, it has nowhere to go but up, and when it does, it gets cold.
    - When air gets cold, it can no longer hold as much water vapor. As the airflow from the Indian Ocean cools, it begins to precipitate. It condenses out first as small ice and water droplets to make clouds; it then continues to condense to form falling ice, snow, and rain.

    - As a result, an enormous amount of water falls along the southern end of the Tibetan Plateau, but very little makes it up to the top of the plateau itself. By the time the air reaches as far north as the Gobi Desert, it has lost all its moisture.

- Liquid water on the plateau can be found in some spectacular lakes, such as Qinghai ("Blue Sea") Lake, the largest lake in China.

- At the same time, many places on the plateau can be quite dry. The Changthang region in the northwest is dry and experiences temperatures of –40°F in winter. This area has the lowest population density anywhere on the Earth outside of Antarctica or Greenland.

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Life has evolved on the Tibetan Plateau in unique ways in order to adapt to the extreme cold.

Formation of the Plateau

- As we know, the powerful forces of erosion are constantly ripping down the land and washing it to the sea, and mountains get eroded faster than anything else. The Appalachian Mountains were once the Himalayas of their day, but after hundreds of millions of years, there's not much left of the Appalachians. How is it that the Himalayas are so tall?

- The simple answer is that they're very young. In fact, they are still being built up. The Himalayas are our best current example of the collision between two continents.

- By 100 million years ago, India had broken away from Africa with Madagascar; soon afterward, it broke away from Madagascar and moved toward Asia.
    - By 60 million years ago, India had already started to collide with Asia, and as it continued to move northward, everything that lay in between India and China—ocean seafloor, marine sediments, volcanic island arcs in the ocean, even microcontinents—was smashed to create this massive plateau.

    - As the collision occurred, the rock was forced upward. But at some point, the bottom part of India began to slide beneath China. Now, beneath the southern part of the plateau is a double layering of continental crust. The average thickness of continental crust elsewhere in the world is about 40 kilometers; in the Tibetan Plateau, the thickness is about 80 kilometers.

    - This collision also explains why sedimentary rocks with fossils in them can be found on top of Mount Everest. The rock is limestone, and it was once formed at the bottom of the ocean seafloor.

    - Some parts of the Tibetan Plateau are still rising quickly. Nanga Parbat, for example, is rising at about a centimeter a year. Other parts of the Tibetan Plateau are eroding quickly.

- Interestingly, some parts of the plateau are rising faster than they are eroding because of the fact that they're eroding. This paradox makes sense when we consider the process of isostasy, the balance that affects the elevation of the continents.
    - Isostasy is the reason an ice cube pokes a little bit above the water in a glass. Because the ice is a little bit lighter than water, it sits above the top of the water.

    - In the same way, continental rock is a little bit lighter in terms of its density than the rock underneath. When continents smash together and build up a continental mountain, a deep root is also created.

    - As the rock starts to erode, the whole continent starts to rise up. Think of sitting down on the edge of a bed. When you sit, the whole bed goes down; when you start to get up, the edge of the bed rises up again.

    - As the top of a mountain is removed, the whole plate starts to rise up. In places with a few high peaks, if the valleys are carved away, the peaks rise up higher. Thus, it's possible to have the tallest mountains rising even while the rest of the mountain range is being eroded away.

- At an elevation of 5.5 kilometers above sea level, there is half as much air as there is at sea level. At the top of Everest, which is more than 8.8 kilometers above sea level, the air pressure is one-third of the air pressure at sea level.
    - At this pressure, a person who would normally have to breathe 20 or 30 times a minute would have to breathe 60 to 90 times a minute just to get the same amount of oxygen. For this reason, using bottled oxygen has become standard in climbing these tall peaks.

    - As of 2008, Everest had been climbed about 4100 times by 2700 different people. Out of those 4100 climbs, there have been 220 deaths.

    - The difficulty of climbing Everest meant that it took almost 50 years to determine that it was indeed the world's highest mountain. Even today, some uncertainty exists about the height of Everest.

The Collision of India and Asia

- The collision of India into Asia causes tectonic disruption throughout Asia. In fact, most earthquake-related deaths in the world stem from this particular plate collision. A tectonic map of Asia shows widespread faults across the area.

- The Tibetan Plateau has also played a role in cooling the planet, particularly over the past 60 million years.
    - A small amount of acidity naturally exists in the atmosphere in the form of carbonic acid, which forms when carbon dioxide in the atmosphere combines with water vapor. The rain that falls out is generally slightly acidic, having a pH of about 5.5.

    - This carbonic acid reacts with rock and dissolves it away; ions, such as bicarbonate ions, are then washed down rivers and into the sea, where they are eventually locked away as limestone within the Earth.

    - Mountains are like sponges that soak up carbon dioxide from the atmosphere. The more mountains that exist, the more rapidly carbon dioxide is pulled from the atmosphere.

    - As we know, carbon dioxide is a critical greenhouse gas that keeps our planet warm. In the time just before the Himalayas were formed, the carbon dioxide levels were about 4 to 8 times what they are now, but as soon as the Himalayas rose up, the whole world began cooling.

    - On a very long time scale, our global temperatures have been continuously cooling over the past 65 million years; this cooling is, in large part, the result of the rise of the Himalayas.

Top Mountain Peaks

- The Andes in South America is the longest mountain range in the world. The Altiplano is a tall, vast plateau in South America that was formed by both tectonic and volcanic processes. The Andes began to form at least 1 billion years ago from multiple plate collisions and have grown continuously over the past few hundred million years, thanks to a nearly continuous subduction zone.

- Mount McKinley in Alaska is the single largest mountain in the world. McKinley is part of the Alaska Mountain Range, which runs for about 1000 kilometers.

- The Rocky Mountain Range begins in New Mexico and ends about 3000 kilometers later in British Columbia. The Rockies formed 80 to 35 million years ago in a mountain-building event called the Laramide orogeny.

- The Alps are the major mountain range of Europe. Like the Himalayas, the Alps are part of a long mountain chain that is associated with the closing of the ancient Tethys Sea following the breakup of Pangaea.

Suggested Reading

Palin, *Himalaya*.

Zurick, *Illustrated Atlas of the Himalaya*.

Questions to Consider

1. Some rivers cut right across the Himalayan range. How do you think they might have formed?

2. Which do you think should be called the "world's tallest mountain": Everest, McKinley, Chimborazo, or Mauna Kea?

The Ganges Delta—Earth's Fertile Lands

Lecture 9

In the last lecture, we talked about the many mountain ranges that exist on the massive Tibetan Plateau, formed by the collision of India with Asia. Up to 3 billion people get their water from rivers that start in these mountains. In this lecture, we'll look at two of those rivers, following them to their end to focus on the Ganges River delta. The Ganges River that runs on the south side of the Himalayas and the Yarlung Zangbo and Brahmaputra rivers that run on the north side and around the edge of the Himalayas join together and flow into the Indian Ocean in the Bay of Bengal. This is the site of the world's largest delta.

Description of the Ganges Delta

- The Ganges delta is about 350 kilometers across and covers an area of about 60,000 cubic kilometers. It can really be fully appreciated only from space, as seen in satellite photos. Such photos give us a sense of the complexity of the network of streams there, as well as the biological lushness of the region.

- The Ganges delta is extremely flat, creating an incredible potential for flooding. The Ganges delta basin is home to about 400 million people, and about 150 million live within the delta proper. Thus, a large number of people live in constant danger of catastrophic flooding.

- Rivers are, in a sense, great consensus builders. They collect rains that fall across a wide area and channel them into just a few locations.
    - For example, most of the rain in the United States that falls anywhere in between the Rocky Mountains and the Appalachian Mountains eventually flows through a set of tributaries into the Mississippi River and gets dumped into the ocean at one location: Louisiana. That means that nearly all the sediment that the river carries—between 200 million and 500

million metric tons per year—eventually gets dumped at that one location, as well.

- The sediment from the Ganges and the Yarlung Zangbo/ Brahmaputra rivers is all deposited at the mouth of the Ganges. The Ganges delta is tied with the Amazon delta for receiving the most sediment per year of any river—about 1 billion metric tons.

- About half of the sediment is dumped into the sea, pushing out the edge of the land, and half is deposited in the complex network of delta stream channels. Over time, the river can significantly increase the land area of the continents.

Structure of a Delta

- The Ganges delta is a tidal delta. The land is so flat that the rising and falling ocean tides significantly change the shape of the shoreline over the course of days to months.

- Tidal deltas have many channels that form during large storms or over the course of the monsoon season and then slowly fill in over time. So much sediment is dumped here that the channels continually get clogged up and new ones develop. The land is constantly shifting.

- In a sense, with a delta, the whole structure of the river is like a tree. The tributaries of the river all come together to form one large river as it approaches the ocean (the trunk of the tree), but then, as the river reaches the tidal delta, it branches out again into multiple channels (the roots). The result is a large and wide delta with fertile sediment spread out over a large region. This region is sometimes called a green delta because of its fertility.
  - One of our most precious resources as a society is topsoil, that rich layer on the surface of the ground. Topsoil is a combination of sand, clay, and organic material.

  - Poor agricultural practices around the world are causing a great deal of topsoil to be eroded and lost. Almost 2 percent of the world's topsoil is washed down rivers each year. But in a delta region, the soils are continuously replenished by annual deposits of sediments during the rainy season.

- The fact that the Ganges dumps so much sediment shouldn't come as a surprise to us. The Himalayas are, after all, the largest mountain range on Earth, and a good bit of rain and snow falls in the Himalayas. The Himalayas are also the fastest eroding mountain range on Earth, and all that sediment eroded out of the mountains gets dumped in one place at the Ganges delta.
    - The eroded sediment on both the north and south sides of the Himalayas makes its way to the Ganges delta. Interestingly, the sediments on the north side travel all the way around the Himalayas to the east and then back to the west again.

    - This circuit starts as the Yarlung Zangbo River runs through the deep South Tibet Valley just on the north side of the Himalayan range. This stretch of the river is 1200 kilometers long, and the valley, at places, is 300 kilometers wide. The Yarlung Zangbo is the world's highest major river, traveling across the top of the Roof of the World.

The Yarlung Zangbo River

- When the Yarlung Zangbo comes out of the mountains and down into the state of Assam, it behaves like a totally different river. It even gets a new name: the Brahmaputra. It now travels more slowly and smoothly but still has another 1700 kilometers to go before it reaches the ocean.

- The Zangbo/Brahmaputra River is a great example of a braided river. Rivers usually travel as a single channel, but when they carry so much sediment that they become choked with it, they tend to continuously split apart and come back together again, looking like a braided rope. Sometimes, this process creates huge islands in the middle of the streams.

- It's also the nature of heavily sediment-laden streams to continuously change their channel locations. The Brahmaputra is constantly shifting its strands, especially as it approaches the Ganges delta, where the land becomes increasingly flat.

The Ganges River

- The other main river that feeds the Ganges delta is the Ganges River itself. It carries the snowmelt runoff and sediment from the southern side of the Himalayan range. The Ganges River is 2500 kilometers long, and more than 400 million people live along it.

- The Ganges varies greatly over the course of a year because of the intense variability of the monsoon climate of India. It floods enormously during the rainy season—generally June through September—but can then run very low through the spring.

The sacred city of Varanasi (once called Benares) is one of the holiest sites along the Ganges.

- The Ganges is the holiest of all rivers in the Hindu religion. Visiting the river is considered the surest way to reach heaven. Its water is considered pure and spiritually purifying—ironic given that the Ganges is also one of the most polluted rivers in the world.

- Despite the fact that the water quality has lessened greatly over the years and much of the original forests have been cleared for agriculture, the Ganges delta maintains a great diversity of life. One of the best places to see wildlife is in a region called the Sundarbans, a protected area of swamp-water forests. Here, visitors can see the rich diversity of Indian mammals, including elephants, clouded leopards, crocodiles, and Bengal tigers.

The Future of the Ganges Delta

- One of the greatest concerns for the future of the Ganges delta and the people living there is that it is susceptible to extreme flooding, not just along the coast but inland, too.
    - During the rainy season of a normal year, about 20 percent of Bangladesh routinely gets flooded from swollen rivers. This flooding kills about 5000 people a year and destroys about 7 million houses.

    - Because of the rapid global increase in temperatures that has occurred in recent decades, the sea level is currently rising at the rate of about 3 millimeters a year. It is projected that sea levels will be about 2 to 6 feet higher around the world by the end of the century. However, a sea level rise of only 1.5 feet would force 6 million Bangladeshi to evacuate their homes.

    - Unfortunately, the sea level has the potential to rise a great deal. The last time there was this much carbon dioxide in the atmosphere—about 400 parts per million—sea levels were 75 to 100 feet higher than they are today. This is the direction that our oceans are heading.

    - A sea level rise of just 20 feet would displace more than 100 million people in Bangladesh. It's projected that the mass migration of Bangladeshis—many tens of millions fleeing the coastal areas—will be the largest human migration in history. Such a mass movement of people could result in increased disease, heightened political and religious conflict, and severe shortages of food and fresh water.

- At the same time, the Bangladeshis are quite resourceful, given that they have had to live for years with the extreme flooding and overcrowded conditions in the Ganges delta.

- A short-term danger in Bangladesh is the increasing intensity of storms, brought on by rising sea temperatures. Strong typhoon surges can cause local sea levels to temporarily rise by tens of feet. One of the deadliest floods that occurred there in recent times was the result of the Bhola cyclone that hit Bangladesh in 1970. Flooding along the banks of the river from the storm surge along the coast and the ensuing starvation and disease killed between 300,000 and 500,000 people.

Top River Deltas

- The Amazon River delta is the other largest delta in the world in terms of sediment carried, 1 to 1.2 billion tons per year. The Amazon River is so strong that it doesn't have a well-developed delta structure. The sediment is carried far out into the Atlantic Ocean.

- The Nile delta is different in appearance from the Ganges delta in that it has a straight, smooth coastline. The Nile is fed from Lake Victoria in Tanzania. It flows down through an extremely dry area of Sudan and eastern Egypt, and its sediment is dumped just east of Cairo, helping in the process of closing up the Mediterranean.

- The Mississippi delta in Louisiana is a bird-foot delta. The weaker currents in the Gulf of Mexico allow the sediment to build far out into the sea at any one time. The result looks like a bird's foot, which is where this form gets its name. This buildup can also greatly increase the land area over time.

- The third largest delta by sediment output is at the Huang He River in China. This river is also fed by the snows of the Tibetan Plateau and has devastating floods. In 1931, flooding along the Huang He River killed more than 4 million people, the worst natural disaster in documented history.

Suggested Reading

Trojanow, *Along the Ganges*.

Wohl, *A World of Rivers*.

Questions to Consider

1. What do you think will happen to all the sediment in the Ganges delta over the next 50 million years?

2. Why do so many people live in such a small area in Bangladesh?

The Amazon Basin—Lungs of the Planet

Lecture 10

Of all the objects in the solar system, Earth is the only one that has liquid water at the surface. Most of our planet's water—perhaps the equivalent of 5 or 10 oceans—is actually located within the rock of Earth's mantle. Most of the liquid water at Earth's surface—97 percent—is in the ocean, and most of what's left over is in the form of giant ice sheets in Antarctica and Greenland. A large portion of the remainder is in the Amazon River Basin, the most remarkable river system in the world.

Description of the Amazon Basin

- A basin is a region where rainwater is collected through a series of tributaries, from which it travels out the main trunk and into the ocean at the delta.
    - At the point where the Amazon River drains into the Atlantic Ocean, it contains as much water as the next seven largest rivers combined. An average of more than 200,000 cubic meters a second comes out the mouth of the Amazon.

    - The Amazon is responsible for 20 percent of all the world's fresh water returned to the ocean. That amount of water supports a significant level of vegetation throughout the Amazon Basin and produces 20 percent of all the oxygen of the planet.

- The water of the Amazon flows with such force that when it hits the ocean, it creates a plume of fresh water that is detectable more than 400 kilometers offshore. In fact, the Amazon flows with such strong force that it doesn't have a true delta. Its sediment is washed far out to sea.

- The Amazon is more than 4000 miles long, second in length only to the Nile. It has, by far, the largest basin area, almost twice as large as the next largest river basin, which is the Congo in Central Africa. The Amazon Basin covers 7 million square kilometers.

Rainfall in the Amazon

- One reason there is so much water in the Amazon Basin is that it receives an average of about 2 meters of rain per year. Several places in the world average more rain over the course of a year, but nothing compares to the total rainfall received over the whole Amazon region. To understand why the Amazon receives so much rain, we need to look at why rain falls in the first place.

- As mentioned in an earlier lecture, when the air temperature cools, water precipitates out of the atmosphere as either rain or snow. One way for air to cool is to force it to flow up and over a mountain range. Why is so much air flowing across the Amazon Basin?

- A large rotating planet has a strong air current that blows along the equator in the opposite direction of the rotation. This is the result of a process known as the Coriolis effect.
    - As the Earth spins, its surface is moving much faster at the equator than it is closer to the poles. The equator simply has a lot farther to go in one rotation over 24 hours.

    - Air flowing southward from the Northern Hemisphere toward the equator will find itself moving eastward at a slower rate than the land is moving eastward at the equator. This causes the air to bend to the right.

    - In other words, as the air comes down, it flows behind and, therefore, westward compared to the air at the equator. The same thing happens in the Southern Hemisphere but with the opposite direction. The air also bends to the west, but this time, it's moving to the left instead of to the right.

    - Why is air flowing toward the equator in the first place? In general, air masses rise along the whole equatorial belt as a result of the intense heating from the Sun. The air gets pulled in from both the Northern and Southern hemispheres to take the place of that rising air, and as this air flows toward the equator, the Coriolis force moves it westward.

- The equator runs right through the northern part of South America. Warm air filled with water vapor that has evaporated off the surface of the equatorial Atlantic Ocean blows westward across the coast of Brazil and into the Amazon Basin, where it cools. The water vapor condenses and then rains out onto the land. In addition, the Andes Mountains block and lift the air, causing any remaining moisture to rain out.

- The Amazon has a wet season (generally, January through June) and a dry season (July through December). The fact that water levels rise and fall to a great degree throughout the Amazon results in a strange phenomenon, flooding forests. Many of the forests of the Amazon are totally flooded for a significant part of the year, allowing for an unusual collection of life forms to evolve.

Schools of piranha, otters, manatees, and electric eels swim around the base of the trees in the Amazon's flooded forests.

Human Habitation in the Amazon

- Because the Amazon Basin receives such a large amount of rain, relatively few people live there. Some villages are built on stilts to adapt to the flooding, and people get around by boat for part of the year. Some villages, such as in Iquitos in Peru, are entirely floating; all the houses are built on rafts.

- For a long time, many anthropologists believed that the Amazon forests could not accommodate large cultures. The difficulty of carrying out agriculture in the forest was thought to limit the maximum village size to about 1000 people. Further, the lack of stone or metal in the forests prevents significant building.

- Recently, however, archaeologists, geographers, and other scientists have accumulated evidence that the western Amazon was inhabited for hundreds of years by sizable, regionally organized populations in both the valleys and the uplands. Some of these communities had up to 50,000 people organized into highly structured villages.

- The people from these times carved fascinating earthworks called geoglyphs into the ground. The geoglyphs extend over an area of about 1000 kilometers, from Brazil into Bolivia, and consist of trenches dug into the ground in geometric shapes. It's not clear what purpose these geoglyphs served, although they may have been associated with rituals. They date to as early as 2500 B.C.E.

Islands, Wetlands, and Rain Forests

- The Anavilhanas Archipelago is the world's largest freshwater archipelago, or group of islands. In this area, the river is so large that it has more than 400 separate islands, each one a separate community of life forms.

- Another remarkable region is the Pantanal, which is the world's largest region of wetlands, about 75,000 square miles, covering Brazil, Paraguay, and Bolivia. About 80 percent of it is totally flooded during the rainy season.

- Rain forests occupy only about 2 percent of the world's surface, but they contain about half of all its known species. One reason for this biodiversity is that the jungle has been in existence in the Amazon for an extraordinary amount of time, at least 70,000 years, allowing for a continued divergence of organisms.

- Ironically, this remarkable biodiversity may also exist because rain forests have some of the world's worse geologic conditions for life. The significant amount of rain in tropical regions washes away nutrients from the top of the soil and carries them down into the ground, and the thickness of soils in tropical regions can be many hundreds of feet. As a result, the soils in these regions are almost worthless, leading to intense competition for resources among life forms and extreme diversity.
  - The top layer of soil is generally rich organic material from all the organisms that are present in a given area. Beneath that is a layer of rich topsoil, then a zone of leaching, where water is dissolving minerals out of the rock and percolating downward. Those minerals are often redeposited in a deeper layer, a zone of accumulation. Below that is a zone where the bedrock is being converted into soil, and below that is the bedrock itself.

  - In temperate regions, this profile might be meters to tens of meters thick. In tropical regions it can be 100 or more meters thick. Essentially, anything worthwhile has long since been washed down.

  - Ironically, life in the tropical jungles has evolved to keep what nutrients are available aboveground. Multiple canopies of plants absorb most of the rain that falls. Organic material that falls to the ground, such as leaves, is often ground up by insects and carried back to their nests in the trees. The rain forest works to keep nutrients away from the ground, because there, they are washed out and disappear forever.

- The diversity of the rain forests is incredibly fortunate for us. Eighty percent of the world's diet originates in rain forests, including fruits, vegetables, and spices. The Amazon is also a wonderful place to find medicines. About 25 percent of current Western drugs are made from rain forest products, even though less than 1 percent of all the rain forest trees and plants have been tested as possible sources for pharmaceuticals.

- Preserving the integrity and biodiversity of the Amazon jungle is in the best interests of us all. As we said, the world gets 20 percent of its oxygen from the Amazon. The rain forests are also an important absorber of global carbon dioxide, significantly reducing the greenhouse effect. The prognosis today for the Amazon jungles is somewhat mixed; deforestation has decreased, but global warming has caused a significant drop in rainfall in the Amazon and a corresponding drop in vegetation.

Top River Basins

- The Congo River in Africa is the second largest basin in size and water outflow and drains most of the equatorial tropical jungles of Africa. It is fed by some of the African Rift Valley lakes, such as Lake Tanganyika on the east side of Africa.

- The Nile River Basin is essentially a narrow, linear oasis, stretching through an arid desert. Interestingly, Egypt's climate was much different between 7000 and 5000 years ago; the area was lush and supported large human populations.

- The Mississippi River delta drains most of the interior of North America. Its drainage basin is a fairly recent formation, developed after the last ice age. The Army Corps of Engineers works through a series of levies and dikes to keep the Mississippi in its current channel.

- The Yenisey River in Siberia is the largest river system that drains to the Arctic Sea. It drains a large portion of Eurasia, Siberia, and Russia, and its headwaters start in such places as Lake Baikal and parts of Mongolia.

Suggested Reading

Davis, *One River*.

Hemming, *Tree of Rivers*.

Questions to Consider

1. What would the Amazon Basin be like if the Andes Mountains didn't exist?

2. The island of Barbados, in the Caribbean, is at a subduction zone, but unlike most other islands in the area, it is not a volcano. It is made of sediments. Find it on a map; why do you think it is there?

Iguazu Falls—Thundering Waterfalls

Lecture 11

The Iguazu River starts near the city of Curitiba, just south of Rio de Janeiro and São Paolo in Brazil. Because a ridge of mountains runs along the coast, the river actually flows westward. Just as it reaches the border with Argentina, the river turns a wide corner and opens into the Iguazu Falls. These falls are not the world's tallest, don't have the highest annual flow, and don't even have the widest single sheet of water. But Iguazu Falls is the widest, at 2.7 kilometers, and because it is sometimes divided into 275 separate falls and cataracts as high as 60 or 80 meters, it is truly the most spectacular of the waterfalls around the world.

Erosional Power of Water

- The erosional power of water is quite remarkable. We might not think that water would have much of an effect on rock, but it is relentless. It beats on rocks repeatedly over the course of years, sandblasting them with sand and silt. Water can roll large rocks across the bottom of a river and can even develop swirling eddies that can turn a rock into a drill, boring down into the bedrock below. Of course, water creates these features over the course of thousands or millions of years.

- The erosional effects of rivers can give rocks varied textures, depending on the strengths of the rocks or the presence of preexisting cracks—joints that erode at different rates. These varying textures often account for the interesting appearances of waterfalls.

- You often don't need to travel great distances to see waterfalls. Such sites as Great Falls National Park on the Potomac River, near Washington DC, offer lovely views of waterfalls, although they may be small in comparison to Iguazu Falls.

A Tour of Iguazu Falls

- Iguazu Falls spans the Brazilian and Argentinian border. About two-thirds of the falls are on the Argentinian side, but the best views are from the Brazilian side. About half of all the water of the river flows down into a dramatic U-shaped waterfall called the Devil's Throat, which is both the tallest and the widest of any of the individual falls here.

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Many of the falls on the Argentinean side of Iguazu are spectacular in their own right and have individual names.

- A train takes visitors to the Devil's Throat, and a series of walkways allows people to get very close to the falls in many places. Some tour boats bring people under the falls. There are also trails to San Martin Island, which offers great views down the falls on both sides.

- Though people in South America lived with these falls for years, the first European to document them was one of the Spanish conquistadors, Álvar Núñez Cabeza de Vaca, in 1540. The local tribes had called the river Iguazu, which means "big water." One of the local legends attributed the existence of the falls to the wrath of a god who had planned to marry a beautiful mortal woman. The woman supposedly fled in a canoe with her mortal lover, and the angry god sliced the river, creating the waterfalls to make the lovers fall.

Formation of Iguazu Falls

- Like the layers of the Grand Canyon, Iguazu Falls is also a result of different rock layers that erode away at different rates but in a different way.
  - Here, a hard layer of rock sits on top of a softer layer underneath. As the water flows down over the top of the waterfall, it has a difficult time eroding the top cap rock, but it wears away at the bottom of the waterfall. That erosion eventually destabilizes the top layer, which will break off and fall to the bottom.

  - In this way, the river doesn't develop a gradual slope. The top stays level and then drops down at the fall, constantly receding backwards over time.

- Part of the explanation for this process is simply that water carries a tremendous amount of gravitational potential energy. The Sun provides this energy by evaporating the water, bringing it up into the atmosphere, and having it fall out as rain; as the water runs back down across the surface, its energy goes into erosion on the ground. Erosion is especially powerful at the bottom of a waterfall, where water falls a great distance.

The Tristan Hotspot

- At Iguazu Falls, the tough, resistant cap rock is a layer of basalt that flowed out across the land a long time ago. There are actually about 11 distinct layers of this basalt. But why do we find this igneous rock—formed at mid-ocean ridges—in the middle of the South American continent? The answer is related to the breakup of Pangaea but in a different way from what we've seen thus far.
  - Two million years ago, North America was breaking away from Africa and Eurasia, but South America stayed attached to Africa for another 60 million years. Starting about 135 million years ago, lava began pouring out of a spot along the location where Africa and South America would eventually break apart.

  - These eruptions of basaltic lava occurred for about 10 million years and are known as the Paraná-Etendeka flood basalts. The eruption would have been staggering—lava of a thickness of more than 1 kilometer erupting over an area of 1.5 million square kilometers.

- The cause of this eruption is thought to be related to a hotspot, just like the hotspot that is causing volcanism on the Galapagos Islands and may be related to the breakup of Africa. In fact, the hotspot still seems to be active. It is called the Tristan hotspot and is currently beneath Tristan da Cunha, an island in the Atlantic that is right along the Mid-Atlantic Ridge.

- The geologic community is engaged in a great deal of debate about the role that hotspots play in relation to mid-ocean ridges and the breakup of supercontinents. It doesn't seem possible that a hotspot like Tristan would be powerful enough to split South America away from Africa, but something similar seems to be happening beneath the Afar region in Africa right now.
    - Some geologists think that other forces were responsible for breaking up Pangaea and that the hotspot only helped, perhaps by making the separation easier.

    - The Tristan hotspot volcano is connected to the ancient flood basalts on Africa and South America by two ridges of elevated rock along the ocean floor. These ridges represent the continued volcanism that has erupted onto the ocean seafloor for more than 100 million years as the plates have moved apart.

- Two hypotheses have been put forth to explain why the Tristan hotspot (and several others) is at the Mid-Atlantic Ridge.
    - The first theory is that mantle hotspots control the location of ridges. In other words, the plates move around, but the place where they separate always gravitates toward the top of an anchored hotspot in the mantle.

    - Another theory is that mantle plumes can be swept toward ridges by the mantle wind. They may start somewhere else down deep, but as rock is moving apart at a mid-ocean ridge and the mantle flows up to fill that gap, the plumes might get swept in toward the ridges.

Hydroelectric Power

- The fact that a large amount of energy is released by falling water is important from a human perspective. This energy is tapped by hydroelectric power plants. Hydroelectric power is more important than wind, photovoltaic, and concentrated solar combined in terms of supplying energy for human use. It currently supplies 20 percent of the world's electricity.

- The second largest hydroelectric power plant in the world, Itaipú Dam, is a short distance up the Paraná River from the spot where it is joined by the Iguazu River. This power plant generates 14 gigawatts of power, an enormous amount of energy. It supplies 90 percent of Paraguay's electricity and about 20 percent of Brazil's.

- The Itaipú Dam, which elevated the water behind the dam, covered over the world's largest waterfall at that time, measured by flow. This was the Guaíra Falls that had flows of up to 50,000 cubic meters per second. Two of the world's other largest waterfalls, along the Columbia River between Washington and Oregon, have also been submerged by dams.

Top Waterfalls

- Victoria Falls is located on the border between Zambia and Zimbabwe in Africa, along the Zambezi River. Victoria Falls has the largest single sheet of water, 1.7 kilometers across. The locals call this waterfall Mosi-oa-Tunya, which means the "smoke that thunders," because of the large amount of mist that rises up from the base of the waterfalls from the crashing water.

- Niagara Falls is along the border between the United States and Canada. The combined Bridalveil Falls, in the United States, and Horseshoe Falls, in Canada, have the largest mean annual flow of any waterfall in the world. The water flows at a tremendous volume of 4 million cubic feet a second.

- Niagara formed when glaciers receded at the end of the last ice age, and water from the newly formed Great Lakes carved a path through what's called the Niagara Escarpment on its way to the Atlantic via the St. Lawrence River.
- The water here flows over a tough, erosion-resistant layer of limestone and dolomite. It then erodes away a weaker layer underneath, largely shale, called the Rochester Formation. This erosion causes the falls to recede southward at a fairly fast rate when compared to Iguazu Falls. Niagara has moved about 11 kilometers upstream in the past 11,000 years.
- The U.S. Army Corps of Engineers has changed the routes of some of the falls in recent decades to clear out debris and try to prevent the falls from falling at a faster rate. In one unusual instance, the Niagara Falls shut off naturally on its own. In March of 1848, ice blocked the falls, and no water went over for about 40 hours before the ice dam burst.

- Angel Falls in Venezuela is by far the tallest waterfall in the world. It's called the Kerepakupai Vená, "waterfall of the deepest place," by the local people. The waterfall here drops over the edge of the Auyantepui Mountains in the Canaima National Park. It has a total height of almost 1 kilometer and a single plunge of more than 800 meters.

- Plitvice Falls in Croatia is not the largest in any category but is possibly the most beautiful, with a long network of multiple waterfalls. Here, the water cascades gradually down a height of about 600 meters over a distance of 8 kilometers; it goes into 16 separate lakes and forms countless small falls throughout the whole forested area. The complexity of Plitvice Falls is the result of a network of caves that runs beneath the surface.

Suggested Reading

Lewis, *Waterfalls*.

Palmerlee et al., *Lonely Planet Argentina*.

Questions to Consider

1. What are the transfers of energy that occur in the process of obtaining and using hydroelectric power?

2. What do you think will happen to Lake Erie when Niagara Falls erodes all the way back to it?

Mammoth Cave—Worlds Underground

Lecture 12

In the last lecture, we looked at Iguazu Falls and some of the world's most spectacular waterfalls, but water doesn't just flow on the surface; it also flows underground. The result can be some of the most amazing geologic wonders on Earth: caves. The feature of this lecture is right in the middle of the United States: Mammoth Cave National Park in Kentucky. Mammoth Cave is currently mapped at more than 390 miles, but that number keeps growing with continued exploration. As we visit this wonder, we'll focus on caves as essentially missing rock, looking at networks of cave passages, huge caverns, and enormous holes that extend deep into the ground.

Cave Formation

- Most caves are found in limestone, a fairly abundant rock. Limestone is primarily made of calcium carbonate; the pure form of this is the mineral calcite, which dissolves in acid. In the atmosphere, carbon dioxide and water vapor naturally combine to form carbonic acid. In fact, rainwater itself is slightly acidic, and as it flows down through the ground, it picks up a variety of other acids, such as tannic acids. The reaction between limestone and water is one of the most common processes by which caves are formed.

- Another important aspect of cave formation is the fact that a good deal of water sits underground within small pores in rocks; these pores can make up 5 or 10 percent of rock. About 100 times the amount of fresh water at the surface is under the ground as groundwater. This groundwater is largely concentrated in the top part of the Earth because it has more pore spaces.

- In the very top part, the pore spaces of the rocks are usually filled with air. When it rains, that rainwater percolates down through this layer and accumulates in a fully saturated zone below that. The boundary between the air-filled pore spaces and the water-saturated pore spaces is called the water table. Unlike the surface of the Earth, the water table fluctuates over time, depending on climate. If there's a good deal of rainfall, the water table will go up.

- Caves form when the water table is above the rock, saturating the rock with water. Initially, the limestone is dissolved away and replaced by a red, iron-rich, clay-rich soil called terra rosa. In young cave passages, when the water table drops low, the flow of cave streams washes out the terra rosa, leaving empty passages behind. Cave formation is a runaway effect: more water, more erosion, more cave passages that allow more water, and so on.

- After an ice age, the enormous amount of runoff from melting ice causes the water table to rise up near the surface. During those periods, cave passages open up and widen. As the climate changes and the water dries up, the water table will eventually pass down through, exposing the caves, which now become filled with air. This iterative process takes place over, perhaps, hundreds of millions of years.

- At Mammoth Cave, a broad layer of limestone is capped by a stiff sandstone layer that has kept the cave stable and prevented the ground from eroding. This structure is similar to Iguazu Falls, with a tough capstone on top. The tough sandstone layer prevents the whole area from eroding too quickly; in a sense, it protects the cave network underneath.
  - The limestone rock that underlies Edmonson County in central Kentucky formed about 300 million years ago in the Mississippian Period. Interestingly, this period is also referred to as the Carboniferous Period because of the large amount of swampy plant matter from this time that was eventually compacted to form coal.

  - The United States has the largest coal reserves of any country because of the large amount of swamp and jungle land that covered much of the interior of the continent a few hundred million years ago.

- o At that time, places in the middle of the North American continent, such as Kentucky, were often at or near seal level, covered either with swampy vegetation or shallow seas where coral reefs grew. These reefs became buried by sediment, which compacted to become a layer of sandstone on top of the layers of limestone.

Formation of Mammoth Cave

- One reason that Mammoth Cave exists is that the land in this part of the country has a slight tilt, just enough to let water drain from the south to the north through this cave network. To the southwest of Mammoth Cave is a region called the Pennyroyal Plateau. Here, the hard capstone has eroded away, allowing water to percolate down into the exposed limestone layers. Once the water gets in, it runs through the vast network of underground caves toward the north, where it eventually flows out as springs into the Green River.

- The network of caves is quite complicated and spread out over a wide area. Many of the paths for the caves are aligned with parallel sets of cracks—jointing—that form during plate tectonic activity.

- Different layers of limestone have separated the caves into five vertical layers. These layers developed largely independently, although there are connections where water flows down through them. Large streams still flow through the bottom layer.

Mapping Mammoth Cave

- Many expeditions have taken place in Mammoth Cave, and some mapping is currently being done by the Earth and Planetary Sciences Department at Washington University in St. Louis. These expeditions can be extremely strenuous; geologists hike up and down jagged passageways and crawl through narrow fissures in total darkness.

- Unlike mapping topography on land, everything in a cave is in three dimensions, especially at Mammoth, where there are five separate layers of caves. At the surface, if you want to know where you are, you pull out your GPS device, which gives you latitude, longitude, and elevation, but because radar doesn't go through solid rock, all the mapping of caves must be done by hand, usually with fiberglass tape measures.

- The mapping of caves also involves the use of a Brunton compass, which responds to the magnetic field to indicate north, and an inclinometer, which gives angle readings. Newer techniques for mapping use a light detection and ranging (LIDAR) device, which provides a three-dimensional picture of the cave interior.

Description and History of Mammoth Cave

- Because of the overlying sandstone cap in Mammoth Cave, relatively little water leaks in from above; thus, the passageways are often empty and have none of the spectacular formations, such as stalactites and stalagmites (speleothems), seen in other caves. One famous formation in Mammoth Cave is a room with an enormous canopy of flowstone, called the Frozen Niagara.

- Visitors are attracted to Mammoth Cave for its sheer size: passageways that head straight for miles, solution pits that drop down to enormous depths, giant natural domes that develop by the repeated collapsing of a ceiling, and caverns that could fit whole houses.

- Partly becomes of its great size, Mammoth Cave has had a particularly interesting history. The mummified remains of Native Americans from at least 4000 years ago have been found there. These remains are so well preserved that researchers have been able to determine what these people ate and speculate about the kind of society in which they lived.

- The land above Mammoth Cave was purchased in the late 1700s by Valentine Simons, who immediately started mining it for saltpeter—potassium nitrate that is a key ingredient in gunpowder. This area was an important source of saltpeter during the War of 1812, when the British navy blockaded American ports. After the war, prices of saltpeter and other minerals fell, and the cave began to be used for tourism rather than mining.

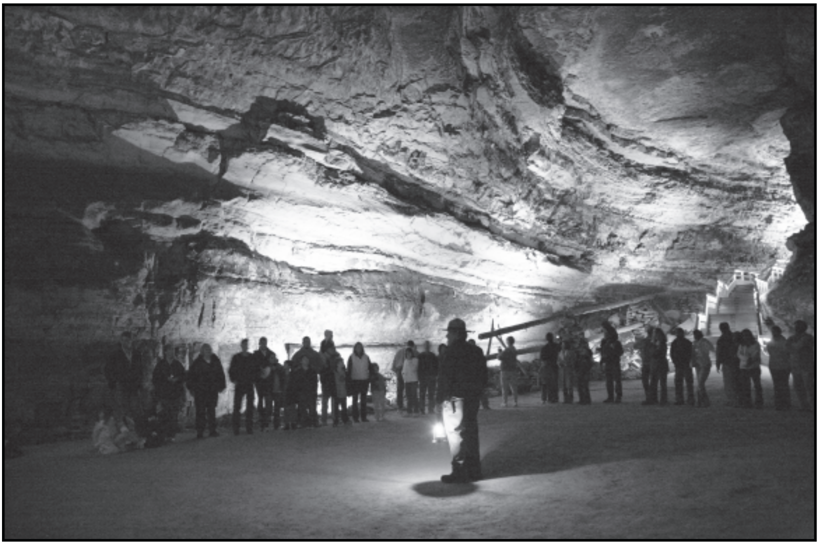
- In 1838, the cave was purchased by Franklin Gorin. His African American slave, Stephen Bishop, made many discoveries in the cave. Bishop found passages heading down into the lowest level of the cave and discovered the flowing River Styx, where parts of the cave are still forming today.

- In the late 1800s, with travel opened up to the Midwest by the railroads, Mammoth Cave became an international geologic wonder, and many people came to visit. The famous actor Edwin Booth, brother of John Wilkes Booth, visited the cave. In fact, a room is named after him, Booth's Amphitheater. A famous violinist at the time, Ole Bull, gave a violin concert at Mammoth Cave, and a room is now named after him, Ole Bull's Concert Hall.

- Mammoth Cave was finally commissioned as a national park in 1926 but, because of legal problems, was not fully established until 1941. Since then, continued exploration has found not only many unknown passages but also links between many of the competing caves. In 1972, a single link was found between the large Mammoth Ridge Cave system and the Flint Ridge Cave system, two separate cave networks that had been mapped independently.

- Today, the park runs tours to many parts of the cave, some of which allow visitors to experience what caving is really like. For those who are in good shape, the half-day tour provides the best feel for the size and scope of the passages.

- A unique, delicately balanced ecosystem exists in Mammoth Cave. It is home to bats, albino salamanders, the Kentucky cave shrimp, and rare blind beetles. A whole world of life goes on underground, totally removed from our lives at the surface, somewhat analogous to the strange ecosystems we saw at the mid-ocean ridges.



The tours of Mammoth Cave range from an hour to more than 6 hours; for some, visitors have to bring their own lanterns.

Top Caves

- In the rugged and heavily forested Phong Nha-Ke Bang National Park in central Vietnam is Son Doong Cave. This cave has corridors that are 150 meters wide and extend for 5 kilometers and has by far the largest single cavern in the world, only discovered in 1991.

- Deer Cave in the Gunung Mulu National Park in Borneo is situated in a mountainous equatorial rain forest. One part of the cave is about 170 meters wide and 120 meters tall. It held the record for the world's largest cave before the Vietnamese caves were discovered.

- Mexico's Cave of Swallows, in the mountainous area northeast of Guadalajara, has the tallest continual vertical shaft in the world, dropping straight down 1200 feet from the surface. The Chrysler Building in New York City would easily fit inside this cave.

- The Skocjan Caves Regional Park is just south of the capital of Slovenia, Ljubljana. This is a huge underground canyon, 3.5 kilometers long, 140 meters high, and 10 to 60 meters wide, with a river running through it.

- Voronya Cave in Abkhazia, a breakaway republic of the country of Georgia, is the world's deepest known cave. It has now been mapped down to 2191 meters—more than 2 kilometers into the Earth.

Suggested Reading

Molloy, *A FalconGuide to Mammoth Cave National Park*.

Palmer, *Geological Guide to Mammoth Cave National Park*.

Questions to Consider

1. Many cave systems have channels that follow straight lines. How do you think these might have formed?

2. Why is limestone the most common host rock for caves?

Cave of Crystals—Exquisite Caves

Lecture 13

In the last lecture, we looked at Mammoth Cave and the largest cave systems in the world. In this lecture, we will focus on the spectacular crystals and formations that can be found inside caves. To see these structures, we will visit the site of the world's largest known crystals, the Cueva de los Cristales, or Cave of Crystals, in Mexico. This amazing site was found only because it happened to be in the same area where mining was taking place. The accidental discovery of the Cave of Crystals reminds us that we have literally just scratched the surface in terms of exploring the geologic treasures of the Earth that lie underground.

Crystal Formation

- If you put table salt (sodium chloride) in water, the polar nature of the molecules of the water will break that mineral apart into separate sodium and chlorine ions. When the water evaporates or boils away, the other materials are left behind; the ions come back together again and re-form the original mineral.

- You can see this process yourself by dissolving borax, sugar, or salt in hot water; inserting a string in the mixture; and leaving it for a few hours or days. When the water evaporates, you'll find that crystals have re-formed along the string. If you use sugar for your experiment, you can make rock candy.

- As mentioned in the last lecture, a cave is empty space inside rock. Water—with many minerals dissolved in it—drips down into the cave and then evaporates, leaving behind those dissolved minerals, which then begin to crystallize. Water dripping down from the ceiling of the cave may begin to deposit the multiple layers of a stalactite.

- Caves usually form in limestone, which is mostly made of calcite, a mineral composed of calcium, carbon, and oxygen (calcium carbonate). Because calcite dissolves easily in slightly acidic water, the minerals that usually deposit in caves are also calcite. Water percolating down through the limestone dissolves the calcite along its path, flowing through narrow holes and cracks; when it reaches an open cave, the water evaporates and the calcite recrystallizes.

- Calcite precipitates hanging down from the ceiling are called stalactites, and those building up from the floor are called stalagmites. Stalactites aren't usually very long, but some can be enormous. The tallest known is more than 200 feet long, hanging down from a ceiling of a cave in Cuba, the Cueva Martin Infierno.

Types of Cave Formations

- A typical limestone cave has stalactites in different forms hanging down from the ceiling. Stalactites can be single or in large groups. Sometimes, they cover the entire cave ceiling in a beautiful display of different sizes and shapes. Sometimes they form narrow conduits, known as soda straws, and sometimes they flow out in wide drapery-shaped structures, known as flowstone or dripstone.

- Stalagmites sometimes appear as a jumbled heap of structures, or they may look like fascinating towers or elaborate candelabras. They may form in a variety of colors—a result of the fact that water travels through different rock deposits at different times, dissolving various kinds of minerals.

- When a stalactite and a stalagmite grow toward each other, they may eventually form a column, which can stretch long distances, from the floor all the way up to the top of the cave. Sometimes these columns have incredibly textured appearances, with fluted or corrugated shapes.

- Sitting water within a cave may form lily pad–like structures on the ground. These are actually calcite pads that grow horizontally because the water that's present is supersaturated in calcium carbonate. When the pads are exposed above the water surface, stalagmites may grow out of the top.

- Because many caves are made of limestone, it's also possible to see fossilized objects hanging down from the ceiling, such as fossilized stromatolites. These are deposits of ancient algae that formed a large mat in some tidal lagoon hundreds of millions of years ago and became buried and fossilized.

Gigantic Crystals

- Up until a few years ago, the Cave of Crystals, part of a larger cave area called Naica Cave, was totally flooded with water. It was drained because it's in the middle of a large mining complex that contains large amounts of silver, gold, zinc, copper, lead, and other metals.

- In 1910, workers at the Naica Mine in Mexico first discovered a room, about 400 feet deep, with many crystals measuring 1 meter long; the room was dubbed the Cave of Swords. The crystals there were made of a mineral called selenite, which is a form of gypsum that has water as part of the crystal structure. The Cave of Swords had huge numbers of long, thin crystals hanging from the walls.

The Cave of Crystals is maintained with high heat and humidity; even with protective gear, people can stay in the cave for only 10 or 20 minutes at a time.

- The Cave of Crystals is located at a greater depth beneath the Cave of Swords. It's a small room, about 10 meters by 30 meters. When it was first discovered in 2000, it was totally filled with water that was about 136°F. Because mining was going on at a level below the Cave of Crystals, the water was pumped out, uncovering giant selenite crystals up to 11 meters long and 1 meter thick and weighing up to 55 tons. These crystals are the largest found anywhere in the world.

- Scientists aren't exactly sure how these giant crystals formed. According to one leading hypothesis, volcanic activity in the region more than 25 million years ago heated the deep groundwater, which then began to percolate up along a series of faults. These faults formed as part of a set of stresses that pushed up the layers of the rock to form an upside-down V shape, called an anticline in geology.
    - It's not clear whether the caves already existed, but it's probably the case that the rising hot water was responsible for creating the Naica Cave system by dissolving away the rock.

    - The exact manner in which the giant crystals formed is a little bit less certain. Most likely, hydrothermal waters that are rich in calcium and sulfate dissolved out the deeper rocks; within the cavities that were dissolved, the mineral anhydrite began to crystallize.

    - Anhydrite is stable only at high temperatures, above about 136°F. As the water began to cool, the large amount of anhydrite began to dissolve back into calcium and sulfate ions and then immediately recrystallize into selenite, which is stable at slightly cooler temperatures.

    - The water remained supersaturated with calcium and sulfate ions as the anhydrite slowly—over the course of hundreds of thousands of years—dissolved to form selenite. Scientists re-creating the conditions of the cave in a lab have found that the crystals grow at the rate of about one-billionth of a meter per day. That means that the largest of these crystals could be much more than 1 million years old.

- Ironically, these crystals survive only in water; once out of water, they start to dry up, lose their transparency, become brittle, and crack. The air inside the cave is now kept at about 112°F with 100 percent humidity. It is likely that the cave will eventually be allowed to flood again to preserve the crystals.

- Why do selenite crystals have their particular shape? Though crystals can grow quite large, they form one atom at a time, and for every particular mineral, the atoms have particular ways of combining. Salt crystals tend to form perfect cube shapes, quartz crystals tend to have six sides, and so on. Selenite tends to have long, column-shaped crystals, although it can also form table-shaped or rose-shaped crystals.

- It's no coincidence that these crystals were found in a mine with gold, silver, and lead. The location of our mineral reserves on the surface of the Earth is directly connected to plate tectonics.
    - As we discussed, incompatible elements, such as gold, tungsten, and so on, are dissolved out of rock at hydrothermal vents in mid-ocean ridges and deposited as a layer on the surface of the ridge. Over time, those surface minerals reach a subduction zone and sink back in. The ridge is like a conveyor belt carrying minerals out of the ocean seafloor and bringing them to a subduction zone.

    - Of course, volcanoes occur at subduction zones. The minerals are dissolved out of the rock again and brought up close to the surface, removing them from hot areas and precipitating them in colder areas. The locations of rich mineral resources around the world are not random; they are a direct result of the particular geologic histories of each region of the Earth.

Top Cave Formations

- The Aven Armand Cave is located in a wild, beautiful, mountainous area of southern France in the Cévennes National Park, not far from the Mediterranean coast near Montpelier. The main chamber of this cave is about 75 meters high. The cave itself has some of the most spectacular examples of a particular type of stalagmite that has a fluted pinecone or stacked-plate shape. These structures form in places where the ceiling is high and the water that falls through splashes outward when it drips down on the floor. The tallest of these pinecone-shaped stalagmites is about 30 meters (100 feet).

- The Baradla-Domica Cave in Slovakia is about 21 kilometers long. It's part of a larger network of about 700 karst caves spread out over about 200 square miles. The caves here are filled with beautiful structures that include cascading dripstone shields and drums and bizarre onion-shaped and pagoda-shaped stalactites.

- The Jeita Grotto in Lebanon is a 9-kilometer network of caves. It can be visited only by boat along an underground river. Some of the calcite dripstone here is pure white, and some is red as a result of the presence of iron oxide. The cave's main claim to fame is an 8.2-meter (27-foot) stalactite that is said to be the longest stalactite known anywhere in the world.

- Lechuguilla Cave is in the Carlsbad Caverns National Park in New Mexico. Unlike other caves, this one was formed by rising sulfuric and other acids released underground from oil and natural gas reserves. The sulfuric acid colors some of the rock structures yellow or orange. A large number of rare cave features are found here—20-foot-long gypsum chandeliers, soda straws that reach down 10 or 15 feet, hydromagnesite balloons, cave pearls, and helictites and rusticles.

Suggested Reading

Palmer, *Cave Geology*.

Waltham, *Great Caves of the World*.

Questions to Consider

1. The Cave of Swords contains the same kind of selenite crystals as the Cave of Crystals, but they are at most about 1 meter in length, while the crystals in the Cave of Crystals can be more than 10 meters long. Can you think of a reason that might account for the difference?

2. Footprints in the surface of the ground might last for only days or weeks, whereas they can last for thousands of years inside a cave. Explain why this is so.

Great Blue Hole—Coastal Symmetry in Sinkholes

Lecture 14

Belize has the second longest coral reef in the whole world, second only to the Great Barrier Reef in Australia, and it's a favorite location of scuba divers and snorkelers. In a section of the Belize Barrier Reef called the Lighthouse Reef is an almost perfectly circular hole that's 318 meters across (almost 1000 feet) and plunges straight down to a depth of about 125 meters (more than 400 feet). The water inside appears deep blue, and the walls of this beautiful Blue Hole are lined with coral and even stalactites.

A Top Spot for Scuba Diving

- Part of the reason for the name of this geologic wonder, the Great Blue Hole, is the deep blue appearance of the water inside the hole compared to the surrounding water.
  - Water naturally absorbs a certain amount of red light; the longer that light passes through water, the bluer and darker it appears.

  - The water around the hole is quite shallow and clear, and the sand is white, made from ground-up coral. Light that penetrates the water there travels only a short distance through the water, reflects off the white bottom, and travels a short distance back through the water. In such a short distance, only a small amount of the red light gets absorbed by the water; thus, the light is a very light blue.

  - When you look at the hole, however, most of the light that's coming out of the water has had to travel a much greater distance and looks dark blue.

- This region was made famous by the oceanographer Jacques Cousteau, who considered it to be one of the top places in the world to scuba dive. The reef is made of many layers of coral, produced by organic processes. It is home to many kinds of fish, including rays and sharks.

- If you scuba dive down into the Blue Hole, at first, you see vertical walls sloping slightly inward, but when you reach a depth of about 35 meters, you begin to see stalactites. Some of these are as long as 8 meters—more than 25 feet. Toward the bottom of the hole, the walls slope back outward, giving a rough hourglass shape to the entire hole.

Formation of Sinkholes

- Circular sinkholes form in limestone rock all over the world above land. Such sinkholes are part of a particular type of geologic terrain called karst terrain. In an area with a great deal of limestone, such as the area around Mammoth Cave, networks of caves develop underneath the surface, and at times, the surface can begin to collapse. Over time, the surface develops a pitted look, with circular sinkholes where cave roofs are collapsing under the weight of the ceilings. In a sense, development of sinkholes is an extension of the cave-making process.

- Another possible explanation for the existence of the Blue Hole relates to rising sea levels.
    - The sea level has risen by 400 feet since the end of the last ice age. The coral reef of Belize is shallow now because it's actually a continent that has been flooded, and the reef sits on top of a layer of limestone that is a fossilized reef from hundreds of millions of years ago. The Blue Hole is a sinkhole that formed when it was far above water, with empty caves below the surface, and the roof fell in.

    - Now that the sea level has risen, the sinkhole is below water, new coral is growing around it, and a new reef is growing on top of the ancient reef.

    - In fact, Belize isn't the only place where a continent is underwater. Much of the world's continental material is ringed by a continental shelf that can extend seaward for hundreds of miles. Thirty-nine percent of the Earth's surface is continent, but 30 percent of the surface is land; the missing 9 percent is continent that has flooded—the continental shelf.

Rising Sea Levels

- Sometime between 20,000 and 24,000 years ago, we were still in the midst of a deep ice age, but as the climate began to warm, the ice melted and the sea level began to rise. Starting about 15,000 years ago, the sea level rose rapidly, not leveling off until about 7000 or 6000 years ago. During that period, enormous amounts of water flooded into the oceans from melting ice.

- The melting of the ice was part of a much larger cycle that has continued for millions of years. A plot showing the average temperature in Antarctica, based on ice cores taken from the present back 800,000 years, reveals a 100,000-year ice age cycle.
  - Earth's orbit around the Sun varies from close to circular to much more elliptical. This eccentricity is driven by the gravitational tug of Jupiter, Saturn, Venus, and Mars as they orbit around the Sun.

  - When our orbit becomes stretched out a little bit more, our planet, on average, spends more time farther from the Sun. Climates grow cold, and we get an ice age. When our orbit becomes more circular, we get more sunlight over a year and the climate warms up.

  - The eccentricity of Earth's orbit, combined with the tilt and procession of its axis, changes the amount of sunlight we get over a year and how it is distributed between the Northern and Southern hemispheres. This is what drives the cyclical nature of our ice ages.

- The temperature changes correspond to a change in carbon dioxide in the atmosphere, both increasing or decreasing together. Of course, carbon dioxide is a greenhouse gas and is vital in insulating us from the chill of space.

- Still not entirely known is why the temperature increased so quickly 15,000 years ago. It seems that such increases come suddenly at the end of a long period of ice ages, as the environment returns to a fairly short period of warm temperature (an interglacial). Some scientists believe that methane trapped in ocean sediments along shallow coastline areas may be released when sea levels drop, spiking a runaway greenhouse effect that suddenly turns the climate warm.

- At one time, the Great Blue Hole was just another sinkhole; with so much ice on land near the poles, it was almost 400 feet above sea level during the last ice age. The bottom of the cave went down about 400 feet, right at sea level. Caves were drying out underground at this time, and the roof of one of them simply fell in. It was at just the right elevation to then be below sea level, creating perfect conditions for the growth of coral.

Inside the Great Blue Hole

- About 50 meters down into the Great Blue Hole, a cave extends off the side into the limestone wall on the west. That cave begins to slope upward, rising more than 40 meters; it then extends almost 50 meters farther west and is filled with the skeletons of animals that have gotten trapped inside.

- Dripstones extending down from the ancient cave ceilings are sometimes tilted by up to 5 degrees. It's possible that when the Blue Hole was a cave, air currents caused the dripstones to lean in one direction as they formed.

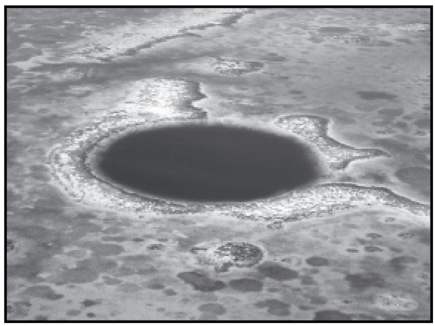
- Another unusual discovery is a layer of brownish water that extends from about 90 to 100 meters below the surface with high concentrations of hydrogen sulfide. Water above and below this layer is crystal clear, but the water underneath doesn't contain any dissolved oxygen. This means that the very bottom of the Great Blue Hole is lifeless.
    - This unusual hydrogen sulfide layer seems to be caused by a layer of microorganisms that feed on organic sediment drifting

down in the hole. As the organic sediments are decomposed, the microbes consume the oxygen and give off the hydrogen sulfide.

- o The lack of oxygen makes this deep water extremely acidic, which may be a factor in forming the hourglass shape of the sinkhole.

- The bottom of the hole is so deep that the normal activity of burrowing worms doesn't occur there, as it does in other ocean sediments. The sediments that fall remain undisturbed for thousands of years. Further, there are no waves or ocean currents below a depth of about 20 meters here. Incredible as it may seem, scientists are learning how to correlate periods of severe desertification in the Sahara with the history of global climate changes by looking at sediments at the bottom of the Blue Hole.

Top Sinkholes



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The Blue Hole is aesthetically beautiful, and it reveals geologic clues that tie in with global events.

- The Bahamas are covered with sinkholes sitting just under the water; the deepest of these is Dean's Blue Hole, which goes down 202 meters. The largest number of these sinkholes is found around Andros, the main island of the Bahamas. Like the Great Blue Hole, these sinkholes formed during ice ages when the sea level was low.
  - o The caves extending off the blue holes in the Bahamas are as spectacular as any caves elsewhere, with such features as stalactites, flowstones, soda straws, and so on. They remain largely unexplored because of the difficulties they present for divers.

    - Black holes form a bizarre subset of the sinkholes in the Bahamas. In the Black Hole of Andros, at a depth of about 18 meters, the perfectly clear water suddenly becomes black and purple, with a jellylike layer of bacteria that eat sulfates in the water. The layer is about 1 meter thick, after which the water becomes clear again.

- El Zacatón, located along the Gulf Coast, not too far south of the border with Texas, is the deepest water-filled sinkhole anywhere in the world at 1112 feet. The bottom has been mapped by a NASA probe that was developed to look at conditions where life might exist on other planets or moons.

- The Arecibo radio telescope, the world's largest radio telescope, is built inside a sinkhole in Puerto Rico.

- In China, the Xiaozhai and Dashiwei sinkholes are the world's largest, both at more than 600 meters wide and 600 meters deep. In Chinese, they are called *tiankeng*, which means "heavenly pit" or "sky hole."

Suggested Reading

Cousteau, *Three Adventures*.

Dobbs, *Reef Madness*.

Questions to Consider

1. What is the connection between cave systems and sinkholes?

2. What would the Blue Hole look like if the sea level hadn't risen?

Ha Long Bay—Dramatic Karst Landscapes

Lecture 15

In the last few lectures, we've talked about caves and sinkholes, but we might think of what happens at Ha Long Bay on the northern coast of Vietnam as something like caves and sinkholes taken to their extreme. Geologically speaking, caves and sinkholes are early stages of karst geography. In some areas that have sinkholes and are subject to a great deal of rain over a long period of time, the sinkholes merge together, leaving numerous caves and underground rivers beneath the surface. Much of the surface itself collapses, and only the toughest, most weathering-resistant features remain standing. The result is a landscape such as what we find in Ha Long Bay.

Description of Ha Long Bay

- Ha Long Bay is a spectacular region off the coast of Vietnam that consists of thousands of islands, primarily tall, often cone-shaped limestone towers. Some of them are more than 200 meters high. To understand what's happening in this striking landscape, we have to think about what we don't see here.

- Try to imagine the land that was here before it was eroded. Perhaps it was a high plateau surface far above the tops of the current towers. When you look with the eyes of a geologist, you suddenly see all the limestone rock that has been worn away.

- Recall from the last lecture that the sea level has risen 400 feet over the past 20,000 years. The Ha Long Bay area was far above water not too long ago, with the coastline down to the south. Now, the whole area is flooded with a fairly shallow layer of water. In fact, the sea level has sat at many different levels over time; we can see this in the history of the erosion along the sides of the limestone towers.

Formation of Ha Long Bay

- Many of the limestone rocks here date back to a time 500 million years, when the whole area was flooded by the ocean. Around 350 million years ago, this area underwent a major tectonic collision that caused the layers of rock to be tilted and folded. By 70 million years ago, the area was caught in another giant mountain-building process associated with the movement of India across the Tethys Sea and its collision with southern Asia.

- That collision pushed up the rocks of Ha Long Bay to high elevations, forming tall mountains that immediately began to erode. Even more important for the formation of the current karst towers, the collision created a broad set of parallel cracks in the rocks called joints.

- These joints provided places for rainwater to percolate down into the rock over the course of tens to hundreds of millions of years, causing fissures to develop in caves underground. Over time, these cracks widened until there were large spaces between the towers.

- The rainwater percolating down through the towers has created an extensive set of caves throughout this whole area. When parts of the towers collapse, they often reveal unknown caves within them. The rising and falling sea level affects the towers, as well. It has created notches in the bases of the towers and keeps them steep-sided.

- The islands at Ha Long Bay are sometimes covered with lakes that are essentially filling in the collapsed sinkholes along the very tops of the towers. Again, that's another clue that we're looking at a very eroded, old surface. The whole region used to be covered with these sinkholes. Some of them have grown so large that they've worn everything away except for the towers.

Human History at Ha Long Bay

- People started living at Ha Long Bay around 16,000 years ago. They fed largely on a diet of freshwater shellfish that are commonly found in mountainous areas of China and Vietnam today. This evidence tells us, again, that Ha Long Bay was once a mountainous area, not at all near the ocean.

The limestone in Ha Long Bay was formed when the area was flooded by ocean, in much the same way that the rock of the Grand Canyon and Burgess Shale formed.

- By 5000 years ago, the sea level had risen close to its current level and the ancient peoples had to develop boats to get around the islands that had formed.

- The name "Ha Long" means "dragon descending"; many local myths are told about how the islands formed, and they're always associated with dragons. According to one legend, Ha Long Bay was formed when the forefathers of the modern Vietnamese were forced to defend their lands from Chinese invaders. The gods sent a family of dragons to help the defenders, and the dragons spit out jewels that formed the islands when they hit the water, providing shelter and protection for the people there.

- In the year 1288, a famous sea battle occurred in Ha Long Bay between the Vietnamese and the Mongol forces of Kublai Khan, grandson of Genghis Khan. The Vietnamese navy trapped Kublai

Khan's ships in the labyrinth of channels of the Bach Dang River at Ha Long Bay, winning a rare victory against the Mongols. Unfortunately, that battle was not the last warfare this region has known. Many of the channels around the islands are impassable today because of mines installed by the United States during the Vietnam War.

- Today, the area of Ha Long Bay is sparsely populated, with only about 1500 people living there in floating fishing villages. Increasingly, tourist boats are polluting the waters.

Top Karst Formations

- The spectacular towers along the Li River in the Guilin region of China have inspired Chinese art and poetry for centuries. Guilin has about 5000 square kilometers of truly dramatic karst towers.
    - The karst peaks in Guilin come in two general categories: as standalone towers, called fenglin, and as cones that are often closely spaced and connected at their bases, called fengcong.

    - Archaeological remains of people have been found near Guilin, dating back 30,000 years ago, some of the earliest people coming from Africa that reached the far eastern end of Asia. The city of Guilin itself was developed more than 2000 years ago during the Qin dynasty.

    - The names of some of the hills here give a sense of their striking appearance: Cloud-Catching Pavilion, Bright Moon Peak, White Horse Cliff, Five Tigers Catch a Goat Hill, Folded Brocade Mountain, Elephant Trunk Hill, and Nine Horses Mural Hill.

    - Because these are karst lands, there are also numerous spectacular caves in the area, many of them developed for tourists to visit.

- Phang Nga Bay is a region of about 400 square kilometers in the Andaman Sea, between mainland Thailand and the island of

Phuket. The 42 islands here have a similar appearance to Ha Long Bay. Again, these are karst towers that were flooded when the sea level rose at the end of the last ice age.

- By far the most famous of the Phang Nga towers is the so-called James Bond Island. This tower featured prominently in the James Bond movie *The Man with the Golden Gun*.

- Another unusual site in this region is Ko Panyi village, where about 2000 people live in houses built on stilts in the middle of the water of the bay.

- The chocolate hills in the island province of Bohol in the Philippines form a strange landscape, consisting of more than 1000 small, cone-shaped hills in weathered limestone. Some of these mounts may be 30 to 50 meters tall.
  - Though the general area is forested, the hills themselves are covered with grass; thus, they're bright green in the rainy season and turn a dark brown in the dry season, giving the appearance of more than 1000 Hershey's chocolate kisses, which is the origin of their name.

  - The limestone here tends to be sandy and rubbly, which explains the cone shapes seen here, as opposed to the steep towers at Ha Long Bay. The limestone also contains many marine fossils.

- The mogotes in Cuba are rounded limestone or marble hills that rise up above flat plains. Because they have a capstone—stiff limestone on top of a layer of weak, rubbly limestone—the mogotes in Cuba tend to be very steep. We saw something similar in Iguazu Falls.

- The karst development in these parts of the world has been going on for so long that scientists can sometimes use stalagmites in caves to determine the history of climate change, such as the timing of the monsoon rains during the last period when the climate was in between ice ages.

- Stalagmites and stalactites take tens of thousands of years to form and use whatever atoms are available at the time to build up their calcite crystals; this buildup gives us a record of the minerals that were in the water in earlier times, from which we can get a sense of climate change.

- For example, in the Dongge Cave in the Guilin region of China, climate scientists use radioactivity to determine the ages of the layers of the stalagmites, then use the chemical composition of the stalagmites to determine when the heavy rains of a monsoon climate occurred in the past.

- These scientists have found that monsoons turned on suddenly 129,000 years ago, which corresponds to the start of the last interglacial period. The monsoons suddenly turned off about 10,000 years later, marking the start of the last ice age.

- Interestingly, some human communities grew larger during the last interglacial period, about 130,000 years ago, taking advantage of the warm climate and fertile soils. However, the climate returned to an ice age before civilization could take hold. Another long warm period has since allowed civilization to become firmly entrenched before the next ice age starts.

- The Earth reached a temperature peak about 8000 years ago and started to drift back into an ice age, but we have moved ourselves out of that ice age by putting 35 billion tons of carbon dioxide into the atmosphere each year. When oil and coal run out and we stop putting carbon dioxide into the atmosphere, will we return to an ice age?

Suggested Reading

Gregory, *The Earth's Land Surface*.

Veni et al., *Living with Karst*.

Questions to Consider

1. What might control the distance between karst towers in terms of how they initially form?

2. When you look at all the places that have tall karst towers, can you describe the geologic history they must share to be so similar?

Bryce Canyon—Creative Carvings of Erosion

Lecture 16

In the past few lectures, we've seen some geologic wonders that occur in karst regions, where weathering and erosion from rain wear away both at the surface and in the interior of layers of limestone. In this lecture, we'll look at other forms of erosion caused by rainwater, specifically in Bryce Canyon in the state of Utah. To some degree, everything on the surface of the Earth shows the effects of erosion. Most geologic features on Earth's surface, such as mountains, form slowly over millions of years, and they erode as they form, but even those features that form quickly, such as volcanoes, still show the effects of weathering and erosion almost as quickly as they are built.

Weathering and Erosion

- The processes of weathering and erosion are slightly different. Weathering is the disintegration of particles of rock in place and is done by a variety of mechanisms, including mechanical (abrasion, expansion of ice in rocks) and chemical. Erosion is the removal of weathered rock. The two processes work together: Weathering breaks down the rock, and erosion wears it away and carries it away.

- Weathering occurs over human time scales, and humans are increasing the rate at which weathering operates by increasing the acidity of rainwater. The result is that buildings and sculptures made by humans start eroding as soon as they are erected. Sometimes, we can even quantify the erosion rate by looking at the dates on a building or a tombstone.

- Remarkable geologic features that have been carved by erosion can be found almost everywhere.

Hoodoos on the Colorado Plateau

- The sudden appearance of Bryce Canyon out of a broad, level plateau is similar to what visitors experience in approaching the

Grand Canyon. But here, instead of rock layers exposed by the down-cutting of the Colorado River, we see a bizarre display of pinnacles jutting out of the ground that don't seem to have any obvious means of formation.

- In reality, Bryce Canyon isn't a canyon at all because it wasn't formed from a river; technically, it's called an amphitheater. It has the densest display of "hoodoos" found anywhere in the world; hoodoos are unusual totem-pole structures that are much wider at the top than in the middle.

- We've already discussed some of the geologic processes that are at work in Bryce Canyon, such as the deposit of sedimentary layers in an ocean environment, the formation of joints and cracks, and differential erosion. In Bryce Canyon, these processes began more recently—about 100 million years ago—than in other sites we've visited.

Bryce Canyon is eroding at the rate of about 1 centimeter a year, or 1 meter every 100 years; in geologic time, it won't be long before the spectacular hoodoos are entirely gone.

- During the Cretaceous period—the age of the dinosaurs—an inland ocean called the Cretaceous Seaway existed in Utah. It was surrounded by mountains on either side, in California and Colorado.
  - If we look at a geologic cross-section of Arizona and Utah, we see that the rock layers of the Grand Canyon and Bryce Canyon are related. The layers at Bryce Canyon are on top and are much younger (40 million to 60 million years old) than the youngest rocks at Grand Canyon (240 million years old).

  - In between Grand Canyon and Bryce Canyon are some other spectacular locations, in particular, Zion National Park. The rocks there are younger than those of the Grand Canyon but still about 100 million years older than those at Bryce Canyon.

  - This sequence of rocks, from the deeper, older rocks of the Grand Canyon to the younger rocks of Bryce Canyon, is known as the Grand Staircase.

  - Again, on a diagram, we see that the layers of the Grand Canyon extend for great distances in all directions. When we follow the layers to Bryce Canyon and Zion Canyon, we find that the same layers are deep underneath those structures.

  - If you travel in this area, when you cross from one layer into the next, you go through several staircases: the Vermilion Cliffs, the White Cliffs, Zion Canyon, the Gray Cliffs, and Bryce Canyon.

- The process of forming these staircases started about 70 million years ago, the time when the Rocky Mountains were starting to form and the Colorado Plateau was lifting up. This uplift closed off the Cretaceous Seaway; the latest sediments there would become Bryce Canyon. These sediments, beginning about 60 million years ago, consist of alternating layers of limestones, siltstones, and mudstones.

- The Colorado Plateau began its major uplift phase starting at about 20 million years ago. This uplift caused the jointing that cracked the layers and created opportunities for water to seep in and begin forming the spectacular rocks we see at Bryce Canyon. It also caused faulting that lifted up the canyon.

- The Colorado Plateau isn't just one single block of rock. It's broken into several blocks that are separated by faults; these blocks moved different amounts at different times. The faults brought different parts of the plateau to different resting elevations.

- The breaking up of the Colorado Plateau into several different blocks exposed the edges of the blocks where they were separated by faults. This process allows an increased rate of erosion to occur at these locations.

- Bryce Canyon exists along the edge of one of these faults, called the Paunsaugunt Fault, and the topmost layer of Bryce is called the Paunsaugunt Plateau.

- The uplift here also played a role in creating vertical joints that run throughout Bryce Canyon; these joints provided channels for water to flow down, causing weathering and, eventually, wearing away the rock to yield the spectacular hoodoos.

Weathering at Bryce Canyon

- The mechanism for weathering at Bryce Canyon is not the same as we saw at Ha Long Bay because the environments are different. Ha Long Bay is at sea level and only about 20 degrees north of the equator. Bryce Canyon is about 37 degrees north of the equator and more than 1.5 miles above sea level; the weather is cold here both at night and in the winter. Thus, what causes the erosion at Bryce Canyon is not rain but ice.

- The process of frost wedging is an efficient and effective way to destroy rock. During the day, when temperatures are warm, water finds its way into cracks in the rock. At night, this water freezes into ice and expands by about 10 percent. When the temperature warms up again during the day, the water seeps farther down into the cracks and then freezes again.

- It's not unusual for Bryce Canyon to have 250 days out of the year when this cycle of freezing at night and melting during the day takes place. The effect is like a pickaxe tearing down into the rock.

- The fact that Bryce Canyon sits at the edge of the Paunsaugunt Plateau is not accidental. The top layer of the plateau is a resistant carbonate rock called dolomite. It erodes from the plateau very slowly. At the edge of the plateau, much softer rocks underneath, such as shales, siltstones, and mudstones, erode quickly, undercutting the dolomite capstone. The heavy rocks on top of the hoodoos are formed from this capstone.

- The edge of the plateau eventually wears away, forming a set of fins. With further erosion, these fins develop a set of windows that will eventually break open, forming individual towers with varying widths, depending on the differential erosion of the rocks.

Rock Colors

- Another striking feature of Bryce Canyon is the fantastic colors found in the rocks. This range of colors is common for badlands topography.

- The varying colors are the results of slightly different chemical compositions within the weathered rocks; the minerals that cause the colors are usually oxides, principally iron and manganese oxides. The brown, pink, and red colors tend to come from small amounts of hematite, an iron oxide; the yellows come from small amounts of limonite, another type of iron oxide; and the purples are from a manganese oxide call pyrolusite.

- Note that the color of a rock is not necessarily a good indicator of what it is. Rocks that form in different environments from different types of sediments may have within them the same minerals, giving them similar colors.

Top Erosional Features

- Arches National Park in Utah has more than 2000 arches; these features form in sandstone when erosion takes advantage of parallel joints to wear away fins and leave windows. Some of the arches here are enormous, such as Landscape Arch, which is 290 feet long. In fact, of the 14 natural arches in the world that are longer than 200 feet, 8 of them are on the Colorado Plateau and 6 are in Utah.

- Also in Utah is Monument Valley, with buttes that jut out of the flat plains. A butte is generally composed of a layer of tough, erosion-resistant sandstone that sits on a weaker layer of crumbly shale. It's a result of differential erosion, as we've seen elsewhere.

- Next, in New Mexico, is Bisti Badlands, not far from the Four Corners region. Again, the hoodoos here are composed of a tough sandstone cap over a weaker shale layer. They aren't as tall or as colorful as the hoodoos at Bryce, but they form an even stranger set of shapes.

- In Arizona is the Chiricahua National Monument, a broad expanse of stone forests with rounded, layered towers. Unlike the sedimentary rocks in the previous locations, Chiricahua formed from a layer of volcanic ash. The ash is similar in composition to granite, but because it comes out of the surface, it has a different name, rhyolite. The ash was hot when it fell, and it welded together to make a rock called tuff that erodes fairly easily.

- Another striking set of rocks is found at the City of Rocks State Park in New Mexico. The rocks here resemble a city with houses separated by straight streets.

- The Lena Pillars in Siberia is an impressive wall of rock towers rising up more than 450 feet from the Lena River. The pillars seem out of place in the broad, flat, unpopulated Siberian forest.

- Wulingyuan Park in the Hunan province of China is an area where quartzite has weathered down to form about 3000 narrow towers, some of which are 800 meters tall.

- The “fairy towers” at Cappadocia in Turkey are among the most fascinating erosional wonders anywhere in the world. The basalt capstone on the hoodoos here tends to erode away to form sharp points. The tuff here is so soft that people carved homes into it 3000 years ago.

Suggested Reading

Chronic, *Roadside Geology of Utah*.

Chronic and Chronic, *Pages of Stone*.

Questions to Consider

1. In the not-too-distant geological future, Bryce Canyon may capture a nearby river. What will happen to the canyon when it does?

2. The different shapes and colors of the hoodoos at Bryce Canyon are the result of different rock compositions. Why are different rock types present in the layers? What does their presence say about the geologic history of the canyon?

Uluru/Ayers Rock—Sacred Nature of Rocks

Lecture 17

If you fly in to Alice Springs, the largest city in the middle of the central Australian desert, and head south, you travel about 200 miles across a long, flat, dry region before you see Ayers Rock, or Uluru, rising out of the desert floor. On a clear day, you can see Uluru from many miles away. Uluru is an example of an inselberg, which literally means an "island mountain." It is a single rock that has resisted erosion compared to the surrounding rock layers. The ground here has weathered, washed, or been blown away, but Uluru has remained. In fact, it seems to have grown in size relative to the surrounding desert.

Description of Uluru

- Uluru rises more than 1000 feet, about 350 meters, above the surrounding plain. Most of its bulk is actually still buried; estimates are that it extends at least another 2.5 kilometers underground. Its circumference is about 6 miles.

- What makes Uluru remarkable is its resistance to the erosion that takes place in this part of the world. Rocks usually weather along joints or bedding planes—the planes separating the limestone, sandstone, and shale—but this process doesn't seem to happen at Uluru. We see no obvious sets of joints here and relatively little weathering on the bedding planes.

- About 25 kilometers to the west of Uluru is a set of similarly rounded hills rising up out of the plains. These hills are called Kata Tjuta (meaning "many heads"), or the Olgas. The colors of Kata Tjuta are different from those of Uluru, and it is clear that they are made out of a different kind of rock. But the two formations are also clearly related because there are few places in the world where massive rocks sit high above the desert floor.

- The rocks of this region are ancient. In fact, Australia has some of the oldest rocks in the world, dating back more than 4 billion years. Such ancient rocks are usually buried deep beneath the surface, under layers of sedimentary rocks deposited at times when shallow seas flooded the continents. The "basement rocks" in this region of central Australia are about 1.5 billion years old.

Composition of Uluru

- Uluru is made of a particular type of sedimentary rock that we haven't yet seen in this course. It's a type of sandstone called arkose that contains unusual angular grains.

- If we look at beach sand under a microscope, we see smooth, rounded grains, mostly of quartz. The grains become smooth from a long history of tumbling down streams or being washed repeatedly against a shoreline. Sandstone that forms from ocean beaches, rivers, or even desert sand dunes typically contains these rounded grains. Arkose is made from sand that did not travel very far from where it was weathered and eroded and, unlike most sandstone, was never in an ocean environment.

- The composition of the Uluru arkose is about 50 percent feldspar, about 25 to 35 percent quartz, and the rest, other minerals. Feldspar is the most common mineral on the surface of continents. It's made by combining atoms of silicon and oxygen—which form the building blocks for almost all minerals on Earth—along with atoms of sodium, calcium, aluminum, and potassium.

- Most of what crystallizes out of typical continental volcanic magma is feldspar. Even large parts of the basaltic lava that make up ocean seafloor crystallize as feldspar. When this rock is weathered and moved and forms new rock, it still has the grains that existed in the volcanic rock.

- Granite is a typical volcanic rock found in the region of Uluru. This granite has a number of mineral grains, such as feldspar and quartz, and when it is broken down and carried away, it will come together again to form arkose.

- About 550 million years ago, rocks in the region of Uluru were pushed up in a plate collision as Australia was being assembled from smaller continental blocks. As the resulting mountains eroded, those rocks were deposited in a wide fan of sediment that hadn't moved very much. From that sediment, rocks such as Uluru were made.

- Uluru and Kata Tjuta were formed from the eroded sediments of different starting rocks; thus, they ended up with slightly different compositions. Kata Tjuta is made from a coarser gravel that was compressed to form a sedimentary rock called a conglomerate.

History of Uluru and Kata Tjuta

- By 500 million years ago, this area of Australia was flooded by a shallow sea, and marine muds and sands were deposited on top of the sands of the alluvial fans that would eventually form Uluru and Kata Tjuta, compacting them and turning them into rock.

- As mentioned in an earlier lecture, the global sea level rose 400 feet at the end of the last ice age, when all the ice on land melted and flooded the ocean. But even if all the ice in the world melted, the sea level would rise only 230 feet, and the region around Uluru wouldn't have been flooded.
  - The mid-ocean ridges, because they push up into the ocean, actually push water out of the ocean and onto the land. When the processes of plate tectonics are active, there are more mid-ocean ridges, and they are wider. They push an enormous amount of water farther out onto the land.

  - This is the reason that so many sedimentary rocks around the world formed 500 million years ago: The rocks are a result of a period of revved-up plate motions.

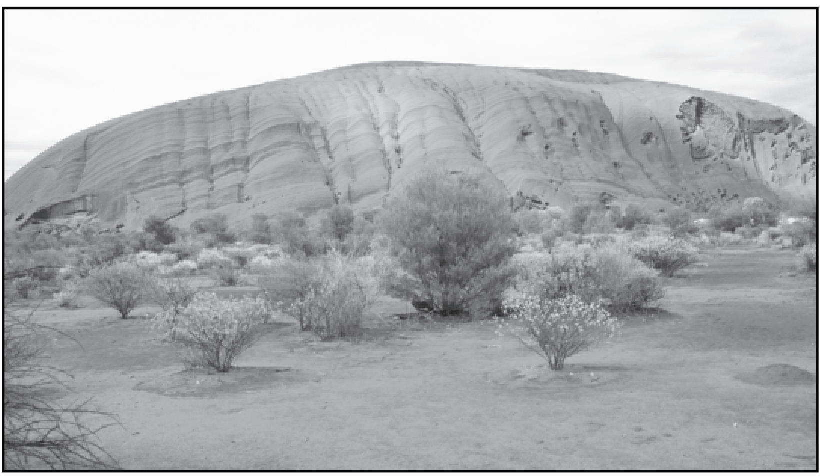
- By 400 million years ago, when the action of plate tectonics slowed down a bit, the seas dropped away, but another mountain-building event folded and pushed some of the rock, causing this area to fault. At this time, the rocks in the region of Uluru were titled by as much as 85 degrees.

- At this point, the rocks of Uluru were still far down beneath the surface, but erosion would eventually reach them. By the end of the Cretaceous period, 65 million years ago, a valley existed between Uluru and Kata Tjuta. It was being filled in by river sediments, but essentially, the lands have been largely unchanged since then.

The Dreamtime

- Uluru has been physically important to people living in the region for some time. The caves on the sides of Uluru have provided shelter, and the rain that flows down this giant inselberg onto the plain below produces a narrow but fertile strip of land at the base, where native people have grown food.

- Uluru also figures prominently in the aboriginal Dreamtime. One definition of this concept is that the Dreamtime is a sort of calling forth of the world into physical existence based on the spiritual world.



Climbing on Uluru is strongly discouraged by the native Pitjantjatjara people because this landscape feature crosses a prominent track of the Dreamtime.

- During the Dreamtime, our ancestors roamed about the Earth, creating both the traditions that we live by and the features of the Earth itself. In fact, some of the features on the land are considered to be the hardened dead bodies of ancestors. Such a rock as Uluru, therefore, has great power; the energy of the ancestors is still alive in the rock and can be called on to give life in the current world.

- Different cracks, cliffs, and caves all enter into the story of the Dreamtime. Ceremonial events, such as initiation rites, are held in some of the caves on the north side of Uluru. The caves also contain sacred cave paintings that help teach the story of the Dreamtime to succeeding generations.

Top Weathering Sites

- Mount Connor is another Australian inselberg, this one with the shape of a mesa. It has a flat top that rises about 300 meters above the surrounding desert. Mount Connor is made of rocks that are about 200 to 300 million years older than the rocks of Uluru and Kata Tjuta, but in fact, they are part of a layer that extends deep beneath those other regions.

- Another fascinating area is called the Bungle Bungles, a mountain range in northern Australia that takes the form of a strange set of rounded sandstone peaks. The sandstone here is made from the riverbed of an ancient river that once flowed through the area. The Bungles are visually striking because of the bright banding that alternates between orange layers and gray layers, caused by the cyanobacteria that live there.

- In Western Australia, the Pinnacles is a set of limestone formations that juts up out of the desert sands, almost resembling trees made out of rock. Geologists do not quite know how these pinnacles formed.

- One of the most famous of any of the rock outcrops in Australia is Wave Rock in the town of Hyden in Western Australia. It looks like a 50-foot-high breaking ocean wave. Wave Rock is made of granite that is 2.5 billion years old, much older than anything else we've seen so far. The wave itself formed about 60 million years ago by chemical weathering of the granite underground, which was then washed away by streams, leaving this dramatic overhang of unweathered granite.

- Roraima, on the triple border of Venezuela, Guyana, and Brazil, is a flat-topped feature called a table rock. Unique plant and animal life has evolved here, separated from the rest of the jungle 400 meters below.

- Table Mountain in Cape Town, South Africa, is another table plateau, similar to Roraima. Here, sandstone has been eroded away, leaving a 3-kilometer-wide plateau.

- The harbor at Rio de Janeiro is one of the most scenic locales of any city around the world. It has huge granite monoliths that stick up out of the ocean; by far, the most impressive of these is Sugarloaf Mountain, with a peak that stands almost 400 meters out of the harbor.

Suggested Reading

Johnson, *The Geology of Australia*.

Kerle, *Uluru*.

Questions to Consider

1. What is the difference between the process of formation of Uluru and the process for karst towers?

2. Uluru and Kata Tjuta sit in the middle of a desert. What do you think they would look like if they were in a tropical region?

Devils Tower—Igneous Enigmas

Lecture 18

Imagine that you are a Hollywood producer, making a movie about aliens that come to Earth to communicate with humans. You want the meeting place to be somewhere spectacular and strange but also familiar to moviegoers. What site do you choose? Devils Tower in Wyoming, of course, as Steven Spielberg did when he filmed *Close Encounters of the Third Kind*. This striking rock rises almost vertically more than 1200 feet above the surrounding plains. It seems to be formed with a number of tall columns that can sometimes be as much as 8 feet in diameter and taper strangely from the bottom to the top. In this lecture, we'll learn how this strange shape and these columns formed.

Phonolite

- As you can probably guess, Devils Tower is the result of the process of differential erosion, just as we saw with Uluru. Devils Tower, in fact, used to be entirely underground, when the level of the ground was at a much higher elevation. It is made of a type of igneous rock called phonolite that is between a granite and a basalt in composition.

- Igneous rocks are much stronger than sedimentary rocks for a number of reasons. First, the crystals that grow when an igneous rock forms completely interlock with one another, filling in all the cracks in the original molten rock. In contrast, sedimentary rocks are formed when mineral grains are held together with some kind of cement; such rocks are easily broken apart.

- Phonolite is a fairly rare type of rock, commonly associated with melting in the middle of a continent. As mentioned, its composition is somewhere between a basalt and a granite, but it has more quartz in it than a typical basalt rock. Basalt lava erodes fairly easily, but granite weathers more slowly. The quartz in phonolite makes it tough and weathering-resistant.

    - At Devils Tower, very hot rock from beneath the mantle began to rise up, probably still in solid form, and come into contact with the bottom of the continent. From there, it heated the base of the continent and began to melt the rocks there.

    - This process is quite common when there is a hotspot sitting underneath a continent, as we saw in the African Rift Valley. The magma at the base is a combination of different compositions. It has some of the magma from the mantle rock, which tends to be dark and black and comes out as basalt. As it goes through the continental rock, it also melts some of that more granite-type composition and comes out as phonolite.

- The rocks of Devils Tower have a gray-green appearance. They stand out quite a bit from the surrounding sedimentary rocks, which tend to be alternating layers of sandstones and shales (reddish) and limestones (whitish).

Geologic History of Devils Tower

- The surrounding rocks for Devils Tower formed at a time when the continent was flooded with shallow seas, about 225 to 100 million years ago. During the mountain-building process that began in the western United States about 70 million years ago, magma intruded into and up through the crust, and there were episodes of volcanoes. Devils Tower formed from one of those events—from magma that pushed its way up through the surrounding rocks about 40 million years ago.

- What happened next in the history of Devils Tower is not known, although two competing theories have emerged.
    - According to one theory, Devils Tower is the former conduit of an ancient volcano that erupted out at the surface, above lands that are now gone because they have eroded away. In other words, the top of the volcano was once much higher, but the whole top has eroded away. The flat top represents a former erosional surface. Given that the igneous rock of this volcanic

pipe is so much harder than the surrounding sediments, it stands up higher above the surrounding rocks.

- The other theory holds that Devils Tower could be the remains of a laccolith. This is a region of magma that pushed its way up into the rock between sedimentary layers during an episode of volcanism, but it never made it to the surface and, thus, cooled underground. Erosion occurred, just as in the volcanic pipe scenario, and flattened off the top.

- This second scenario is a little strange, but it happens in other places, such as at the Palisades cliffs, right across the Hudson River from Manhattan. As the hot magma rises up, it breaks into the sedimentary layers and begins to cool. As it cools, it becomes thicker and more viscous, and it may no longer be able to crack its way to the surface. Sometimes it cools as a long, flat sill of rock. If the magma becomes very thick, it bulges up to form a more domelike structure—the laccolith.

The fact that geologists don't know how the columns at Devils Tower formed demonstrates the vibrancy of science in general and our ability to constantly improve our understanding of the natural world.

- It's difficult to determine which of these theories is correct. If Devils Tower is the result of a volcano, we should find evidence of ash and lava that erupted at the surface, but we don't. However, because all the overlying layers of rock have been eroded and washed away, it's not clear that any of this lava and ash would still be present. Sometimes, the geologic evidence that is left after many millions of years is simply insufficient to determine the history of a given feature with any degree of certainty.

Formation of the Columns

- As it cooled, the volcanic rock of Devils Tower began to shrink and develop parallel cracks that resulted in parallel columns. We can see a similar process in an experiment with dried mud or a mixture of cornstarch and water, both of which develop cracks as they cool. If the cooling occurs very slowly, the surface cracks into nearly perfect hexagons.

- The reason that hexagons are formed is that this shape allows for the most shrinkage with the fewest cracks. In other words, this is the minimum energy state for the process. We see this idea of minimum energy in many other aspects of nature, such as the hexagonal shape of honeycombs made by bees and polygon-shaped salt flats in the desert.

- One of the most famous places on Earth where you can see similar columns is the Devils Postpile, near Yosemite. This fairly recent lava flow is about 400 feet high. When the lava here flowed down, it was dammed up by a glacial moraine and formed a tall pond that cooled slowly. The columns in the Devils Postpile tend to be smaller than those in the Devils Tower, perhaps 2 to 3 feet wide and 60 feet long. Hexagonal columns can also be found at Jungmun Beach in Korea, the harbor at Tenerife in the Canary Islands, and in the Columbia River Valley.

- As with Ayers Rock, Devils Tower is sacred to the Native American tribes that live in the area, particularly the Lakota Sioux, Cheyenne, and Kiowa.

Top Volcanic Plugs

- Shiprock in New Mexico, near the Four Corners, is an ancient volcano made of a dark black rock called Minette. Shiprock is about 1500 feet high. It initially formed about 1000 meters beneath the surface from volcanic activity about 27 million years ago. The vertical walls heading outward from the volcanic plug here are called radial dikes. As the magma of the volcano pushed its way up, it squirted radially along cracks. After the sandstones and shales eroded away, the initial pipe remained, with walls heading away from it.

- Sigiriya is a magma plug in central Sri Lanka. It is also quite tall, rising about 1200 feet above the surrounding lands, and was formed from a volcano that erupted long ago. For more than 2000 years, Sigiriya has been a Buddhist temple, with monks living on the flat top. For a brief time, in about 450 C.E., the ruler of Sri Lanka moved the capital to the top of this rock and built it up as a strong fortress.

- Giant's Causeway in Northern Ireland is one of the best known of these columnar basalt features. There are more than 40,000 separate basaltic columns here, coming right up out of the water. Some of them are 12 meters long, and a large number are perfectly hexagonal. In the local legend, this feature was built by the Irish giant Finn McCool, who built it as a causeway to walk to Scotland to fight his rival.

- Fingal's Cave in Staffa, Scotland, was formed by the same geologic event that formed the Giant's Causeway. It has been the subject of literature, poetry, and even music. In fact, this outcrop of basaltic columns and the unusual echoes inside the striking cave inspired Felix Mendelssohn to create what's known as the *Hebrides Overture*, or *Fingal's Cave Overture*.

Suggested Reading

Besser, *Wyoming Road Trip by the Mile Marker*.

Gunderson, *Devils Tower*.

Questions to Consider

1. Though perfectly hexagonal basaltic columns would be the easiest way for cooling rock to contract, this rarely happens; the columns are usually a combination of forms ranging from four-sided to seven-sided. Why?

2. Why do you think the columns form only vertically? Why are there no horizontal cracks?

Antarctica—A World of Ice

Lecture 19

This lecture on Antarctica isn't completely in keeping with the rest of our course because it highlights an entire continent as a geologic wonder. But the truth is that most of the continent showcases features that can't be seen anywhere else on the planet, at least not at this time. Of course, the big story here is ice on a grand scale. The volume of ice in Antarctica is about 25 million cubic kilometers. If it were to melt, the world's sea levels would rise about 63 meters—more than 200 feet! In this lecture, we'll look at ice flow in Antarctica and how climate change on this continent affects the rest of the world.

The World's Largest Desert

- The average thickness of ice in Antarctica is about 2 kilometers, but in some places, it's as thick as about 4.7 kilometers, or about 3 miles. The thickest ice is in East Antarctica, toward the center. The ice thins toward the edges, and along the west side of West Antarctica is a much shallower region. Antarctica is about 30 percent larger than Europe, and everywhere, ice is flowing out toward the ocean. It sometimes breaks off in giant sheets that are larger than individual U.S. states.

- East and West Antarctica are separated by the Transantarctic Mountains, one of the few regions in Antarctica where rocks stick up above the ice. East and West Antarctica have very different geologic histories. East Antarctica is an ancient piece of continent; it has been around for billions of years. West Antarctica is more recent, assembled from many different pieces formed by interactions between plates. It contains two large, floating sheets of ice right at sea level: the Ross Ice Shelf and the Ronne Ice Shelf.

- Technically, Antarctica is the world's largest desert, at least as defined by the rate of precipitation. The average rainfall here is equivalent to about 16 centimeters a year, a little bit more than 6 inches, which of course, falls mostly as snow. The mean temperature in the interior of Antarctica over the course of a year is –57°C, or –70°F. The record low is almost –90°C, or –129°F.

Ice Flow

- The ice is so thick in Antarctica that it actually pushes the rock of the continent down. The average elevation of the rock surface of Antarctica is only about 153 meters above sea level, but it's as much as 2.5 kilometers below sea level in some places. Around the edges of Antarctica, the ice flows, in a sense, up and over the mountains or through mountain passes. The result is similar to rivers that flow out at a single point.

- The flow rates are not steady. In much of East Antarctica, where the ice is thickest, the ice does not flow very quickly, but it tends to flow out through narrow channels. Some of the fastest flow rates, with the greatest amount of ice, occur at the Amery Ice Shelf, fed by the Lambert Glacier—the largest glacier in the world. The Lambert Glacier drains about 8 percent of the ice of Antarctica. The ice stream here is about 60 miles wide at the mouth and extends 400 miles up into the continent; the ice it places is more than 2.5 kilometers thick.

- This massive ice sheet drains out much of Antarctica to the Amery Ice Shelf; the flow rate is more than 1 kilometer per year in some places. The presence of this giant ice stream is explained by the fact that it sits over a large rift system, the Lambert Rift, with a fairly thin crust.

- In many places, ice accumulates in large, flat ice shelves that extend out over the ocean. These ice shelves are continuously breaking up and off to form enormous icebergs that then float away. Icebergs are much less stable than ice sheets and much more susceptible to changes in climate.

Exploration and Research in Antarctica

- Antarctica has a long history of being explored. The continent was first sighted in 1820, but it wasn't mapped until 1840, by U.S. Admiral Charles Wilkes. The first human beings to reach the geographic South Pole were the Norwegian explorer Roald Amundsen and his party in December of 1911. Another group, led by Robert Scott, reached the pole 34 days later, but these men all died of starvation and cold on the way back.

- Many countries have laid claim to parts of Antarctica, but it is owned by no one. In 1959, representatives from a dozen countries met to draft the Antarctic Treaty, which has since been signed by 47 nations. This treaty prohibits military activities, mining, and nuclear blasts in Antarctica; supports scientific research; and protects the continent's ecological zones.

- Ongoing experiments are conducted in Antarctica by more than 4000 scientists from many countries and with a variety of research interests. For example, seismologists have installed equipment there to learn about the geology of Antarctica and the behavior of glaciers. Other scientists travel to Antarctica to study meteorites or to examine the thickness of the ozone hole.
    - In the 1980s, a large hole began to form in the ozone layer of the atmosphere, which protects us from ultraviolet radiation. By the mid-1990s, that hole stretched more than 25 million square kilometers—about the size of North America.

Giant calving events, where large icebergs break off, can release energy that is the equivalent of magnitude 7 earthquakes.

As we now know, the hole was caused by the release of chlorofluorocarbons into the atmosphere.

  - By the mid-2000s, with the banning of chlorofluorocarbons, the hole showed a small decrease in size, though it probably won't heal fully until the year 2060.

Mount Erebus

- We saw Mount Erebus in Lecture 4 as the site of one of the five lava lakes in the world. This volcano dominates Ross Island, not far from McMurdo Station. Mount Erebus is huge, reaching 4 kilometers above sea level, and it is the southernmost active volcano in the world.

- The volcano has large towers entirely made of ice that extend down a ridge directly away from the summit crater. These towers are the result of gases, primarily water vapor and carbon dioxide, leaking out along the ridge; these gases melt the ice, turn it into vapor, and then redeposit it along the sides of these large ice towers. The towers can be more than 30 to 35 feet tall.

- The hot gases underneath also create a spectacular set of ice caves with unusual ice crystals. The interiors of these caves glow with a stunning aquamarine color, caused by sunlight filtering down through the ice. The caves are also very dangerous; their shapes and locations shift based on changes in the patterns of hot gases leaking out the sides of the volcano.

Climate Change

- Interestingly, deposits of coal have been found in Antarctica. As we know, coal is metamorphosed, fossilized swamp material—rich organic material from swamps that has been buried, compacted, and turned into rock. This process takes place only in tropical areas, which means that in the past, this region—now the coldest, most frozen part of the world—once contained lush, green forests.

- Given the amount of ice in Antarctica, the effects of climate change here are important to the rest of the world. Although global temperatures have been warming slightly over the past century, the regional variations in temperature change in Antarctica are unusual. In many places in the interior of East Antarctica, the temperatures have gotten colder over the past century. But the fastest warming of almost anywhere in the world has been in the Antarctica Peninsula. Some places there have warmed by more than 8 degrees in the last 40 years.

- One place of particular interest in the context of climate change is the Larsen Ice Shelf. This formation is made up of separate ice shelves at the end of the Antarctica Peninsula. Larsen A, the smallest one, broke up in January of 1995. In the winter of 2002, a piece of Larsen B broke up and disintegrated in a single season.
  - These floating ice sheets are grounded at the base, but as the temperature warms and melting occurs at the surface, the whole ice sheet lifts up a bit. Crevasses become filled with melted water during the summer, which causes calving of the ice sheet.

  - Doug MacAyeal, a glaciologist at the University of Chicago, has suggested that long-wavelength ocean swells from distant storms may aid in breaking up ice sheets.

- The instability of the ice shelf and the delicate balance of floating ice shelves mean that in warm times, the ice shelf can entirely break apart. This apparently has happened during warm interglacial periods at the end of the Pliocene Epoch, about 2 million years ago. If the West Antarctica Ice Sheet disintegrated, sea levels would rise about 20 feet, flooding parts of many major cities. This ice sheet does seem to be deteriorating, but there's no sign that it will disintegrate in the near future.

- The fact that parts of the interior of Antarctica are getting colder seems to be related to the presence of the ozone hole. The loss of ozone causes a cooling of the stratosphere, which increases a circulation of westerly winds around Antarctica called the polar vortex. These winds trap cold air in the middle of Antarctica, but they also bring warm water and cause outer regions to warm up. Repairing the ozone hole might slow the collapse of the West Antarctica Ice Sheet, but it might also warm the interior and increase the flow of ice out of the center.

- The current icecap began about 35 million years ago. It started as alpine glaciers in the Gamburtsev Mountains in East Antarctica, which are now buried under 2 kilometers of ice. As a result, Antarctica holds a record of past climate change that has advanced our understanding of the large-scale cycle of warming and cooling that occurs on our planet.

Top Ice Sheets

- Greenland is the only other giant ice sheet on Earth, and it's melting at a fairly rapid rate. If it were to melt entirely, it would contribute another 7 meters to the sea-level rise.

- The North Pole icecap is freshwater ice, like Antarctica, but it's floating on the Arctic Sea. It's a very thin layer, about 3 to 4 meters in the places that don't melt annually, with occasional ridges of up to 20 meters or so. The Arctic ice sheet becomes much larger in the winter and shrinks in the summer, but the amount it shrinks has been steadily increasing.

- During past ice ages, North America has been covered with enormous amounts of ice. Just 15,000 to 20,000 years ago, for example, Chicago was under about 2 kilometers of ice. The ice from this period left us the Great Lakes and many glacial features across North America.

Suggested Reading

McGonigal, *Antarctica*.

Myers, *Wondrous Cold*.

Questions to Consider

1. If all of the ice were suddenly removed from Antarctica, the sea level would rise instantaneously and would then continue to rise slightly for a long time. Why?

2. Sometimes, airplanes land on the ice plateaus in East Antarctica. Why is it then challenging to get them started again?

Columbia Glacier—Unusual Glacier Cycles
Lecture 20

In Antarctica and Greenland, which are covered with ice that flows out in all directions, the glaciers are simply massive, both in length and width. These are continental-style glaciers. In these regions, ice flows down to the coasts whether mountains are present or not. In the rest of the world, glaciers operate differently. They snake between and around tall mountain peaks, eroding away the mountains themselves in the process. In this lecture, we'll discuss alpine glaciers and visit one of the most remarkable glaciers in the world: the Columbia Glacier in Alaska.

Formation of Glaciers

- Glaciers start from snow, which as we know, is light and fluffy. The density can be only about 8 percent of water. In the formation of glaciers, snow gets compacted, largely by the process of melting and refreezing during the summer. Eventually, the snow becomes névé, a form of snow made from small, round ice crystals that is about half as dense as ice.

- On a glacier, the névé survives the summer; it becomes a new layer of ice on top of the glacier called the firn. Year after year, multiple layers of firn accumulate and continue to compact. The final density of the ice of glaciers is, therefore, much higher than that of snow. It's about 85 percent of the density of water.

- The ice of glaciers tends to have a blue color to it; contrary to popular belief, this coloring is not due to the scattering of light off of air bubbles within the ice. Glaciers appear blue for the same reason that ocean water appears blue. Water slightly absorbs red light, removing it from white light that passes through it, which gives the remaining light a slightly blue color.

Slow-Moving Rivers

- Alpine glaciers are much like rivers of liquid water, although they move much more slowly. Still, glaciers may move even more rock than rivers do. Essentially, we can think of them as giant conveyor belts, tearing down whole mountain ranges over time.

- A glacier gains its mass through accumulation—snowfall in the higher parts. The glacier then runs downhill, eventually losing ice, either by direct melting or through a calving off of pieces at the front, a process called sublimation.

- Glaciers tend to start small at higher locations and become larger as they flow downhill, ending up with a system of tributaries, much as rivers do. Technically, ice is a mineral, one with a very low melting point. Like basalt, it can flow, and it flows faster down the middle than it does along the bottom or the sides. That's also similar to how a river behaves.

- The process called glacial plucking involves the ice ripping up large chunks of rock as it slides along. The rock is then embedded into the bottom of the glacier, which accelerates the process of grinding out the rock underneath. In some places, after a glacier is gone, you can see long streaks, called glacial striations, carved out by rocks embedded in the glacier.

- A glacier doesn't move constantly at the same speed, and anytime it goes down over a slope, it tends to speed up. That's when it forms crevasses: Essentially, the glacier starts to flow too fast for the ice to remain flowing in a fluid manner; it then cracks and opens up crevasses. As soon as the glacier levels out again, the crevasses close.

- Though glaciers are made of ice, they're often not white because of all the rock that gets torn off along the sides or falls down onto the glacier. In fact, an enormous amount of rock can pile up at the bottom of a glacier.
  - As the rock gets torn off the sides of mountains, it creates long lines that run through the middle called medial moraines. At

the edge of the glacier, all the rock that is deposited is called the terminal moraine.

- The front of a glacier can be stationary, advancing, or retreating, but at all times, ice is still flowing downhill, depositing any rock within it at the front. If temperatures are warming, the front of the glacier might retreat uphill, but the ice is still flowing downhill. If temperatures are gradually cooling, the front of the glacier advances. If the glacier front is sitting still, all the rock gets deposited in one place, similar to what we see in a river delta.

- Once glacial sediment is deposited, melted ice water carries that sediment downstream in sediment-clogged braided rivers. We saw this in the lecture on the Ganges Delta. A network of streams also carries sediment under the glacier.

Types of Glaciers

- A wide variety of factors, including snowfall, elevation, temperature, humidity, and topography, can make glaciers behave in different ways and take different forms.

- A surging glacier, for example, can suddenly flow 100 times faster than normal. In Alaska, these glaciers tend to start and stop suddenly and may experience up to 100 surge events per year. In Norway, surging glaciers tend to start and stop gradually, sometimes over a period of years. This process is often controlled by a buildup of water underneath the glacier.

- In the case of a debris-covered glacier, so much rock has fallen on top of the glacier from surrounding slopes that a significant fraction of its mass is rock. This greatly affects the rate at which the snow melts because rock tends to absorb sunlight much more efficiently than ice.

- The Columbia Glacier in Alaska is a tidewater glacier, meaning that it dumps its ice directly into the ocean, where icebergs break off and float away. This glacier is one of the most studied in the world.

Recession of the Columbia Glacier

- The first map of the Columbia Glacier was made in 1899 by a team led by George Harriman. At the time, the Columbia Glacier was 66 kilometers long from its end up to the top, making it one of the longest in the world. The glacier has been revisited regularly in the time since, and for 80 years, not much changed. Starting just before 1980, however, the glacier started to recede upstream at a remarkable pace.

- By 1995, the Columbia Glacier was only about 57 kilometers long; by 2010, it was 49 kilometers long, with no indication that the retreat would stop anytime soon. In this process, the whole glacier has thinned by about 400 meters, as well.

The recession of the Columbia and other glaciers in Alaska has had a significant impact on plants and animals there, moving their habitats northward at the rate of about 12 meters a decade.

- Alpine glaciers around the world have been melting and receding at a rapid rate in response to globally increasing temperatures. Over the last couple of decades, glaciers have lost an average of about 1 meter of ice and thickness each year. Over the past 50 years, the total loss has been about 14 meters, or 50 feet. But the Columbia Glacier has lost 400 meters, which tells us that something more complicated is going on here.

- The behavior of tidewater glaciers—and other types of glaciers—is not a direct response to climate change or other factors on the ground, such as sea level, humidity, and so on.
    - Instead, tidewater glaciers are part of a complex feedback system that involves the amount of snowfall, the area of accumulation, the level of water into which the ice flows, and the construction of the terminal moraine. As a result of these factors, tidewater glaciers advance and retreat in a particular cycle.

    - At the beginning of the cycle, very little of the glacier is exposed across the water. The glacier then goes through a period of advancing; the front begins to move outward, pushing the terminal moraine. It reaches some final point, with the terminal moraine growing quite large and essentially blocking up a large amount of ice.

    - Then, some trigger goes off, and after moving forward at rates of 10 to 50 meters a year, the glacier will suddenly move back and its speed will increase. An enormous amount of ice is dumped into the water. It's likely that recent rising temperatures have provided the trigger that started the Columbia's rapid recession.

- This unusual process of tidewater glaciers advancing slowly over decades or centuries and then receding rapidly over a much shorter time makes them fascinating geologic oddities. They also have an important relevance on a larger scale. When a tidewater glacier recedes, it dumps an enormous amount of ice into the ocean, which directly affects sea level. By the end of this century, global sea level may rise 1 to 2 meters with an increased flow of glaciers, particularly the tidewater glaciers in Greenland, playing a major role.

Top Alpine Glaciers

- On the west end of the Tibetan Plateau the world's greatest concentration of 8000-foot mountains sits amid the Karakoram, Kunlun, Pamir, and Tien Shan mountain ranges. The world's longest alpine glaciers are also found here, and the largest among them is the Fedchenko Glacier, at 77 kilometers long. It's in Tajikistan in the Pamir Mountains.
  - The Fedchenko Glacier starts at an elevation of more than 20,000 feet and drops more than 10,000 feet, ending at the Balandkiik River. The Fedchenko is only about 3 kilometers at its widest, and the maximum thickness of the ice is about 1 kilometer.

  - Still, with all the tributaries that flow into it, the Fedchenko contains about 35 cubic miles of ice. From the many medial moraines, we know that many different tributaries combine to flow down into this one stream. Some of these tributaries used to be separate glaciers, with separate termination points, but they have been encompassed by the Fedchenko into a large tree-shaped pattern.

  - The moraine at the end of the Fedchenko also shows that the front of that glacier has been rapidly receding over the past century.

- The Siachen Glacier in the Karakoram Mountains of India is the world's second longest glacier, at 70 kilometers. It sits along the border of Pakistan and India and has the dubious distinction of being the world's highest military battleground. India and Pakistan have fought over this border intermittently since 1984, and both countries still maintain costly military bases there at elevations of more than 6 kilometers.

- The Biafo Glacier is also in the Karakoram Mountains. It is the world's fourth longest glacier, at 63 kilometers. At the very top of the Biafo Glacier is another long glacier, the Hispar Glacier, which is 49 kilometers long. The two create the longest continuous glacial system anywhere outside of Antarctica.

- The world's third largest glacier is the Brüggen Glacier, at 64 kilometers, in southern Chile. This glacier empties into the vast Southern Patagonian Ice Field. Note that we don't find glaciers only in Alaska or on the Tibetan Plateau; anywhere that tall mountains exist, we will find snow, ice, and glaciers.

Suggested Reading

Hambrey, *Glaciers*.

Sharp, *Living Ice*.

Questions to Consider

1. How are the Pamir Mountains related to the Himalayas?

2. Long Island, New York, is a glacial moraine that formed during the ice ages as ice flowed down from Canada, carrying rock within it. Why do you think Long Island sits south of the Connecticut coast?

Fiordland National Park—Majestic Fjords

Lecture 21

In the last lecture, we discussed the power of glaciers, carrying a continuous stream of ice and rock from the tops of mountain ranges down to the base, often the sea, as at Columbia Glacier in Alaska. In this lecture, we'll look at what's left over when the ice is gone. For this, we'll visit Fiordland National Park, on the South Island of New Zealand, a classic and spectacular example of glacial erosion. The park covers a large region with many fjords, lakes, mountains, and tall cliffs that rise up out of the sea. The fjords here are called sounds, and in this lecture, we'll look at three famous ones, Dusky Sound, Doubtful Sound, and Milford Sound.

Three Famous Sounds

- Dusky Sound is the largest of the fjords in Fiordland National Park. It's 40 kilometers long—that's a 40-kilometer arm of the ocean reaching up into the mountains—and 8 kilometers wide at the mouth. Dusky Sound has many different islands and inlets. During an active rainy season, this whole region breaks into hundreds of waterfalls, cascading beautifully down the steep slopes of the fjords.

- Doubtful Sound was originally named Doubtful Harbor by the famous British explorer Captain Cook because he wasn't sure if it was navigable by boat. The sound here heads up into three large fjords, which also break out into hundreds of waterfalls in the rainy season. Two of the waterfalls, Browne Falls and Sutherland Falls, are permanent and are among the tallest in the world.

- Milford Sound is much smaller than Dusky or Doubtful Sound, but it's the real attraction for visitors to this area. Within Milford Sound, massive rocks reach out of the water to heights of almost a mile. Mitre Peak, the most striking of the rocks here, is the tallest continuous sea cliff anywhere in the world. There are also two permanent waterfalls here: Lady Bowen Falls and Stirling Falls. Milford Sound receives about a million visitors a year.

Features of Alpine Glaciation

- Milford Sound and the surrounding fjords contain excellent examples of many of the features we find where alpine glaciation has occurred. For instance, we see many examples of the classic U-shaped glacial valleys. Many glacial valleys begin as V-shaped stream valleys, but as the ice flows throughout the valley, it carves the land into a wide U shape.

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Doubtful Sound breaks into hundreds of waterfalls in the rainy season and has a rare abundance of sea mammals, including seals, dolphins, and whales.

- Often at the back end of one of these glacial valleys, we find a cirque, a half-bowl–shaped formation, that represents the far area of ice carving. Cirques often contain large boulders that have fallen down from the surrounding hills, and they often block the water to form lakes that are known as glacial tarns.

- An unusual structure found in alpine regions is the hanging valley. Here, one arm of a glacier has cut off another arm, resulting in a sudden drop, where one glacial valley ends and plunges downward to the floor of another glacial valley. These tend to be the locations of some of the most spectacular waterfalls, such as Sutherland Falls in Fiordland National Park.

- Mitre Peak in Milford Sound is a perfect example of a horn. This feature forms by the action of glaciers carving a mountain away on all sides until all that's left is a tall, narrow, razor-sharp peak in the middle. The Matterhorn in the European Alps is a classic horn.

Formation of Fiordland

- If these valleys were once filled with ice, why is there now ocean extending great distances through them? We've seen the answer to this question in previous lectures. The sea level rose 400 feet at the end of the last ice age. When these valleys were being carved out by ice, they were above sea level, but as the sea level rose, the ocean wove its way in between these peaks.

- The mountains at Fiordland are at the edge of the Southern Alps. The mountains rise quickly here to more than 10,000 feet—about 2 miles—but they are not the result of continental collision.
    - The island of New Zealand lies right along the boundary between the Pacific Plate and the Australian Plate. North of New Zealand, the Pacific Plate is plunging underneath the Australian Plate at the large Tonga and Kermadec subduction zones. South of New Zealand, the subduction goes in the other direction. The rock of the Australian Plate plunges underneath the Pacific Plate.

    - This situation isn't stable; in fact, the process is tearing the island apart at what's called the Alpine Fault, one of only three transform faults in the world. There is motion across this fault of several centimeters per year that has been taking place for more than 20 million years. In fact, the rock on the north part of the South Island is actually the same as the rock in the southwestern part of New Zealand. It has been dragged to the northeast by the motion along this fault.

    - As a result of this fault and many others in New Zealand, the island is seismically active. The Alpine Fault has had four large earthquakes in the past 1000 years and seems to be overdue for a fifth.

    - Compression along the Alpine Fault is pushing up the Southern Alps at a rate of about 7 centimeters a year.

- The stunning cliffs and peaks of Milford Sound are made of granite. This composition is a typical one for the cores of continents but not for the rocks at the top of continents. Granite has large interlocking crystals and is very hard; thus, it can maintain steep vertical slopes for long periods of time.
  - This granite forms deep underground. Both the Appalachian Mountains in the United States and the Southern Alps were once much taller than they are today. Much of the rock has eroded away, exposing rock that was once deep within the cores of the mountains. In the case of the Southern Alps, there may have been as much as 20,000 feet of sedimentary rock that has eroded away from the top.

  - The rock that is pushed downward in a subduction zone, forming the "roots" of mountains, heats up, and some of the minerals melt, eventually becoming granite. Because magma is lighter than the surrounding rock, it begins to move upward, but if the mountains are tall, it can't reach the surface to erupt. It cools underground as large granite plutons or batholiths.

  - As the mountains begin to erode, the plutons are exposed. Not only do the mountains erode down, but the weight is lifted off of the crust, which rebounds upward. This uplift brings the granite that was once miles beneath the surface up to the top.

- Metamorphism is another geologic process that occurs when plates collide and mountains form. Here, the mountain-building process causes metamorphic reactions that create other rocks from preexisting rocks, through temperature, pressure, or the action of hot fluids flowing through.
  - At the Fiordland National Park, one of the most culturally important metamorphic rocks is a particular type of jade called greenstone. This rock is made from fibrous minerals, such as asbestos.

  - Greenstone is used by the Maori culture to make jewelry, weapons, tools, and religious talismans.

Top Glacial Erosion Sites

- Yosemite in California is the classical example of a glacial valley and of the exposure at the surface of a giant granite pluton—the Sierra Nevada Batholith. This region formed 200 to 150 million years ago, when the Farallon Plate was subducting beneath the western United States. Uplift in the region began about 10 million years ago, exposing the granite, which was then exposed even more by glacial erosion that began in the region starting about 3 million years ago.
    - Most people visit only the small Yosemite Valley at the west end of the park, but the east side shows fantastic examples of a process called exfoliation. Essentially, as layers of rock erode, the release of pressure enables the rock behind to expand, causing cracks and a new layer of rock to peel off.

    - One of the most recognizable features of Yosemite is El Capitan, a stunning vertical face of granite, about 1 kilometer high. In fact, El Capitan is actually post-vertical in places, which makes it a favorite of rock climbers.

    - Another famous site in Yosemite is Half Dome, again, created by the activity of glaciers. Yosemite also has some spectacular waterfalls, including Yosemite Falls, the highest waterfall in North America at almost 1 kilometer high. Bridalveil Falls in Yosemite is a classic hanging valley fall, similar to what we saw with Sutherland Falls in New Zealand.

    - Those who visit Yosemite in the spring may see frazil ice. As the snowpack of Yosemite starts to thaw, the streams begin to overrun their banks and flood through the whole valley, turning all of the snow into a giant, slowly moving wall of slush.

- In Norway, we find Geirangerfjord and Sognefjord. Geirangerfjord is the most visited fjord in Norway, and Sognefjord is the longest fjord in Europe, stretching more than 200 kilometers inland. Surrounding cliffs rise a kilometer above the water, but they are actually much steeper because they extend beneath the surface of the water almost another mile down.

- The only fjord in the world that's longer than Sognefjord is Scoresby Sound in Greenland. Scoresby Sound is 350 kilometers long. It branches out like a huge tree into many other fjords that cover a total area of Greenland of almost 40,000 square kilometers. Scoresby Sound is often filled with a variety of large icebergs of many unusual shapes.

- Gimmelwald and Grindelwald are two small, beautiful glacial valleys in the Swiss Alps. The valleys are very narrow, with pine forests and green fields along the floor. The cliffs rise up incredibly high on one side to the spectacular peaks of the mountains Eiger, Munch, and Jungfrau.

Suggested Reading

De Roy and Jones, *New Zealand*.

Patrick and Peat, *Wild Fiordland*.

Questions to Consider

1. Why is the granite rock of the cliffs of Milford Sound stronger and more resistant to weathering than sedimentary rocks?

2. What do you think will happen to New Zealand if earthquakes continue to occur along the Alpine Fault?

Rock of Gibraltar—Catastrophic Floods

Lecture 22

In the last lecture, we looked at tall rocks that rise up out of the sea at the stunning fjords of Fiordland National Park in New Zealand. In this lecture, we'll visit another rock that rises out of the sea; it's not as tall, but perhaps it's more well known: the Rock of Gibraltar. Primarily limestone and shale, this rock is connected to Spain by a long, flat stretch of land called a tombolo. The Rock of Gibraltar is not large by the scale of some of the places we've visited—say, the giant mountains in the Himalayas or the Andes—but it's distinctive, and it plays an important role in the history of early humans.

Description and History of Gibraltar

- The Rock of Gibraltar is oddly shaped. It is gently sloping on the west side—where most people live in this small British territory—and quite steep on the east side. The rock rises about 1400 feet out of the water and is a popular tourist destination.

- The rock contains limestone, shale, and interbedded layers of dolomite and sandstone. Limestone, as we've seen, tends to form caves, and in fact, more than 100 caves are accessible from the surface of the rock.
    - Gorham's Cave, on the steep eastern side, holds the remains of Neanderthals who lived here as recently as 24,000 years ago.

    - The caves here also played a role in the Great Siege of Gibraltar by the Spanish in 1779–1783 and were used in the British Operation Tracer during World War II.

- The Rock of Gibraltar has a counterpart called Jebel Musa on the African side of the Strait of Gibraltar. Gibraltar itself was originally called Jebel Tariq. These rocks form what the early Greeks called the Pillars of Hercules.

- According to one Greek myth, Hercules split open the Atlas Mountains to make the two sides of the strait, but in another myth, he closed up the strait, making it narrow to prevent sea monsters from entering the Mediterranean. The existence of these two opposing stories is telling.

- Satellite images show the Mediterranean closing into this narrow spot at the straits. It's just a short distance across from Jebel Musa to Gibraltar. In fact, this separation hasn't even been present at various times in the past.

- The early Phoenicians sailed through the Pillars of Hercules to explore the Atlantic coast of Africa. In 711, the African general Tāriq ibn Ziyād brought his Muslim forces across the Mediterranean from Africa and captured what is now Spain. The Moors were removed from the Iberian Peninsula by the Spanish in 1492, although the Islamic presence in the region is still strong.

- Spain had control of Gibraltar until 1704, when a combined English and Dutch force captured it. The English took control, and Gibraltar has been a British territory ever since, though Spain tried to reclaim it in the late 1700s and again in the 1950s.

Geologic History of Gibraltar

- The Iberian Peninsula was part of Africa for hundreds of millions of years, even during the time that the supercontinent Pangaea formed. At that time, Spain was adjacent to Newfoundland. Spain broke away from Africa about 170 million years ago and has jostled against North Africa ever since as a separate microcontinent. The jostling of these pieces of continent has caused the rock there to be highly deformed. Some of the blocks of rock have rotated relative to others.

- Two interesting clues here give us a sense of the extreme tectonic history of the region. First, the layers of rock in Gibraltar are highly folded and deformed; thus, we know they have been caught up in tectonic plate collisions.

The sedimentary rocks that make up the Rock of Gibraltar formed about 200 million years ago, during the Late Jurassic.

- Even more interesting is the fact that these rocks are actually upside down. The oldest rocks of Gibraltar are on the top, and the rock gets younger as it goes down into the Earth. This inversion may even explain why the Rock of Gibraltar still exists. The weathering-resistant capstone has allowed it to survive while rocks around it have eroded away.

Unusual Ocean Currents

- The competing myths of Hercules opening and closing the Strait of Gibraltar are not too far off the mark. In fact, the strait has opened and closed at various times in its history.

- Fifty million years ago, there was no Mediterranean Sea. Africa was still far enough away from Europe that there was an open ocean from the Indian Ocean to the Atlantic. A strong equatorial ocean current ran westward between the two continents that would have changed global climates tremendously, allowing warm equatorial water to circulate around the globe.

- But by 30 million years ago, Africa had rotated counterclockwise enough that the Mediterranean closed in the east. We saw this in our first lecture on Santorini; in fact, this is the reason that Santorini and similar volcanoes exist. This was also the start of an unusual ocean circulation pattern.

- A map of the bathymetry of the Mediterranean and Black Seas shows a shallow section by Gibraltar in a region called the Camarinal Sill; the maximum water depth there is just 290 meters.
    - The water is even shallower—just 250 meters deep—in the Strait of Messina, between Sicily and Italy. In fact, Sicily is actually a continuation of the African land.

    - There are really two separate Mediterraneans here—a deep basin in the east and one in the west. Any water that flows between them must cross the shallow straits on either side of Sicily.

- The patterns of water circulation throughout the Mediterranean are unusual. In the region of Gibraltar, the surface ocean currents seem to indicate that water flows only into the Mediterranean, but the Mediterranean isn't filling up. Where does this water go?
    - If we look at the Mediterranean in a cross section, we see water coming in from the Atlantic at the surface at Gibraltar, but we see it heading back out into the Atlantic just beneath Gibraltar.

    - Water coming in from the Atlantic evaporates away quickly in the Mediterranean, but it leaves salts behind. When the heavier water flows back out to the Atlantic, it has to move up over the Camarinal Sill at Gibraltar, and it then flows down into the Atlantic.

- At certain times in the past, the Mediterranean has been entirely cut off from the Atlantic and has actually dried up. This was caused by a combination of tectonic collisions between Spain and Africa, narrowing the strait, and the occurrence of ice ages, lowering sea levels. The evidence for the drying up of the Mediterranean is found in large layers of gypsum and salt on the Mediterranean seafloor.

- The bottom of the Mediterranean Sea is as much as 5 kilometers below sea level, 3 miles down. Early hominids in this environment would have experienced air pressures of 1.7 atmospheres, almost twice the pressure at the surface. Further, the temperatures at this depth would have been about 170°F.

- The Atlantic finally broke through for the last time about 5.3 million years ago. The Mediterranean probably would have filled up in a matter of years, and the channel that we now see just east of Gibraltar would have been carved out on the Mediterranean seafloor.

- But the story doesn't end there. At the northeast end of the Mediterranean is the narrow, shallow channel that connects the Mediterranean through the Dardanelles, the Marmara Sea, and the Bosporus. During the ice ages, when sea levels were 400 feet lower, the Bosporus, which is only about 118 feet deep, would not have existed; the Black Sea was not connected with the Mediterranean.
  - As the ice ages ended and the ice thawed, melting ice water would have flowed into a depression that is now the Black Sea and made a large freshwater lake. Over time, the lake would have begun to dry out, and the level of the Black Sea would have dropped.

  - At some point, about 7600 years ago, the sea rose high enough in the Mediterranean that it broke through the Dardanelles, the Bosporus, and flooded into the Black Sea. Some scientists believe that it flooded catastrophically, in a fairly short period; others think the flooding happened gradually.

  - The interesting point here is that some anthropologists place the homeland of the earliest speakers of the proto-Indo-European languages to be in the area just north of the Black Sea. It was from these people that came all the major languages spoken by peoples from India and westward. Perhaps the flooding here played a role in shaping the lives and cultures of these early people and, therefore, the lives of those who spread throughout Europe and Asia.

Top Straits and Catastrophic Flood Sites

- The Bering Strait, between Alaska and Siberia, is another artificial divider of continents. The Bering Strait is fairly wide—about 85 kilometers at its narrowest—and incredibly shallow—only about 30 to 50 meters deep. This whole region was about 240 feet above sea level during the peak of the last ice age. About 14,000 years ago, some people and other large mammals came across from Siberia and settled into the northern parts of North America.

- In eastern Oregon and Washington, we find the Channeled Scablands, ancient ripples on the ground formed from the catastrophic flooding of Glacial Lake Missoula. This flooding took place in about 40 separate flows some 15,000 to 13,000 years ago. The ice lake here could fill up as much as 2000 feet and burst out in a volume of water equivalent to 10 times the amount of water in all the world's rivers combined. Such flooding carved out enormous canyons and spillways and dramatically shaped the land.

- Similar flooding occurred at the juncture of Russia, Mongolia, China, and Kazakhstan, as we see in the spillway of the Altai flood. The ripple marks on the ground here are larger than those in Oregon and Washington—as much as 50 feet high and 650 feet apart. The flood that took place here may be the largest one for which we have geologic evidence.

- The Dover Strait and English Channel were also carved out by catastrophic floods. About 425,000 years ago, an ice-dammed lake in the North Sea overflowed and rushed southward, carving out the weak chalk layer and beginning to separate England from France. About 225,000 years ago, another giant lake overflowed and finished the job of carving out the Dover Strait and English Channel and creating the beautiful cliffs of Dover.

Suggested Reading

Johnson, *Secrets of the Ice Ages*.

Ryan and Pitman, *Noah's Flood*.

Questions to Consider

1. What do you think the climate might have been like when the Mediterranean was open at both ends and a warm equatorial current flowed freely through it?

2. Many cultures have a story of being expelled from their place of origin, never to return again (such as the Sumerian/Babylonian/Judeo-Christian story of being expelled from an Eden). What might be the geologic origin of these stories?

Bay of Fundy—Inexorable Cycle of Tides

Lecture 23

In the last lecture, we visited the Rock of Gibraltar, with its unusual history of ocean currents and catastrophic floods. In this lecture, we'll visit a place where the sea level can rise or fall an enormous amount in a matter of hours: the Bay of Fundy in eastern Canada. This area is stark and largely low-lying; it's peaceful and undeveloped, but it's renowned for having the largest ocean tides anywhere in the world. At the Bay of Fundy, the water can rise and fall more than 50 feet two times a day.

Tidal Range at the Bay of Fundy

- More than 200 million years ago, the supercontinent Pangaea was starting to break up, and several rifts began forming in various places. The Bay of Fundy was one of these early rifts. It started opening about 220 million years ago, but then it stopped, as many rifts did.

- The largest tidal range anywhere in this region—with a variance of 17 meters—is measured in a place called Burntcoat Head. The highest water level ever recorded in the Bay of Fundy occurred during a tropical cyclone, Saxby Gale, that hit on October 4, 1869. In one location of the head of the Minas Basin, the water level reached a record of 71 feet.

- During the 12.4 hours that varies between high tides, 115 billion tons of water flow in and out of the Bay of Fundy. How and why does this happen?

Why Do Tides Occur?

- The force of the Moon pulls on the Earth, although not the same amount everywhere. Gravity falls off as 1/distance^2; thus, as we get farther from the Moon, the effect of gravity becomes less and less. This means that the Moon pulls more on one side of Earth than in the middle; it stretches the Earth into a prolate ellipsoid—a football shape. The effect of the Moon pulling on the Earth is very small; the Moon stretches the Earth about 2 feet on either side, although for the oceans, this can be several meters.

- The Sun does the same thing, but Earth is much farther away from the Sun; thus, the relative effect on either side of Earth is much less. As a result, even though the Sun pulls on Earth much more strongly than the Moon, the effect of the lunar tides from the Moon is twice as great as the solar tides. Of course, both the Sun and the Moon create tides on Earth, and the effects can either add together, creating a spring tide, or subtract from each other, creating a neap tide.

- The bulge of the Earth adjusts as our planet rotates. This effect causes a good deal of tidal friction inside the Earth, which affects the tides on the Moon. In fact, this friction causes moonquakes.

The tidal range is not the same everywhere at the Bay of Fundy; at the mouth, the effect of the tides may be only 6 to 10 meters, but farther in, the tides may reach up to 15 meters or more.

More Questions about Tides

- The Earth rotates once every 24 hours, and in that time, there are two high tides and two low tides, but they're not at the same height. In other words, each day there is a higher high tide and a lower high tide—why? This phenomenon is due to the tilt of the Earth's axis of rotation, which is not exactly perpendicular to the direction that the Earth moves around the Sun or the direction that the Moon moves around the Earth. Our axis is tilted 23.5 degrees.

- Why is the time between high tides about 12.4 hours rather than exactly 12 hours? The Earth makes one full rotation in 24 hours, but in that time, the Moon has moved a little bit in its orbit around the Earth. That "little bit" means that the high tides are spread apart by 12.4 hours, not 12 hours.

- Why is the Bay of Fundy so unusual? As the tidal bulge moves westward, with particular geometries of inlets or bays, the water can take a long time to work its way around the land, and the tide can become much larger. For the Bay of Fundy, there's also a tidal resonance due to a coincidence of timing. The time it takes the water to move up the bay and down is about the same as the time from one high tide to the next; thus, the tides begin to amplify. Very quickly, the result is a huge amount of water in the bay, draining out and back in each period of 12.4 hours.

Saxby Gale

- Several factors came together to yield the record high tide of 71 feet in the Bay of Fundy during the Saxby Gale of 1869. One of these factors was air pressure.
    - Right now, a column of air hundreds of kilometers high is pressing down on top of you. You don't notice it because you're used to it and because it presses around you on all sides equally, but you do notice when it changes, as when your ears pop when you're landing in an airplane.

    - The air pressure also changes when the weather changes; that change is what a barometer measures. Bad weather is usually associated with areas of low air pressure. With an impending storm, the warm, lighter air rises, creating a low-pressure region over the land. The hot air cools, water vapor condenses into water droplets, ice crystals make clouds, and then it rains or snows.

  - During a hurricane, a cell of extremely low pressure can sit right in the center eye of the storm. Less air pressure means that the whole surface can rise up, creating a storm surge that can topple levees.

  - Remember that sea level is never constant in any one place. As low-pressure or high-pressure air cells move over water, the sea level goes up and down in response. This is part of the reason why hurricanes and typhoons are so dangerous for flooding along coastlines, as we saw in the lecture on the Ganges delta. The elevation of the water can change and rise up over levees.

- In addition to air pressure, two other factors came together to create the high tide during the Saxby Gale. The storm took place during a time of spring tide, when the Earth, Moon, and Sun were all aligned, and very strong winds from the hurricane essentially helped push water up into the Bay of Fundy.

Life in the Bay of Fundy

- The area of the Bay of Fundy between New Brunswick and Nova Scotia is a strikingly beautiful place but not in the dramatic way that we've seen in other lectures—there are no tall mountains or steep fjords here. Instead, it has a beautiful weathered appearance, the result of countless winter storms blowing off the North Atlantic and scraping away at the land.

- The rhythm of life here is controlled by the tides to a degree that most of us don't experience in our lives. Fishing has been the major industry along the coast of New Brunswick for centuries, but the fishing boats must wait for high tide. People here are acutely aware of the tidal schedule, and they plan their lives accordingly; they also pay close attention to the weather report because of the ability of storms to amplify the effects of the tides.

- An unusual feature of the incoming tide is a phenomenon called a tidal bore—a wave as the incoming tide rushes into the bay. You can sometimes see the front of the advancing tide moving upstream, against the flow of the river. Sometimes these tidal bores are large enough that people can actually surf the wave as it comes in—surfing upstream in a river!

- In a couple of locations around the Bay of Fundy, you can also see another strange phenomenon: reversing waterfalls. These are rapids that form as the stream goes downhill, but rapids also form as the tide comes in and the water goes upstream. In other words, the rapids form in either direction. This effect can be seen in Maher Point, near Eastport, Maine, and in Saint John, in New Brunswick. Saint John is also the location of the Stonehammer Geopark, which features interesting rock outcrops and a fascinating array of fossils.

- Recent research has shown that not very long ago, tides in many places of the world were much more extreme than they are today. It is also the case that millions and billions of years ago, the Moon was much closer to the Earth. It would have filled a much greater area in the sky and caused much larger tides.

Top Sites for Tidal Phenomena

- Ungava Bay in northern Quebec encompasses an area called Leaf Basin that has a maximum tidal range of 16.8 meters, almost equal to that of the Bay of Fundy.

- The largest tidal bore in the world is the Qiantang tidal bore on China's Fuchun River. This wave can be up to 30 feet high and can move at about 25 miles an hour.

- Along the west coast of England, the Severn estuary, which empties into the Bristol Channel, has a 15-meter tidal range. Although the tidal bore isn't large here, the Severn estuary is famous for surfing. The wave can carry surfers up to 10 kilometers inland.

- The Pororoca in Brazil is the tidal bore on the Amazon River and its estuaries. Tidal bores here can run 13 kilometers inland. The record for surfing is an amazing 36-minute-long ride.

- Whirlpools or maelstroms are among the more unusual effects of tidal currents, and one of the most famous of these is the Lofoten maelstrom in Norway. This whirlpool develops as the tide comes in along the Norwegian coast and goes past a promontory.

- The largest maelstrom is the Saltstraumen, also along the coast of Norway, where strong tidal currents are forced through a narrow strait. Whirlpools here can be more than 30 feet across and make a depression in the water surface, a cone, as much as 15 feet deep.

- The Corryvreckan whirlpool, along the coast of Scotland, is the third largest in the world. A Scottish TV documentary crew once threw a human mannequin with a depth gauge attached to into this whirlpool; the gauge showed that the mannequin had been sucked down to a depth of more than 850 feet.

Suggested Reading

Leslie, *Bay of Fundy*.

Thurston and Homer, *Tidal Life*.

Questions to Consider

1. If the Moon had an ocean, what would the ocean tides there be like?

2. Inlets with large tidal ranges are often proposed as sites for hydroelectric power plants, but the power from them would not be continuous. Explain why.

Hawaii—Volcanic Island Beauty
Lecture 24

We've already looked at a spectacular volcano at a subduction zone, Mount Fuji, and the bizarre volcanic environment at the Galapagos Rift, but in any discussion of volcanoes, nowhere else on Earth compares to Hawaii. The Big Island of Hawaii is not only the biggest volcano on Earth, but it's the biggest mountain on Earth of any kind. The highest point on the Big Island, Mauna Kea, is 13,796 feet above sea level. However, Hawaii actually rises a significant distance from the base of the seafloor, which makes it about 33,500 feet, or more than 6.3 miles, tall, and it's about 100 kilometers across.

A Classic Hotspot

- The state of Hawaii is actually 8 main islands, but the Hawaiian Islands are part of a much larger set of about 130 islands, smaller islets, and rocks that stick up above sea level, spanning 1500 miles. The Hawaiian Islands are the easternmost part of a long chain of islands and underwater islands (seamounts) that extend all the way off to the West Pacific. The chain heads into the subduction zone at Kamchatka, in eastern Siberia.

- This chain is almost 3600 miles long; there were even more seamounts at one point, but they have since subducted back into the mantle at Kamchatka and are gone. Altogether, the amount of volcanic rock on the Pacific seafloor is incredible. Over the past 65 million years, more than 1 million cubic kilometers of lava has erupted. This would have made a single massive volcano, except that the Pacific Plate has been steadily moving westward during this time.
  - The key to understanding how this works comes from dating the rocks taken either from the tops of seamounts or off islands. As we follow the chain, the rocks get progressively older. The seamounts that are now subducting into the trench at the top are about 85 million years old.

- Hawaii is the classic example of a hotspot. There is a large amount of hot rock underneath Hawaii—solid rock, not a plume of magma. As it moves up through the mantle, this hot, solid rock begins to melt as it reaches the surface. At the same time, the Pacific Plate is moving westward, pushing volcanoes out on the surface that are constantly being dragged away. As you go from one island to the next, the ages get progressively older. This explains why all the lava hasn't come out in just one location.

- The idea of hotspots was vital in the early days of the science of plate tectonics to explain volcanoes that didn't occur along plate boundaries. But we have since learned that volcanoes can occur in the middle of a tectonic plate for a number of other reasons. Recent seismic tomography has shown, however, some locations where plumes of hot rock rise up to the surface from deep within the mantle. Hawaii is the quintessential example of this.

- Still not fully understood is the connection between the Hawaiian hotspot at the surface and the giant lower-mantle Pacific Megapile. This is a massive region of hot rock in the lower mantle that seems to rise up as a large cone, occupying much of the lower mantle beneath it. Current research is trying to determine whether this material is rising upward all the way from the core-mantle boundary or whether it represents a hot, dense region of iron-rich rock spawning hotspots.

- An interesting aspect of the Hawaiian hotspot is that the volcanism there seems to be relatively fixed in relation to the mantle of the whole planet. Together with Yellowstone, another fixed hotspot, Hawaii provides a reference frame for measuring the motions of the tectonic plates at the surface.

- The cause of the bend in the Hawaiian-Emperor hotspot chain presents another intriguing question.
  - Perhaps 20 years ago, the bend would have been explained by a change in direction of the Pacific Plate 43 million years ago in response to the subduction of the Kula Plate (a piece

of the Pacific Ocean seafloor) beneath North America. This subduction was thought to have rearranged the motions of the Pacific Plate.

  - More recent work has shown that the Pacific Plate may not have changed direction; instead, it may have been the case that the Hawaiian hotspot within the mantle was moving and didn't stabilize until 43 million years ago.

- Another complication comes from recent work done by seismologists at MIT, who have shown that the hotspot plume may not go continuously from the lower mantle to the surface. In fact, it may reach resistance at the boundary between the upper and lower mantles, spread out at that boundary, and then rise up to the surface just through the upper mantle.
  - The mantle isn't a single layer of rock; there are separate layers depending on the minerals found within the rocks.

  - At a depth of 660 kilometers from the surface is an especially important boundary. At this location, the mineral olivine, the primary mineral in the upper mantle, is squeezed by intense pressure to convert to a rock called perovskite, which determines the boundary between the upper and lower mantles.

  - The hotspot plume for Hawaii at the surface is not necessarily connected to its location in the lower mantle.

Visiting the Hawaiian Islands

- The Hawaiian Islands are at different stages of development; we can get a picture of how an island changes over millions of years just by visiting each island. The island of Maui, for example, is a little more than 1 million years old; Molokai is about 2 million years old; Oahu, about 3; and so on.

- The Big Island is young; it has active volcanoes and lots of lava. As you move west, the amount of lava decreases; erosion increases; the sea cliffs become steeper; deep valleys are carved out by rain; and weathering creates thicker soil, allowing lusher vegetation.

- Some of the most popular beaches in the Hawaii Islands are on Oahu or Maui, while the island of Kauai offers a bit more wilderness. Kauai also has the famous rugged Na Pali coast, a spectacular 17-mile stretch of dramatic cliffs and waterfalls, and Waimea Canyon, known as the Grand Canyon of the Pacific.

- Beaches on the different islands can even have different colors. Some of the islands tend to have a greenish color from the mineral olivine; others can be dark black from the mineral pyroxene. Plivine and pyroxene are the major minerals of the volcanic rock—basalt—that makes up most of the islands.

- As you go farther west, the islands become smaller, and the landscape features are less pronounced. Signs of active volcanoes disappear. Eventually, you reach small, flat islands and then no islands at all. The islands become seamounts.

The Big Island

- The Big Island is a composite of recent volcanoes. The most active are on the southeast side, Mauna Loa and Kilauea. In fact, Kilauea has been erupting continuously since 1980. The lava here is hot (2000°F) and low in silica; thus, it's very fluid. You can stand right next to the lava as it's flowing, pull out pieces with a stick, and watch as they quickly cool into obsidian. The lava usually looks black because it's cooling on top, but underneath, you can see that it glows red.

- Lava can flow all the way to the sea and often does, extending the island outward. Again, because the top of the lava forms a crust, it doesn't seem to be moving, but underneath may be a rapidly flowing river of lava heading toward the ocean. When the lava hits the water, it can explode and steam as it instantly cools, forming lava tubes. At 41 miles, Kazumura is the longest lava tube in the world; it's also the deepest.

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The lava from Kilauea is fluid because it's low in silica; it can slowly ooze great distances horizontally.

- The lava here flows primarily in two forms, either as a sort of ropy texture, called pahoehoe, or as a blocky form, called aa. The difference between the two is largely related to the differing composition of the gases in them.

- The crater called Kilauea Iki is a former lava lake, with steep walls, a strong sulfur smell, and almost no surrounding vegetation.

Earthquakes and Tsunamis

- Hawaii experiences numerous small earthquakes because, as the magma cracks its way up to the surface, it breaks open the rock. The earthquakes may be stronger when large pieces of the edges of the island break off and slide downward. Earthquake activity is closely monitored in Hawaii as an indication of when a volcano might erupt.

- On rare occasions, Hawaii experiences strong earthquakes. The Pacific Ocean seafloor was covered with ocean sediments long before the islands developed. Lava later spread out across this layer of sediment, but the sediment is weaker rock; thus, the Hawaiian Islands are decoupled from the crust. Occasionally, a whole island can suddenly slide down across the seafloor. Destructive earthquakes occurred in 1868, 1951, and 1975 from this phenomenon.

- Tsunamis also represent a hazard in Hawaii. Tsunamis begin in the Ring of Fire, travel great distances across the Pacific, and become focused when they hit shallow regions, such as the broad underwater islands of Hawaii. The Big Island has been severely hit by tsunamis many times in the past century.

- Because of the trade winds that blow from the northeast, the Big Island has an incredible diversity of microclimates, making the surface geology fascinating. The north side, near Hilo, has some beautiful, lush, tropical areas, but to the south is the Ka'ū Desert, and Mauna Kea is so high that it often has snow.

Top Hotspots

- The Louisville hotspot chain in the southern Pacific Ocean is a track of about 70 underwater seamounts that stretches more than 4000 kilometers, from the mid-ocean ridge into the Tonga-Kermadec Trench, where the Pacific Plate is subducting beneath the Australian Plate.

- At the Great Meteor hotspot track in the North Atlantic, magma has been rising to the surface for more than 200 million years. This makes it the longest continuous hotspot on Earth, in both time and distance. The length of this hotspot chain is almost 6000 kilometers, stretching from northern Canada to the African Plate on the other side of the Mid-Atlantic Ridge.

- The Ninety East Ridge is a line of underwater seamounts that extends about 5000 kilometers across the Indian Ocean in a north-south line at a longitude of 90 degrees. It stretches from the coast of Sumatra southward into the Antarctic plates.

- The Chagos-Laccadive Ridge is exactly parallel to the Ninety East Ridge. This ridge began 65 million years ago as the large outflow of lava known as the Deccan Traps in India. Eventually, it jumped across the mid-ocean ridge and is now located beneath the island of Réunion just off the coast of Madagascar.

Suggested Reading

Hazlett and Hyndman, *Roadside Geology of Hawai'i*.

Lillie, *Parks and Plates*.

Questions to Consider

1. Look at a map of the bathymetry of the Pacific Ocean. Notice the shape of the subduction zone where the Emperor seamount chain enters it. Propose a hypothesis to explain the shape of the subduction zone there.

2. Why is it that volcanic eruption on Hawaii rarely causes the loss of any human lives?

Yellowstone—Geysers and Hot Springs

Lecture 25

In the last lecture, we talked about Hawaii, the last in a chain of islands and underwater seamounts that's the result of the Pacific Plate moving over a mantle hotspot. In this lecture, we'll look at what happens when a hotspots lies underneath a continent, the situation we find in Yellowstone National Park in Wyoming. As we'll see, volcanic activity occurs at Yellowstone, but it takes a different form than that in Hawaii. Before the mid-19th century, trappers reported seeing boiling mud, steaming rivers, and petrified trees in the region of Yellowstone, but organized explorations of the area didn't begin until 1869. In 1872, Yellowstone was designated as the first national park.

Visiting Yellowstone

- Yellowstone National Park has tall mountains, spectacular waterfalls, gorgeous valleys, and even a Grand Canyon of the Yellowstone, where the Yellowstone River cuts down a steep valley. It has the largest population of large mammals anywhere in North America, including a herd of bison, as well as elk, grizzly bears, wolves, lynx, black bears, moose, bighorn sheep, mountain goats, and mountain lions.

- One of the most well known places to visit in Yellowstone is Artist Point, which offers great views of the Yellowstone Grand Canyon and waterfalls. This spot is also where the artist Thomas Moran painted some of his famous images in 1871, which helped to convince Congress to make Yellowstone a national park.

- The Grand Canyon of Yellowstone formed in a similar process to the Grand Canyon in Arizona. In this case, the Yellowstone hotspot has lifted up the whole region, and the Yellowstone River has maintained its course; as the land has been lifted, the river has cut down, carving a deep canyon.

- Yellowstone is located right along the Continental Divide. This means that the two major rivers there, the Yellowstone River and the Snake River, begin close to each other but then head in different directions. The Snake River flows west into the Columbia River and, eventually, the Pacific Ocean, and the Yellowstone River flows into the Mississippi River and then into the Atlantic. These rivers make spectacular canyons as they flow through layers of soft volcanic ash that wears away sharply and dramatically.

- Of course, one major reason to visit Yellowstone is the geysers. The park has 300 geysers and a total of at least 10,000 geothermal features. Half of the world's geothermal features and two-thirds of the world's geysers are concentrated in Yellowstone National Park.

Geysers

- Geysers begin with a source of heat; in Yellowstone, this source is the magma close to the surface. Also needed are underground rocks that allow large amounts of water to percolate through them. Rainwater percolates down, sometimes as far as 2 or 3 kilometers, where it comes in contact with rock heated by the magma below. This water becomes superheated and rises up to the surface.

- Why are geysers intermittent? As it's heated, the water underneath the surface builds up pressure, but it's still water—not steam—because of the weight of all the water on top of it. Once it begins to erupt, however, the hot water turns to steam and blows out the top of the geyser. This is similar to the way a pressure cooker works. Once the water erupts, the chambers underground are emptied, and the cycle won't repeat until they are refilled.

- The most famous geyser, of course, is Old Faithful, which can spout more than 8000 gallons as high as 185 feet into the air. The popularity of Old Faithful is the result of its regularity, but Steamboat Geyser, which can spew water 300 feet in the air, is larger.
    - The eruptions at Old Faithful occur fairly regularly, though the interval changes over time, ranging from 45 minutes to 125 minutes over the last century.

- One reason the interval changes is that the water underground can cool and precipitate out minerals that begin to choke off some of the chambers, changing the interior plumbing of the geyser over time.

- Other well-known geysers include Beehive Geyser and Castle Geyser. At Beehive Geyser, the water erupts out of a small cone, only about 4 feet high, but it can reach as high as 200 feet.

- Some large geysers have an "indicator"—another, usually smaller geyser that's a precursor to the main geyser. The indicator for Beehive Geyser is a small cone 10 feet away that erupts 15 to 25 feet high. It begins its eruption between a few seconds and 30 minutes before Beehive Geyser erupts.

Other Geothermal Features

- Other geothermal features at Yellowstone fall into three general categories: (1) fumaroles, places where steam erupts without water; (2) hot springs, where water bubbles up without steam; and (3) mud pots, where hot water comes up through an area with a good deal of sediment, then boils and churns at the surface, like a giant pot of thick soup.

- The most colorful of the hot springs at Yellowstone is the Grand Prismatic Spring. The colors here are not the result of any geologic process. They are entirely due to living single-celled organisms, a particular kind of extremophile called a thermophile. These organisms thrive in areas that would cook almost anything else. They are examples of a primitive life form called archaea.
    - Each hot spring has a slightly different combination of minerals in the water and a slightly different temperature. Each color band in a spring represents a separate zone that's preferred by a particular species of archaea. The archaea themselves are different colors, resulting in the prismatic effect in the pools.

    - A research program is underway to learn about the strange life forms that exist deep inside thermal hot springs. Just as at the

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The travertine terraces at Mammoth Hot Springs are formed from calcium carbonate brought up to the surface by water traveling along an underground fault.

mid-ocean ridges, all the elements are present in hot springs for the development of life: a source of heat, a source of food, and protection from the surface.

- One of the most stunning geologic features at Yellowstone is Mammoth Hot Springs. The hot water coming out at Mammoth contains large amounts of calcium carbonate that precipitates as it cools. About 2 tons of dissolved calcium carbonate—the same material that makes the shells of marine creatures and forms limestone—flows out into Mammoth every day.
    - o The presence of magma underground heats water that rises up through limestone, bringing the calcium carbonate with it.

    - o When the water reaches the surface and cools, minerals precipitate out, resulting in the rock called travertine.

    - Wherever the water sits in a pool, it begins to build a wall of travertine. Over time, these walls can grow very tall, creating deep pools. Water seeps out in different locations and builds a complex stairway of cascading pools.

A Giant Volcano

- The underlying cause of all this hydrothermal activity in Yellowstone is the fact that the park itself is a huge caldera, sitting on top of a volcano that could become active at any time. In fact, at 50 miles across, Yellowstone is one of the largest calderas in the world.

- A caldera forms as part of the cycle of a volcano. After an eruption from a large magma chamber, the loss of the volume of magma causes the top of the chamber to collapse. At some later point, when the magma activity is entirely done, what's left is a large depression. The caldera may still be slightly active, as evidenced by steam and geysers similar to those seen at Yellowstone.

- Yellowstone is, in fact, a supervolcano. It has had some of the largest eruptions in the world. Three large ones occurred in the past 2 million years. Volcanic activity shifted to the current Yellowstone Plateau and peaked 640,000 years ago, forming the current caldera.
    - Since that time, a little bit of doming has occurred in the northeast and southwest sides of the caldera—magma pushing up from below. Between 150,000 and 70,000 years ago, about 1000 cubic kilometers of lava erupted within the caldera itself. No lava has erupted in the past 10,000 years or so. Are we overdue for an eruption?

    - In 2005, GPS instruments in Yellowstone recorded that the area was lifting up at the rate of about 7 centimeters a year as magma flowed underneath. But since that time, the area has started to settle back down.

- In the past, eruptions from Yellowstone have covered much of the continent with thousands of cubic kilometers of ash. Some of the effects of an eruption are visible in the park, such as petrified trees that were essentially cooked and turned to stone when they were buried by ash.

- As mentioned earlier, Yellowstone is over a continental hotspot. The hot rock from the hotspot rises up underneath, but it doesn't come all the way to the surface. It stops underneath the crust and spreads out somewhat. It causes some melting of the granite-type composition there. That granite composition rises up to the surface and erupts, resulting in the formation of rhyolite as it flows outward.

- The path of the volcanoes at Yellowstone is heading to the southwest—the same direction in which North America is moving. It's likely that Yellowstone will last for a long time because it has an active plume underneath. It could potentially continue to poke up volcanoes all the way across North America.

Top Geothermal Features

- Geysir in Iceland is the origin of the word "geyser." This geyser can eject steam more than 200 feet high, but it is dormant for long periods of time. Geysir has a nearby partner called Strokkur that reaches only 15 to 20 meters high but erupts every 4 to 8 minutes.

- The Valley of Geysers is in a remote part of Siberia, the Kamchatka Peninsula; it has the second largest concentration of geysers in the world—about 90. The whole valley seems to be smoking and steaming, but much of it was covered in a massive mudflow in 2007. The geysers will probably return here, but they haven't done so yet.

- The Dallol Hot Springs in Ethiopia are the most spectacular colored hot springs in the world. The greens, yellows, oranges, and reds seen here are caused by various compositions of salts, iron oxides, and sulfur.

- The Pamukkale travertine terraces in Turkey are similar to the beautiful travertine terraces of Mammoth Springs in Yellowstone but on a much larger scale. The terraces may be 1.5 miles long and 2000 feet wide. Almost 2500 years ago, a Greco-Roman city, Hieropolis, was built on top of these travertine terraces.

Suggested Reading

Chapple, *Yellowstone Treasures*.

Smith and Siegel, *Windows into the Earth*.

Questions to Consider

1. Why do some geysers, such as Old Faithful, erupt regularly and some do not?

2. How could the United States prepare for a future eruption of Yellowstone? Should we do so?

Kawah Ijen—World's Most Acid Lake
Lecture 26

In the last lecture, we looked at the features that result when magma and water are mixed underground: the beautiful geysers and hot springs of Yellowstone National Park. In this lecture, we'll look at a different result of mixing water with volcanoes; for this, we'll visit the acid lake at Kawah Ijen on the island of Java. Ijen is the name given both to a group of stratovolcanoes and the 20-kilometer-wide caldera in which they sit. It's also the name given to a small acid lake that sits in the midst of this caldera. Unlike some of the heavenly beautiful beaches and waterfalls we've visited so far in this course, Kawah Ijen is a vision of hell.

The Island of Java

- The area of Indonesia in which Kawah Ijen is located consists of a large number of islands. Ijen happens to be on the far eastern end of Java, across from the island of Bali, but Sumatra, Java, Bali, and numerous other islands form the longest continuous island-arc volcanic chain in the world. The chain is almost entirely made of volcanoes and is a direct result of the subduction of the Australian Plate underneath Southeast Asia.

- On the island of Java, the volcanoes are spread out about 80 kilometers from each other. They are each about 3 kilometers high and run right down the spine of the island. Though some of Java's 38 major volcanoes are currently dormant, any or all of them could erupt in the future. The most active volcano here is Mount Merapi in central Java. Smoke comes out of its summit about 300 days a year, and it has erupted regularly since it became known in 1548.

- Java and the surrounding islands have been populated for a long time. Fossils from an early human found here, *Homo erectus*, known as "Java man," date back 1.7 million years. Evidence of *Homo sapiens* has also been found, dating back more than 130,000 years. Most of the modern humans in Java are related to a second wave of modern humans that settled in the islands about 40,000 years ago.

- o In 2003, a dwarf species of human was discovered, *Homo floresiensis*, only about 1 meter tall. This species lived just 18,000 years ago on the island of Flores, east of Java.

- o The remains of dwarf elephants have also been found in the area, in the same deposits as the humans.

Chemistry of Kawah Ijen

- The volcano Kawah Ijen has a deep crater at the top that's filled with water; gases bubble up out of the crater into the water, forming a lake of boiling acid that is one of the most inhospitable places on Earth. Kawah Ijen is a little less than 3 kilometers in elevation, and the lake is 200 meters down from the crater rim.

- The lake on Kawah Ijen is only about 360 meters across and about 200 meters deep. Fumaroles—gas vents—bubble up into the water

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Local people harvest about 4 tons of nearly pure sulfur every day directly out of the fumaroles at Kawah Ijen.

at the bottom; the water temperature is between 93° and 100°F. The fumaroles contain water vapor, carbon dioxide, nitrous oxides, and sulfur dioxide.

- o Oxygen is a hyperreactive material. It often forms a negative ion that bonds with anything nearby. In fact, almost all rocks are mostly made of oxygen. The crust of the Earth is 93 percent oxygen by volume. Many gases also contain large amounts of oxygen.

- o A common gas that comes out of volcanoes is sulfur dioxide. In the atmosphere, sulfur dioxide mixes with water vapor and forms sulfuric acid. Particles of sulfuric acid make a common aerosol in the atmosphere.

- o As the gas bubbles its way up through the water, it forms both sulfuric and hydrochloric acid. The acid is in such high concentrations that the lake water has a pH of 0.5—about the same pH level as the sulfuric acid in batteries.

- o Note that pH is a measure of the activity of hydrogen atoms, which are also highly reactive. Neutral water has a pH of 7; anything with a pH of less than 7 is an acid, and anything with a pH of greater than 7 is a base. A pH of 0.5 is so acidic that it will burn away skin.

- o The small lake on Kawah Ijen is estimated to have dissolved more than 0.5 million tons of hydrochloric acid and 0.5 million tons of sulfuric acid.

- The liquid sulfur emitted at Kawah Ijen is so hot that it actually burns, but it's about 99 percent pure. It hardens as it cools and is collected by local workers to be used in various industrial processes, such as refining sugar and vulcanizing rubber.

Effects of Volcanoes on Climate

- The sulfur released into the air from Indonesian volcanoes has had a profound influence on life, including our own.

- The sulfur reacts with oxygen to form gaseous sulfur dioxide, which then combines with water vapor in the atmosphere to make an aqueous sulfuric acid. These droplets are aerosols; they're particles that are so tiny they can stay suspended in the air.

- The acidic liquid begins as a vapor but needs something to condense onto to form the small liquid particles, such as ice crystals within clouds, dust carried up from the surface, or ash emitted from volcanoes. These liquid particles eventually grow in size; in the atmosphere, the sulfuric acid droplets are about 0.1 to 1.0 micrometers in diameter. These sulfuric acid aerosols can powerfully block out sunlight and cool the surface of the Earth.

- Only stratovolcanoes produce atmospheric aerosols, but when one of these erupts, the effect is like a giant umbrella, essentially blocking out sunlight.

- In recent history, eruptions from even small volcanoes, such as Pinatubo and El Chichón, produced enough aerosols to drop the amount of solar radiation reaching the surface by tens of percents. Pinatubo dropped global temperatures by a degree for about a year.

- When global climates are cold, more dust tends to be in the atmosphere. More dust in the atmosphere means that there are more particles for the sulfuric acid vapor to condense on to make aerosols and block sunlight. A feedback mechanism develops: more dust, more aerosols, less sunlight, and so on. Thus, a volcano that erupts when it's already cold will have a greater impact on climate, making it even colder.

- A good example of the climate effects of an Indonesian volcano is the eruption of Tambora in 1815. This volcano ejected about 100 to 160 cubic kilometers of material into the atmosphere; it was 100 times larger than the eruption of Mount Saint Helens in 1980. Almost 100,000 people were directly killed, but more significantly, the volcano created the worst famines of the 19th century in 1816, known as the year without a summer.

- The effects of Tambora pale in comparison to the eruption of another Indonesian volcano not far from Kawah Ijen, Toba, about 73,000 years ago. This is the largest known volcanic eruption, even larger than the Yellowstone eruptions. When Toba erupted, it released about 2800 cubic kilometers of ash into the atmosphere. This eruption occurred during a period of glaciation and probably triggered an extension of that period. Genetic research suggests that most of the world's humans did not survive this long period of extreme cold following the massive eruption.

- At some point, it may be possible for humans to control the temperature of the planet by deliberately introducing sulfuric acid aerosols into the atmosphere to counter the effects of the release of greenhouse gases. This approach might be the cheapest way to prevent global warming, perhaps 100 times cheaper than producing the same amount of global temperature change by reducing carbon dioxide emissions.

Top Extreme Lakes

- The Poás Volcano in the Central Valley region of Costa Rica is the site of another extremely acidic lake. The volcano has two separate crater lakes; the northern one, Laguna Caliente ("Hot Lake"), has pH levels of less than 1. This lake is larger than Kawah Ijen—about 1 mile wide and 1000 feet deep.
    - At the Poás Volcano, acid fogs sometimes develop above the lake, drift away, and precipitate out as acid rain; thus, the whole surrounding area has been burned.

    - Poás has erupted about 40 times in the last 200 years, most recently in 2009. Sometimes it emits hot eruptions of gas, called phreatic eruptions, that eject the acid lake water high into the air as acid geysers.

- About 20 kilometers off the coast of the north island of New Zealand is White Island, a small, circular volcano that also has an acid lake in the crater. The temperature of this lake is about 50°C, and the lake has a pH of about 1. As a result of its chemical composition and, remarkably, the presence of single-celled organisms, the lake has an unusual bright green color.

- Lake Natron in Tanzania is the world's most alkaline lake. It has a pH of about 10.5, similar to ammonia. The temperature of this lake is about 50°C, and it's also fed by hot springs that are triggered by volcanic activity in the African Rift Valley. But instead of bringing such minerals as sulfur into the water, these hot springs bring salts, such as sodium carbonate, or soda ash. Types of cyanobacteria and blue-green algae, such as spirulina, give the lake a red color and support large populations of fish and birds, including flamingos.

- The most acidic water found anywhere on Earth is at Iron Mountain in California, which is actually an abandoned mine, not a natural cave. The rock here naturally contains high concentrations of metals—iron, silver, gold, copper, zinc, and others—and as water seeps into and out of the cave, it reaches a pH level of –3.5. This is the equivalent of half-strength pure sulfuric acid.
    - This area is considered one of the most toxic waste sites in America, but geologically, it's fascinating because new types of minerals are forming here that don't exist anywhere else in the world.

    - Almost all life has been eliminated from the streams that are downstream of the mine, with the exception of a few new kinds of extremophile bacteria and archaea. Remarkably, even this extreme environment created on our planet has resulted in the evolution of new life.

Suggested Reading

Lockwood and Hazlett, *Volcanoes*.

Oppenheimer, *Eruptions That Shook the World*.

Questions to Consider

1. Historically, why has there been a demand for sulfur?

2. Why do you think there aren't more acid lakes in the calderas of volcanoes around the world?

Iceland—Where Fire Meets Ice

Lecture 27

Iceland is a geologist's paradise, offering mountains, canyons, waterfalls, geysers, and most important, volcanoes and ice. It even has volcanoes under the ice of glaciers. Iceland is a hotspot, sitting right on top of the Mid-Atlantic Ridge. In fact, it's one of the few places on Earth where you can walk along the mid-ocean rift above land. Eruptions can take place on any one of many segments of the rift here. Eruptions are infrequent, but when they occur, they result in bizarre features, such as entire curtains of lava that rise up along the rift segments. In this lecture, we'll explore some of these features to see what happens when lava and ice are combined.

Volcanism in Iceland

- Iceland has more than 30 separate active volcanic systems. In March of 2010, the Iceland volcano Eyjafjallajökull erupted and shut down airplane flights in parts of Europe for weeks. The volcano Hekla in Iceland has had large eruptions at least 20 times over the last 1000 years. The layers of ash from these eruptions are found across many parts of Europe and serve as good archaeological time markers.

- Recent research has shown that over the past 1000 years, multiple significant ashfalls have blanketed many parts of Europe, disrupting agriculture and civilization. The average interval for these ashfalls is about 56 years, and the majority of them have come from Iceland.

- On a rare occasion, at least from a human perspective, we get to see the process by which a new volcano is born; this happened famously with the emergence of Surtsey in 1963 off the southern coast of Iceland. Surtsey is kept off limits to people in order to allow researchers to learn how an island becomes biologically populated once it emerges.

- Life can arrive on a new island in several ways. It may float in on logs or seaweed; seeds may be dropped by migrating birds; or birds or insects may be blown in by a storm. Surtsey gives us an opportunity to follow this process.

- The island emerged in 1963, and by 1965, the first plants and fungi were already present. Two years later, there were mosses, and by 1970, there were lichens. By 2008, 30 plant species had become established. The island also has birds and hundreds of species of insects. Earthworms and slugs help to break down the rock and make soil, which will allow for much more plant life in the future.

Geothermal Power

- The heat from the volcanoes in Iceland provides a source of energy for most of the island. In fact, most homes are heated directly by the magma underneath the island. Electricity produced at geothermal power plants supplies about 20 percent of the island's electrical needs.

- Geothermal power plants work by pumping water down into the rock, which is heated by magma. The water is heated above its surface boiling temperature. When the superheated water then returns to the surface, the pressure is released, and the water expands into steam and runs a turbine to generate electricity. Essentially, this process is the equivalent of creating a geyser.

- The volcanic regions of Iceland produce steam at very high temperatures, about 1100°C. This temperature is three times more than is minimally needed for a geothermal power station, resulting in incredibly efficient energy.

- Magma that is not far under the ground in Iceland also heats the groundwater and causes a wide variety of geothermal features, including hot springs, geothermal baths, and geysers. One of the most visited attractions of Iceland is the Blue Lagoon geothermal spa, not too far from the capital of Reykjavik. The lagoon there is not a natural feature but is filled with water from a nearby geothermal power plant.

A Harsh Region

- Iceland is generally a difficult place to live; not only does the island have volcanoes, but it also has cold climates and, as a result, poor soil.
    - o The people who live in Iceland now are descendants of the Vikings, who settled the island in the late 1800s, just as the rest of the world was entering the medieval warm period. During this period, the Sun gave off slightly more energy.

    - o Before this time, the sea around Iceland had been impassable—frozen for much of the year. But during the medieval warm period, people were able to sail back and forth from Scandinavia with no difficulty.

- Most of the ice in Iceland is located in one large glacier called Vatnajökull, which is one of Europe's largest glaciers. It has more than 3000 cubic kilometers of ice within it. During the summer, the melting ice creates spectacular waterfalls.

- Because Iceland has both volcanoes and glaciers, a volcano sometimes erupts beneath a glacier, causing an enormous outrushing of water. This phenomenon is called a *jökulhlaup*. In 2011, a large glacier called Grímsvötn erupted, pouring water into the ocean. Grímsvötn also erupted in 1783, as did the nearby Laki volcano.
    - o At that time, these volcanoes poured out about 14 cubic kilometers of basaltic lava and released large clouds of poisonous hydrofluoric acid, as well as sulfur dioxide compounds. The eruption killed more than half of Iceland's livestock, and the famines that followed killed about one-quarter of the population.

    - o The drop in global temperatures following these eruptions caused crop failures in Europe, droughts in India, and famine

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The multi-stepped Gullfoss ("Golden Falls") is among the stunning waterfalls created by glacial melting during the summer in Iceland.

in Japan. The crop failures likely galvanized political unrest in France and contributed to the outbreak of the French Revolution.

Causes of the Iceland Hotspot

- No geologist doubts that Iceland is a hotspot, with an enormous outpouring of lava at this one location, but there is significant debate about what is causing this hotspot.

- Seismic tomographic images show a region of warm rock that extends from the surface deep down into the mantle, but it's not clear how far down it goes. It may not extend all the way into the lower mantle. Geologists are not sure if this is the same kind of hotspot that comes out at Hawaii. The rock coming out of Iceland also doesn't seem to be as hot as the rock at Hawaii.

- A large gravity anomaly is present under this region, which means that the whole tectonic plate structure here seems to be lifted up from below. This would support the idea of a rising mantle plume underneath. We saw this with the Afar hotspot rising up underneath the north end of the African Rift Valley.

- Another hypothesis is that this isn't a hotspot as much as a wet spot, a region of slightly higher water content in the mantle. As mentioned in an earlier lecture, water allows rock to melt (and become lava) at a lower temperature.

- What's coming up at Iceland could also be ancient ocean crust that was subducted down into the mantle during some other time of plate collisions and has been floating there. Now that the plates are opening and this ancient ocean crust is brought toward the surface, it simply melts more voluminously.

- One thing about the Icelandic hotspot is certain: When it first appeared on the surface, it had an effect much greater than changing European climates or shutting down airports—it actually ripped off a whole piece of Europe.
    - When Pangaea was starting to break up, Greenland was part of Europe, directly adjacent to Scandinavia. The Mid-Atlantic Ridge, at that point, ran up between Canada and Greenland through what is now the Labrador Sea.

    - The first outpourings of lava in this region occurred about 70 million years ago. Some geoscientists think that the plume that is now underneath Iceland was, at that point, under Greenland or even on the west side of Greenland and that lava came out in several locations on the border between Greenland and Canada.

    - About 35 million years ago, however, the bulk of the Iceland hotspot lava began to come out between what is now the border of Greenland and Scandinavia. In fact, volcanic rocks from that time can be seen on both sides of the Atlantic, and the Mid-Atlantic Ridge suddenly jumped to a new location.

- The splitting away of Greenland from the rest of Europe was probably due to the Iceland hotspot in much the same way that the Tristan hotspot helped to split Africa and South America.

- It may be the case that when a supercontinent breaks up, mantle plumes are responsible for determining exactly where the plates break. In the case of Iceland, the hotspot is strong enough that it has captured the location of the Mid-Atlantic Ridge. For smaller mantle plumes, the ridge eventually drifts away from the hotspot.

Top Mid-Ocean Ridge Islands

- Jan Mayen Island in Norway is a small volcanic island, about 50 kilometers long, covered partly by glaciers. It also sits along the Mid-Atlantic Ridge, a little bit northward from Iceland. This island grew a few additional square kilometers during a volcanic eruption in 1970.

- Bouvet Island is also part of Norway, but it's located at the southern end of the Atlantic Ocean, near Antarctica. This island is along the spreading ridge between the African and Antarctic plates. It's a small, glacier-covered, dormant volcano that is inhabited only by lichens, mosses, and a few seals, seabirds, and penguins. It has the distinction of being the single most remote land on Earth. Bouvet is 1600 kilometers away from any other bit of continent or other island.

- The Saint Peter and Saint Paul Rocks, under the sovereignty of Brazil, are a small group of islets and rocks at the equator along the Atlantic Ocean. These islets have the unusual distinction of being the only place in the world where rock from the mantle can be seen directly. Faulting that occurs at the mid-ocean ridge there has pulled the crust off the mantle, exposing the rock peridotite, which is found elsewhere in the world directly beneath the crust.

- The Azores, which are part of Portugal, are a cluster of nine volcanic islands and some islets that sit at the junction of the North American, Eurasian, and African plates. There are only a few places in the world where three plates meet at a single point, and it’s often the case that they move away from each other, which happens here. Not surprisingly, this area is volcanically and seismically active.

Suggested Reading

Krakauer and Roberts, *Iceland*.

Thordarson and Hoskuldsson, *Iceland (Classic Geology in Europe)*.

Questions to Consider

1. Why do Iceland’s volcanic eruptions affect Europe more than North America?

2. Iceland gets much of its electricity from geothermal and hydroelectric resources. Why doesn’t it have any resources of coal or oil?

The Maldives—Geologic Paradox

Lecture 28

In this course, we've seen some spectacularly tall mountains—countries at the roof of the world—but the entire nation of the Republic of the Maldives has an average elevation of just 5 feet above sea level. In fact, the highest point anywhere on any of the islands is 7.5 feet. The Maldives consists of 1192 separate islands in the Indian Ocean. They are distributed among a north-south double-chain of 26 ringlike coral atolls over an area of 90,000 square kilometers. These islands make for an unusual-looking country and allow us to see what happens when old ocean volcanoes die.

A Tropical Paradise

- The Maldives is a tropical paradise, where the temperature remains between 75° and 90°F. Currently, tourism is the chief industry, and the islands have a large number of beautiful resorts. In the past, the major industry here was the collection of cowry shells, which were used as a form of money.

- Only about 400,000 people live in the Maldives today, primarily on about 300 of the islands. The country is strictly Islamic, and most of the local people do not mingle with tourists.

- The Maldives was the first country to hold a government cabinet meeting underwater. The purpose of the meeting was to make a statement about the importance of controlling greenhouse gas emissions to combat global warming. Obviously, a rising sea level would not be a good thing for a country where more than 80 percent of the land is less than 1 meter above sea level.

A Country at Sea Level?

- As we've noted in several lectures, the sea level rose 400 feet at the end of the last ice age. Were all of these islands sitting at 400 feet above sea level 20,000 years ago so that the sea level came right up

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The capital of the Maldives is Male, a busy, bustling city in the middle of the ocean.

to their level? The answer is no; the islands at that time were still right at sea level, but they were 400 feet lower.

- It may be hard to imagine, but all of the islands of this nation are ancient volcanoes. Of course, they didn't look the way they do now when they formed. Initially, they looked like any other volcano ocean island—tall, with steep cliffs. But then, they followed a certain progression in changing from a volcano to a coral atoll.

- Over time, when the volcanism that formed an island stops, the island begins to sink down. Its barrier reef of coral, however, stays at sea level, even when the original volcano has been torn away and sunk under the waves. Three factors are involved in this process: erosion of the island, a sea level rise, and the sinking of the ocean plate.
    - o As we've seen, any land that is left alone for long enough, with no features being added to it, will eventually wear down by erosion. We've also seen that the sea level rises and floods island volcanoes. A third reason that ancient volcanoes become

sea mountains, with their tops far below the surface of the water, has to do with the sinking of the ocean plate.

- o When the ocean floor forms at a mid-ocean ridge, the rock is hot and rises high off the surrounding seafloor. As the plate moves away from the ridge, it gets colder, becomes heavier, and sinks. Anything on top of it, such as an island, will sink, too. In other words, over time, the top of a volcano can end up a long way below the sea surface.

- o But if the relative rise of sea level and the erosion are slow enough, the coral reef can keep pace; it can keep growing upward and stay right at the sea level surface.

- o If the sea level rise occurs too quickly or some environmental factor kills off the corals, the atoll will sink for good; the result is a flattop underwater sea mountain.

- o During the recent rise of the sea level, the tops of the Maldives were a few meters under water. But as the sea level rose, the coral reefs kept growing, as well. In fact, the Maldives has grown in height from the seafloor about 400 feet in the past 20,000 years.

Formation of Atolls

- If the atoll grows from the growth of coral and coral live under the water, then why are parts of the atolls above sea level? The answer to that question can be found in ocean waves. The waves grind up the coral of the reef into a calcium carbonate sand. Further, certain fish, such as the parrot fish in the Caribbean, eat coral and excrete a carbonate sand.

- As we've seen, water can hold sediment when it's moving quickly. It drops sediment when it slows down; that's why a delta forms in front of a river. A similar thing happens here. The waves slow down as they reach and then cross over the atolls.

- Waves tend to have very long wavelengths out in the ocean, but that wavelength is a function of the depth of the water. As a wave approaches land, its wavelength shortens. Because energy must be conserved, if the wavelength is shortened, the wave must become taller. That's why waves get high as they approach a beach.

- The waves carry ground-up sand and deposit it up on top of the atoll; thus, the atolls are layers of ground-up coral sand deposited over time by wave action.

Volcanoes in the Ocean

- Why are volcanoes present in the first place in the middle of the ocean? And why are they aligned in a north-south direction?

- Beginning 65 million years ago, India had just recently broken away from Antarctica and was starting to move north, crossing the Tethys Sea. At around the same time, there was a tremendous outpouring of lava from the Deccan Traps in India. This outpouring occurred over a broad region from about 60 to 68 million years ago; it was probably on the order of about 0.5 million cubic kilometers of lava.
    - It's likely that the lava from the Deccan Traps contributed to the extinction of the dinosaurs; this outpouring occurred at the same time as the Chicxulub meteor impact in the Yucatan Peninsula.

    - Interestingly, an impact on one side of the planet can cause seismic waves that are focused on the other side. This phenomenon has been seen on Mercury. At the time of the meteor impact, India was on the exact opposite side of the planet from Mexico.

    - Some scientists have proposed that the impact of the Chicxulub meteor created waves that hit India and caused the melting of the Deccan Traps. However, it seems likely that the energy from those seismic waves would have been many orders of magnitude too small to cause the volcanism in India. The two events may be just an interesting coincidence.

- After the initial outpouring of lava of the Deccan Traps, even more lava came out. Because India was moving north, it ended up making a chain of islands across the Indian Ocean, similar to what we saw in Hawaii.

- At some point, the ridge between the Indian Plate and the African Plate crossed over the hotspot; thus, the islands that had been forming on the Indian Plate began to occur on the African Plate. The hotspot is now located under Réunion Island, just east of Madagascar.

- The Deccan Traps in India, the Maldives, and Réunion Island are all related; they are all the result of the same hotspot. But there is something puzzling about the ages of the islands.
    - If the hotspot is on the African Plate, we would expect that as the plate moved away, it would carry old islands far from the ridge. In other words, the islands should go from younger to older as we move away from the ridge. But we see just the opposite.

    - Both the African and the Indian plates are moving northward. For this reason, the hotspots are essentially anchored in the underlying mantle. In this case, both Africa and India are moving across the hotspot. The ridge is moving northward, as well; thus, we can see that the plates sometimes move significantly relative to the deep underlying mantle.

The Future of the Maldives

- Over the next century, the sea level is projected to rise 1 to 2 meters. Even though the atolls will continue to grow slowly, recent research has shown that this growth is unlikely to keep pace with the rising sea level, and most of the islands will eventually be underwater.

- For this reason, the country is one of the most outspoken against the burning of fossil fuels, which contributes to global warming. As we know, variations in the Sun's output also play a major role in shaping global climates.

- The government of the Maldives plans to create a fund from tourism to buy land in India, Sri Lanka, or Australia and move the country at some point in the future.

Top Transition Sites from Volcanic Island to Coral Atoll

- The Society Islands in French Polynesia include Bora-Bora, Tahaa, Raiatea, Huahine, and Maupiti. They occur in a cluster and represent the first step in the transition from a volcanic island to an atoll. These islands have volcanic summits covered with jungles, steep valleys, and waterfalls, but they're also surrounded by a beautiful lagoon and a ring of coral because they've already begun to sink. The coral ring shows the previous coastline of the islands.

- Aitutaki is in the Cook Islands, north of Rarotonga, about halfway between French Polynesia and Tonga. Aitutaki is what we might call an "almost atoll." The maximum height here is about 123 meters, about 400 feet above sea level. The lagoon, however, is about four times larger than the island; the island already makes up a smaller part of the total area. Over time, the mountains in the middle of the island will wear down entirely to form a raised atoll.

- The Aldabra Atoll is one of the outer islands of the Seychelles, north of Madagascar in the Indian Ocean. It is the tallest raised atoll, about 8 meters above sea level. This island is practically untouched by humans, but it has the world's largest population of giant tortoises. Again, over time, the amount of land here will decrease, resulting in a formation similar to the Maldives.

- Bikini Atoll is in the Marshall Islands of the northwestern Pacific. The atoll here is the set of about 23 islands that are part of a long coral reef surrounding a much deeper, broader lagoon of about 100 square kilometers. Bikini Atoll is in a remote part of the northwest Pacific called Micronesia and was, of course, the site of nuclear bomb testing by the United States from 1946 to 1958.

Suggested Reading

Davidson, *The Enchanted Braid*.

Pilkey and Young, *The Rising Sea*.

Questions to Consider

1. Why doesn't coral grow well more than a few tens of meters below the surface?

2. Changes in ocean chemistry have caused corals in many parts of the world to die off. What are the implications of this for the appearance of oceans a million years in the future?

The Dead Sea—Sinking and Salinity

Lecture 29

In the last lecture, we talked about the country with the lowest average elevation in the world, the Maldives, a chain of coral atolls in the Indian Ocean. In this lecture, we'll get even lower, with the body of water that has the lowest elevation anywhere on Earth: the Dead Sea, along the border of Israel and Jordan. The surface and shores of the Dead Sea are 1388 feet below sea level, but it's also dropping at the rate of about 1 meter per year. If you look at the shorelines and surrounding hills, you can see multiple rings of these past shorelines.

Description of the Dead Sea

- The Dead Sea is only about 67 kilometers long and about 18 kilometers across at its widest point. It sits in a long, narrow valley that stretches from the Red Sea north to Syria, and it separates Israel and Jordan.

- Most lakes eventually drain to the ocean, but that obviously can't happen with the Dead Sea because it's below sea level and most rivers can't flow uphill. What happens to the water here?
  - The Jordan River runs down from the north, first draining into and out of the Sea of Galilee and then flowing down the narrow valley into the Dead Sea.

  - The Dead Sea is a closed basin; the water evaporates as fast as it enters. In fact, it is now evaporating faster than it's being filled because the water from the Jordan River is being drawn off for a variety of purposes by Israel and Jordan.

  - Once the water evaporates, it leaves behind salts. The Dead Sea is one of the saltiest lakes on Earth. It's 33.7 percent salt, which is 8.6 times saltier than the ocean.

- We can see evidence of the salinity of the water here in the unusual salt features that have precipitated along the shore. Some of the formations look like small castles sticking up out of the water.

- The composition of the salts in the Dead Sea is a function of the geology of the surrounding rocks. About 30 percent of the salts are sodium chloride, and 50 percent are magnesium chloride. The remainder includes calcium chloride, potassium chloride, and others. The exact salts vary by season, depth in the water, and temperature.

- The amount of salt makes the water extremely dense. If you go swimming in the Dead Sea, you'll be surprised by how easily you float.

History of the Dead Sea

- The entire region of the Dead Sea has an enormous amount of salt because the valley was flooded by the Mediterranean Sea multiple times.

Salt crystals form on anything in the water of the Dead Sea, such as rocks or sticks.

- About 3 million years ago, the climates were much warmer, and there was much less ice in Antarctica and Greenland; sea levels in general were higher. The Mediterranean flooded in through the Jezreel Valley, which cuts to the Mediterranean just to the southwest of the Sea of Galilee. Each time the Mediterranean receded, the long lake would slowly dry out, depositing another layer of salt. The ancient ancestor of the Dead Sea, the prehistoric Lake Sodom, had an accumulation of salt 3 kilometers thick.

- About 2 million years ago, the land between the Jordan Valley and the Mediterranean was uplifted by tectonic forces. When this happened, the Dead Sea was cut off, and it became a long lake, known as Lake Gomorrah, and no longer flooded.

- The region's climate was wetter at the time, and Lake Gomorrah was a freshwater lake with significant sediments deposited in the lake bottom. These rocky sediments weighted down the layer of salt underneath and pushed the salt up and around the edges of the lake, forming ridges and hills made entirely of salt. For instance, the Lisan Peninsula to the south and Mount Sodom to the west are both made of salt.

- Going back tens of thousands of year, the lake was generally much higher than it is now, but the level has fluctuated greatly. The drop in water level has caused the salinity to increase to the wildly high levels seen now.

- The salinity of the Dead Sea is so high that the bottom part of the lake water is at its saturation point. That means that salt is currently precipitating out of the water, making a new layer of salt on the bottom.

- The shallow levels of the Dead Sea are having some unfortunate geologic consequences around the area. As the sea shrinks, underground layers of salt have dissolved away, leading to the sudden formation of large numbers of small sinkholes that are causing roads and bridges to collapse. More than 2500 sinkholes now line the shores of the Dead Sea, most of which have appeared just since 2000.

Location of the Dead Sea

- The fact that the Dead Sea is so far below sea level can be traced to the breakup of Africa that began 30 million years ago. As we discussed earlier, the Arabian Peninsula had been part of Africa for a long time. Then, it started to break away to the northwest. First, the area experienced volcanism; then, the crust was stretched, thinned, and rifted.

- Starting about 12 million years ago, the Red Sea began as a real ocean. It started as a continental rift, just like the African Rift Valley, but it kept opening up. The strange shape of the Red Sea, the Gulf of Suez, and the Gulf of Aqaba stems from the Dead Sea transform fault, a fault that is allowing the Arabian Peninsula to slide past the Sinai Peninsula.

- The Dead Sea transform fault is not straight; it makes a bend. As the two plates slide past each other, a hole develops at the bend, and that is the Dead Sea. The seafloor of the lake is dropping continuously and could do so for some time because the plate boundaries show no sign of stopping their movement.

Human Occupation

- Civilization in the West began in the Dead Sea region. Jericho, just to the north, is one of the world's oldest cities, dating back before 10,000 years ago. The early cities of Sodom and Gomorrah, mentioned in the Hebrew Bible, the New Testament, and the Koran, were somewhere along the southeastern shore of the Dead Sea. One important implication of the Dead Sea's location along a major plate boundary is that it can have large earthquakes. Some have proposed that an earthquake caused the famous destruction of Sodom and Gomorrah.

- The Dead Sea region is also one of the few places in the world where asphalt seeps directly to the surface, similar to the La Brea

Tar Pits in Los Angeles. This asphalt was prized by the early Egyptians; in fact, many Egyptian mummies were embalmed with Dead Sea asphalt.

- One of the most famous archaeological discoveries in the region is the caves of Qumran, where the 2000-year-old Dead Sea Scrolls were found. These scrolls contain alternate versions of many parts of the Hebrew Bible, as well as many stories that didn't make it into the canonized Bible. The scrolls were from Jewish tribes who lived in the area from about 150 B.C.E. to 70 C.E.

- The unique geologic conditions of the Dead Sea make it a popular tourist destination. More than 1 million people visit each year, largely for the spas that exist along the coast. The high mineral content of the water, the fact that there's low pollen in the area, and the low ultraviolet radiation from the thicker air contribute to the popularity of the site.

Extremophiles in the Dead Sea

- As we have seen in other environments, single-celled extremophiles live in the ultra-saline waters of the Dead Sea. Scientists are interested in these strange organisms because they might be models for the kinds of life that could possibly survive on another planet. One day, we might even discover similar organisms on solar system bodies, such as Mars.

- In times of flood, the salt content of the Dead Sea can drop from its usual 33 percent to about 30 percent or lower. In the wake of this influx of fresh water, the Dead Sea temporarily comes to life. In 1980, after one rainy winter, the normally dark blue Dead Sea turned red. It was teeming with a type of algae called *Dunaliella* that nourished red-pigmented halobacteria, causing the color change.

- Since 1980, the Dead Sea basin has been extremely dry, and the algae and the bacteria have not returned in measurable numbers.

Top Saltwater Lakes

- Tiny Don Juan Pond is in the Dry Valleys of the Transantarctic Mountains, not far from McMurdo Base in Antarctica. The amount of water here is almost insignificant. The pond is currently on average about 4 inches deep, but this depth varies over its extent, which is about 300 meters by 100 meters. The pond seems to be fed from underground water and has the saltiest water found anywhere in nature. When it was first found, its salinity was 40 percent at a temperature of –30°C.

- Lake Assal in the small coastal African country of Djibouti is the saltiest real lake in the world. Its salinity at the surface is 34.8 percent, just edging out the Dead Sea, at 33.7. Like the Dead Sea, Lake Assal is below sea level, about 155 meters, making it the lowest point anywhere after the Dead Sea and the Sea of Galilee. The composition of Lake Assal is primarily sodium chloride, similar to seawater. The small lake is continuously fed by water flowing underground from the Indian Ocean.

- The Salton Sea in southern California, along the San Andreas Fault, formed through the same mechanism of shearing along a bend in a transform fault as the Dead Sea. The Salton Sea is an extension of the Gulf of California, forming as the arm of Baja, California is tearing away from Mexico. The Salton Sea sits about 69 meters below sea level.

- The Turpan Depression in the Xinjiang region of western China also formed from a sheared, pull-apart basin, about 250 million years ago. The Xinjiang region is the hottest and driest part of China and has the lowest elevation of anywhere in Asia, at 154.5 meters below sea level.

- The Caspian Sea is the largest salt lake and the largest lake of any kind in the world, but it has only about one-third the salinity of the ocean. The Caspian Sea has more than 130 rivers draining into it, but it has no outlet; its water never reaches the ocean. Like the Black Sea, the Caspian Sea used to be part of the ancient Tethys

Sea. When Africa, Arabia, and India all crashed into Eurasia and the Tethys Sea closed up, the Caspian Sea became landlocked, forever to be an interior sea.

Suggested Reading

Haviv, *Trekking and Canyoning in the Jordanian Dead Sea Rift*.

Neev and Emery, *The Destruction of Sodom, Gomorrah, and Jericho*.

Questions to Consider

1. The Sea of Galilee sits in the Jordan Valley, just like the Dead Sea, and it drains to the Dead Sea. Do you think it is fresh water or salt water?

2. If Arabia keeps moving northward into Eurasia, what will eventually happen to the Dead Sea?

Salar de Uyuni—Flattest Place on Earth
Lecture 30

In the last lecture, we discussed some of the saltiest lakes in the world, starting with the Dead Sea, along the border of Israel and Jordan. In this lecture, we'll again go a step farther and look at what happens when the salty water disappears and all that's left is salt. For this discussion, we'll visit the world's largest salt flat: the Salar de Uyuni in Bolivia. This area is about 4000 square miles—almost the size of Connecticut and about 25 times larger than the Bonneville Salt Flats in Utah. The Salar de Uyuni has about 10 billion tons of salt.

The Saltiest, Flattest Place on Earth

- The Salar de Uyuni is located high in the Altiplano of Bolivia, the High Plateau of the Andes Mountains. It is exactly 11,995 feet in elevation over almost its whole extent of 4000 square miles. The process for such a large region to become so perfectly flat requires the constant wetting and recrystallizing of the layers of salt.

- Some of the salt may be slightly rough in some places, but then it rains, the salt dissolves and levels out a bit, the water dries off, and the salt may buckle and crack. The rain comes again, dissolves the salt, and fills in all the cracks. Over time, the region becomes perfectly flat for hundreds of miles in any direction.

- Features in the Salar de Uyuni generally measure less than 1 meter. The flat has a slight general trend to increase its elevation slightly—by centimeters—from the south to the north. In addition, there are ridges and mountains on the surface, but these are only centimeters high.

- The flatness of the Salar de Uyuni is analogous to the change in sea level over ocean ridges and trenches.
    - Averaging out the waves, you might think that the ocean surface would be flat, but that isn't the case. Because the composition of the Earth varies in different regions underground, it exerts a

varying gravitational force in different parts of the world that causes the sea surface to rise and fall.

- In a place where cold ocean seafloor is subducting, mass is added, and thus, gravity increases. A rising, hot mantle plume would be more buoyant and have less mass; thus, it would pull with decreased gravity. The effect is to make the whole Earth somewhat lumpy so that even the shape of the ocean surface varies from an ellipsoid.

- In some places, such as around Iceland, the sea surface is significantly elevated, probably because of the rising mantle plume that causes the Iceland hotspot. Just south of India, the sea surface is depressed, a condition that is probably related to the motion of India northward.

- The varying sea surface is called the geoid. The Salar de Uyuni is the only place on Earth where the ground is so flat that we can actually see and measure the centimeter-high variations in the Earth geoid, the true shape of the Earth.

- When the Salar de Uyuni gets a thin layer of water on top, it becomes the world's largest mirror. It is used by some satellites to calibrate their elevation above the surface of the Earth.

- Salt polygons on the Salar de Uyuni represent an expansion of the salt that is analogous to the columnar basalts we saw at the Devils Tower. There, cracks formed from the contraction of cooling basalt. Here, the salt expands slightly when it crystallizes, pushing up tiny ridges, primarily in the shape of hexagons and pentagons.

Effects of Salt in Water

- Salt significantly changes the properties of water in which it's dissolved. An experiment with a hard-boiled egg shows that the density of salt water is greater than fresh water. This higher density explains why you float when you go swimming in a salt lake. Because the salt water is significantly denser than normal, you float higher.

- If you put a beaker of fresh water and one of salt water in the freezer overnight, the fresh water will be frozen in the morning, but the salt water will still be liquid. The presence of the salt decreases the melting point of ice. We see this effect at Don Juan Pond in Antarctica, the 4-inch-deep pond that doesn't freeze during Antarctic winters.
    - At the Salar de Uyuni, the elevation is so high that the temperature at night is often below freezing—for fresh water at least—but the salty water doesn't freeze. Daytime temperatures are fairly stable, about 55° to 70°F, which means that even normal ice would be melted.

    - In an indoor skating rink, salty water at temperatures much lower than 0°C is run through a network of pipes to chill a slab of concrete to below the freezing temperature for pure water. When fresh water is poured on top of the chilled slab, it freezes.

Sources of Salt

- As we saw with the Dead Sea, the whole region of the Salar de Uyuni is a closed basin; water flows into it but not out. The water evaporates and leaves the salts behind. The Altiplano has an extremely low rainfall, but it experiences enough rain to eventually dissolve the salts out of rocks in the surrounding mountains and deposit them in the basin. Water also flows in from streams around the perimeter, such as the Rio Grande river along the southern border.

- Most of the water for the salt flat here comes from the north. During the rainy season, Lake Titicaca overflows its banks, and the rainwater flows down into two small lakes, Uru Uru and Poopó. These lakes, in turn, overflow their banks, and the water flows to two salt flats, the Salar de Coipasa, the smaller one to the northwest, and the Salar de Uyuni. The water eventually evaporates away, leaving behind another layer of salt.

- Most of the salt here dates back to 46,000 to 36,000 years ago, when Uyuni was a large lake, now called Lake Minchin. About 26,000 to 13,000 years ago, at the end of the last ice age, Lake Minchin transformed into another paleolake, Lake Tauca, with a depth of about 140 meters. About 13,000 to 11,500 years ago, the smaller Lake Coipasa formed, and when it dried, it left behind the lakes Uru Uru and Poopó and the two salt deserts.

Structure and Composition of the Salt Flats

- The structure of the salt flats is strange. A thin crust of salt on the surface—perhaps tens of centimeters to a few meters thick—rests on top of a thicker layer of slushy liquid brine—perhaps 2 to 10 meters thick.
    - This brine contains salt crystals that gradually dominate deeper into the layer; eventually, the layer reaches a region where there are no pore spaces between the salt. There is no water here—just solid salt.
    - Because the evaporation rates are so high at the surface, a crust forms over the top of the brine, but right underneath that crust, the salt is porous and there's a good deal of liquid brine. When flooding occurs, the layers alternate between solid and liquid.
- The salt here also has an interesting composition. It's primarily halite, or sodium chloride, but it's highly enriched in other salts, such as magnesium chloride, potassium chloride, and lithium chloride. These other salts are largely concentrated at the top of the briny layer.

Tourist Highlights

- Though the salt stretches out flat for hundreds of miles, some small islands poke up through it in places. Some of these islands are the tops of ancient volcanoes, and some have salt hotels, with walls made of blocks of salt.
- During the rainy season, when a thin layer of water sits on the surface, all you can see is the reflected image of the sky in the water, and it looks as if you are driving across the sky. Because all you see is sky in all directions, it's almost impossible to keep your bearings.

- One highlight for tourists in this area is the train cemetery. In the 1800s, the British built a railway system here to serve the mining industry in the area. When that industry collapsed in the 1940s, the trains were no longer used and were left in one long line.

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The reflection from the thin layer of water that sits on top of the Salar de Uyuni during the rainy season gives drivers the impression of traveling across the sky.

- Very little life is found in the Salar de Uyuni. The salt itself is entirely devoid of life. During the rainy season, a bloom of pink cyanobacteria takes place in the saltwater layer, and the area becomes a nesting ground for flamingos and other birds. The islands host small microenvironments with cacti, rabbits, foxes, and other animals.

- Because the Salar de Uyuni contains more than 40 percent of the world's known lithium, used in batteries, the area is harvested extensively, but removing all the lithium would destroy the appearance of the salt flat.

Top Salt Flats

- The Salar de Atacama in Chile is a salt flat similar to the Salar de Uyuni. It's about one-third the size of the Salar de Uyuni and not nearly as smooth because in many places it no longer floods and is permanently dry. This area contains 27 percent of the world's known lithium but provides about one-third of the world's annual supply.

- The Bonneville Salt Flats in Utah is the largest of many salt flats that are west of the Great Salt Lake. Both Salt Lake and the Bonneville

Flats are the remnants of the once huge Lake Bonneville, which at its peak, 20,000 to 30,000 years ago, was about the size of Lake Michigan but much deeper. Some of the ancient shorelines of the former Lake Bonneville can still be seen high up on the sides of the mountains in Utah. This lake seems to have been a recurrent feature of the cycles of ice ages. It has filled up and dried away at least 25 times over the past 3 million years.

- Lake Eyre is both the lowest point in Australia, about 15 meters below sea level, and the largest lake there—but only when it rains. Lake Eyre is largely a salt pan with some small salty lakes, but occasionally over the course of a century, heavy winter rains fill in the lake. The last time this occurred was in 1976.

- The Makgadikgadi Salt Pan sits in the middle of the dry savanna of northeastern Botswana. It is all that remains of the formerly enormous Lake Makgadikgadi, which once covered a vast area but dried up several thousand years ago.

Suggested Reading

Arrieta, *From the Atacama to Makalu*.

Fletcher, *Bottled Lightning*.

Questions to Consider

1. How did the structure of the salt layers at the Salar de Uyuni (with a layer of liquid brine in between two solid layers) initially form?

2. The valuable lithium is concentrated in one region in the south but still is found throughout the Salar de Uyuni. In your opinion, how much (all, some, or none) of the lithium should be removed from this salt flat?

Namib/Kalahari Deserts—Sand Mountains

Lecture 31

Along the west coast of Africa is one of the world's most inhospitable places: the Namib Desert. There are no volcanoes here or acid lakes; it's just incredibly dry and has been so for more than 50 million years. Still, this region has its own unique beauty. We see colors and shapes here that can't be found anywhere else on the planet. Just over a ridge of mountains from the Namib is the Kalahari Desert, which has a completely different character and much more plentiful life. In this lecture, we'll continue our theme of dry and arid places with a visit to these two fascinating deserts.

"The Land God Made in Anger"

- The Bushmen of the Namibian interior have called the region of the Namib Desert "the Land God Made in Anger." It is one of the driest places on Earth, which is unusual given that it rims an ocean. It receives less than 1 centimeter of rain a year. Deserts are often defined as regions that receive less than 25 centimeters of rain a year.

- Hot deserts have a different appearance than cold deserts. Sand dunes are common in hot deserts, although much more common is a surface called the desert pavement, a hard, dry, packed surface of large rocks and cobbles. This kind of surface forms by different processes, particularly the strong winds that are often found in deserts. The winds blow away lighter dust and small sand particles, leaving the rocks behind.

- The infrequent rains in a desert chemically weather away the rock, dissolving some of the minerals and leaving behind small particles that the wind then blows away. From this process comes the sand for the giant sand dunes of the Namib Desert, which are larger than anywhere else in the world. The sand is blown across the surface and accumulates into dunes.

- The desert pavement can develop by a process of freezing and thawing or wetting and drying of the ground, which causes the ground to expand and contract.
    - This strange process is not completely understood. If the ground is constantly frozen and thawed, large rocks underneath will work their way up to the surface.
    - Freezing and thawing is, obviously, more common in cold deserts, such as Antarctica or the Gobi Desert, but it also takes place in high regions of dry deserts.
    - The freezing and thawing change the volume of the soil. The soil expands when it freezes, but when it thaws, it seems as if smaller rocks are wedged downward, leaving the rocks a little bit higher each time the process takes place.
    - If you vibrate a set of objects of different sizes, over time in certain cases, the larger objects will rise to the surface. Something similar to this "Brazil nut phenomenon" may take place in deserts.
- Even hot deserts, such as the Kalahari, can experience significant temperature swings, with freezing at night. Temperatures in the winter in the Kalahari are often below freezing; the reason for this is simply the lack of water.
    - Water vapor in the atmosphere has a tremendous moderating effect on temperatures. It is actually the strongest greenhouse gas, essentially keeping our atmosphere warm, and it forms clouds.
    - Clouds block incoming sunlight during the day, making the temperature cooler on warm days, but the water vapor absorbs energy that radiates back off of Earth's surface at nighttime, keeping the atmosphere warm.
    - In the desert, with no water vapor in the air, the sun heats the surface during the day, but the heat escapes quickly at night.

- Deserts are generally some of the least inhabited places in the world because of the lack of water, but remarkably, some people live in the Arabian Desert, the Sahara, and other deserts.
    - There is also a growing modern interest in desert regions, at least partially because of their mineral resources.

    - Deserts have many useful resources that form as evaporates, such as sodium nitrate, which is used for fertilizer and in gunpowder; gypsum, which is used for construction; and the salts, such as lithium, that are washed into playas.

A Coastal Desert?

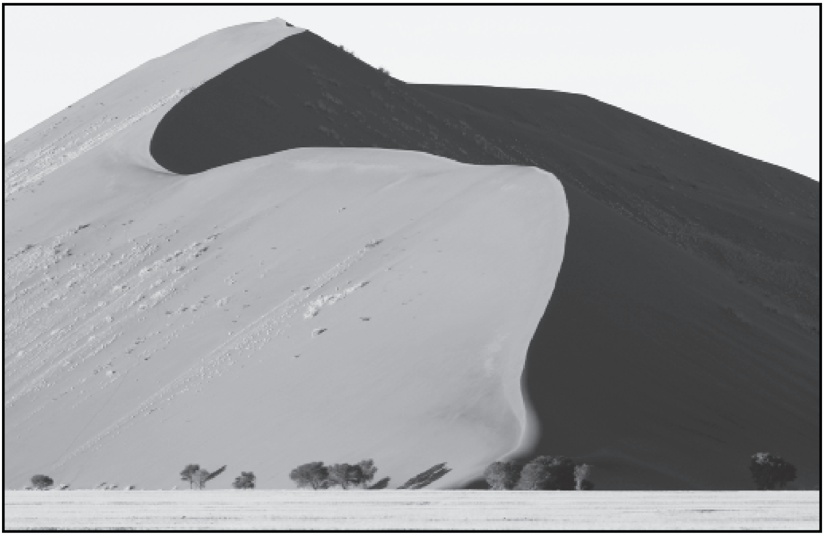
- The coastal location of the Namib Desert seems puzzling. How could this dry region exist right next to so much water?

- The West Coast of the United States is very green, but once you travel up and over the coastal mountains, you reach desert. The reason for this change is that the winds blow in a different direction.

- In the area of the Namib, the prevailing wind blows east to west, which is the opposite of the western United States. As moist air from the Indian Ocean rises up over the Drakensberg Mountains of South Africa, along the east coast, it cools; it loses its water into water droplets that rain out. The air is dry when it crosses the Namib escarpment, and as it drops and warms even further, it absorbs any available moisture, making the ground even drier. For this reason, the area right along the coast is drier than even a little bit inland.

Features of the Namib

- The Sossusvlei region of the Namib is a sea of sand that has a rich ochre color. The dunes here rise more than 1000 feet, 300 feet taller than the next largest sand dunes in the world—in Arabia.
    - The older a sand dune is, the brighter its color. The color itself is the result of two factors: a slow oxidation of minerals that contain iron and tiny fragments of garnets, which make the sand sparkle.



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Some of the sand dunes in the Sossusvlei region of the Namib Desert are more than 1000 feet tall; in other areas, they might qualify as mountains.

  - o The dunes refract spectacular colors as the light changes in the desert, moving from bright orange through red to a deeper mauve color over the course of the day.

- The giant Fish River Canyon in southern Namibia is similar to the Grand Canyon in Arizona. Clearly, at one time in the past, a good deal of water was present here. Beautiful purple, pink, and gray rock layers stretch along a 100-mile course. The canyon walls sometimes drop by almost 2000 feet out of the flat, dry plateau. In some places, the canyon is almost 30 kilometers across.

- Along the coast, the Namib can experience thick, blinding fog. When the dry, hot desert air meets the moist, cold air generated by the Benguela Current, the dry air pushes the moist air down. As it falls and warms, the moist air causes thick banks of fog. This fog is the only moisture that some parts of the desert ever receive, and life has evolved to adapt to it.

Features of the Kalahari

- The Kalahari Desert is much more vegetated than the Namib, and large numbers of mammals live here, including meerkats, lions, jackals, buffalo, and people.

- Technically, much of the Kalahari is not a desert but a steppe, a semiarid region. We don’t find giant sand dunes here; much of the land is low, flat, scrubby, dry bush.

- The most interesting aspect of the Kalahari is in the northern region, where the Okavango River empties into the desert and disappears.
    - In January, heavy rains in Angola flow southward through the Okavango River, which begins to swell. The water slowly works its way southward, finally reaching down into the Okavango Delta after about four months.

    - The delta then becomes, briefly, one of the largest river deltas in the world, 250 kilometers across by 150 kilometers long. The topographical variation across this delta is only about 6 feet.

    - As a result of the flatness of this region, anything on the ground that sticks up, such as a clump of trees, can start to accumulate silt from the incoming water. More vegetation develops, and small desert islands start to build up.

    - The flood in the Kalahari is rejuvenating for desert life, but even during the flood, most of the water evaporates. Only enough of it seeps into the ground to keep the trees alive and to support life until the next year’s flood.

Top Deserts

- The Arabian Desert covers most of the Arabian Peninsula. Though it’s much smaller than the Sahara, it is still more than 2 million square kilometers. The Arabian Desert has vast oceans of sand, with dunes rising more than 250 meters. The sands here are mostly quartz with small amounts of potassium feldspar, giving them a slight orange color.

- Satellite images show evidence of the camel tracks of ancient caravans in certain sections of the Arabian Desert. Archaeologists have found the remains of lost cities here that were once a part of the frankincense trade.

- Before 5000 years ago, monsoon rains fell here, and the deserts were green. Evidence, such as hand flints and other tools, has been found of Paleolithic humans living in what is now a wasteland of sand.

- The Gobi Desert is in Mongolia and part of China. This is an elevated, cold, dry land that's in the rain shadow behind the Tibetan Plateau. Much of the Gobi contains steppe regions that support diverse ecosystems. Because this region is so high in elevation and so dry, it's susceptible to significant temperature changes, sometimes of more than 90°F in a single day.

- The Great Victoria Desert is the largest desert in Australia, about 0.5 million square kilometers. Located in the south-central area of the country, this desert supports a small population of indigenous Australians, though it's unable to support any agriculture.

- The Atacama Desert, along the west coast of South America, is the exact analog to the Namib Desert. It sits on the west side of the continent with air blowing from the east; by the time the air drops down over the Atacama, not only it is devoid of water vapor, but it absorbs any water it comes in contact with. The Atacama is the driest place on Earth. Much of it receives less than 1 millimeter of rain a year.

Suggested Reading

Johnson, *The Ultimate Desert Handbook*.

Martin, *The Deserts of Africa*.

Questions to Consider

1. Along the West Coast of the United States, the situation is reversed from the Namib Desert: Lush vegetation is found from the coast up the sides of the coastal mountains, and dry desert area exists east of the coastal mountains. What causes this reversal from the conditions of the Namib Desert?

2. How has life evolved to adapt to the situation at the Okavango Delta, where there is a good deal of water for a brief period and arid conditions the rest of the time?

Siwa Oasis—Paradise amidst Desolation

Lecture 32

The Sahara Desert is remarkably dry; there's almost no green here. But even in this setting, we find the Siwa Oasis, a well-watered island in a giant sea of sand. The Siwa Oasis sits in a broad depression that is bordered on the north by a set of cliffs at the edge of the Qattara Depression. It's bordered on the south by the enormous dunes of the Great Sand Sea. For ancient caravans, Siwa was the last stop before crossing the large desert into what is now Libya. The springs here are plentiful enough to support several permanent salty lakes, whose seemingly magical presence has spawned many myths about the area.

The Sahara Desert

- The Sahara Desert is enormous; at 9.5 million square kilometers, it is almost as large as the continental United States and Alaska (9.8 million square kilometers). Only the Antarctic Desert is larger.

- The Sahara sits below the top of a Northern Hemisphere Hadley cell; the cool, dry air falls and absorbs available moisture out of the ground.

- The land here is extremely varied geographically. Only about 20 percent of the Sahara is sand; most of the rest of it is desert pavement, called hamada. Mountain ranges pop up in various places, including the Atlas Mountains, which border the Sahara on the northwest side and rise up to 4 kilometers in places.

- The Sahara also has a variety of unusual smaller features, such as the famous Richat Structure in Mauritania, a 50-kilometer-wide "bull's eye." This structure is actually a dome that has been eroded so that what we see now are different layers of rock exposed in circles on the flat surface.

- Cities have existed in the Sahara, but they have been few and far between. Timbuktu, in Mali, was once a major center of the caravan trade, but its importance has steadily declined as the southern Sahara has become increasingly desertified. Essentially, over time, the Sahara has been pushing its border southward.

- The Sahara is divided into three major geographical regions.
    - The Western Sahara starts from the border with the Atlantic Ocean. It encompasses the central mountains in southern Algeria, called the Ahaggar Mountains, and the tall Aïr Mountains in Niger.

    - The Ténéré Desert is a dry desert between Niger and Chad. The Tibesti Mountains, also in Chad, are a set of continental intraplate volcanoes, very similar to Yellowstone. This area sits over a deep mantle hotspot.

    - The region in the far east is known as the Libyan Desert. This region, about 1000 kilometers square, is the most arid, but it contains the Siwa Oasis.

The Oasis

- The Siwa Oasis sits next to an impassable area called the Qattara Depression, up to 60 meters below sea level in some places. The oasis has more than 1000 springs; most of them are too salty to drink from, but a few hundred provide fresh water. The springs support several permanent salty lakes spread over a wide area. The largest of these is Lake Siwa, covering about 30 square kilometers.

- Because the water of the oasis is generally so salty, few types of plants grow here. The date palm has adapted to survive here and provides much of the sustenance of the people. Roof beams, furniture, mats, baskets, and wine are all made from date palms. Olive trees also survive well in the salty soils here.

- The oasis contains about 3000 small mountains and hills, most of which exist because they have a tough capstone at the top.

Human Habitation of the Oasis

- The Berbers have inhabited the Siwa Oasis for at least 12,000 years. At that time, Egypt may have been even drier than it is today.

- From about 9000 to 5000 years ago, northeastern Africa benefited from a wet, moist climate. At that time, it was called the Wet Sahara or Green Sahara. Egypt had a monsoon climate with strong rains for part of the year. The land was green, and people traveled easily from the central to the northern parts of Africa. Now, the Sahara largely cuts off travel; the only corridor is along the Nile.

- Neolithic cave drawings that suggest the presence of large amounts of water have been found in a region south of Siwa called the Wadi Sura.

- Siwa was an independent Berber oasis for thousands of years, but at some point, it was conquered by the dynastic Egyptians, probably Ramses III, and became part of the Egyptian Empire. The caves in some of the hills were used as tombs for wealthy people.

Siwa traditionally traded dates and olives with other communities; as a result, there are probably more caravan tracks leading out of Siwa than any other oasis.

- The Mountain of the Dead, Jebel al-Mawta, is the tomb of a particular merchant named Si-Amun, meaning "man of Amun." Amun was an important Egyptian god who had a temple in Siwa. A famous oracle lived in a nearby village.

- When the Greeks settled in Libya, they heard of this wise oracle and elevated the Siwa Oasis to a place of great honor. Both Cleopatra and Alexander the Great are known to have visited the oracle.

- The Siwa Oasis was occupied later by the Romans, who built many structures that can still be seen throughout the oasis.

- From about 700 onward, Siwa became Christian but was finally conquered by Islamic attackers around 1150.

- Currently, about 23,000 people live on the oasis. The population is Islamic and speaks Arabic but also still speaks the original Berber language and retains Berber culture.

Sources of Water

- The Sahara and other deserts are occasionally interrupted by small regions of water and green, but these regions don't come directly from rain. The water comes from a layer of rock underground called an aquifer. An aquifer can be any type of rock; it's often sandstone, which is both permeable and porous. It has pore space that can hold water, and the water can flow through it easily.

- Water reaches the surface in a number of different ways. When the aquifer comes into contact with the surface, the result is a standing lake that represents the top of the water table. Faults from earthquakes may also cut across the aquifer and allow water to bubble up and reach the surface.

- Often, water is pushed by pressure from the aquifer extending upward, forming a mountain. Rain falls and fills in the aquifer, which is then pushed up and may cause an oasis. The water often enters the aquifer far from where the oasis is, having traveled hundreds or even thousands of kilometers underground.

- Beneath Siwa is a layer of sandstone, called the Nubian Sandstone, that is about 2.5 kilometers thick. Estimates are that this sandstone contains 50,000 cubic kilometers of water.
  - As we've seen several times in this course, layers of limestone and sandstone—the typical sediments of sedimentary rock—formed in Egypt when the ocean flooded the continent and deposited sediments.

  - These layers were initially flat, but in Egypt, they began to be tilted upward in the south by the Afar hotspot. This hotspot has elevated a region at the bottom of the Red Sea.

  - By 35 million years ago, a large river system called the Gilf River drained much of Egypt into the Tethys Sea at the exact location where the Siwa Oasis is now. In fact, Siwa was the location of the river delta.

  - By 25 million years ago, an early Nile was forming, but it ran in the other direction—south, emptying somewhere into the desert.

  - Over time, the Gilf River began to shrink, and the coast moved northward as sediments were repeatedly deposited by the rivers and as sea levels dropped. By 10 million years ago, the tilting of Egypt had increased to the point that the Nile River moved northward and drained toward the Mediterranean, and the Gilf River system was entirely drying up.

- By looking at the chemical composition of materials in the water, scientists have determined that the water being pulled up at the Siwa Oasis was deposited underground more than 20 million years ago. In other words, it sank into the ground when Siwa was topped by a major river system for millions of years. It's essentially fossil water.

- Siwa has a limited future, as do all oases in the Sahara. The current heavy draw on the water is making the soils so salty that even the date palms are starting to die. Groundwater is often needed most in dry areas, but this water found its way into the ground during a time of much wetter climates; it is not a renewable resource during our lifetimes.

Top Oases

- The Chebika Oasis is also in the Sahara, in Tunisia. It sits at the north end of a large sand sea called the Grand Erg Oriental. This area is where the giant sand sea meets the eastern extension of the Atlas Mountains. Two thousand years ago, the Chebika was a Roman outpost; it has been occupied by the Berbers since that time.

- The Huacachina Oasis in Peru is a pretty, round lake that sits in the middle of giant sand dunes at the northern end of the Atacama Desert. This region has become a tourist site; the draw here is sand-boarding down the sides of the enormous sand dunes.

- The Ubari Oasis is located in the western desert of Libya, at the edge of the giant Ubari Sand Sea. This region is extremely dry, sometimes going decades without rain. Ubari sits in a broad, wide, and extremely flat depression, but the area used to be the location of a giant lake during wetter climates, Lake Megafezzan. The ancient lake water charged up an underground aquifer that is now pumped for fresh water.

- In the central Sahara, in Algeria, is the Tuat region, a string of small oases to the south of the sand seas of the Grand Erg Occidental and to the east of the Erg Chech. These oases stretch out over a distance of about 160 kilometers and are remarkably fertile, yet not a single drop of water usually falls here. The water comes from an aquifer that spans more than 1 million square kilometers and is situated only a couple of meters below the surface.

Suggested Reading

Sampsell, *A Traveler's Guide to the Geology of Egypt*.

Vivian, *The Western Desert of Egypt*.

Questions to Consider

1. Why are the Siwa Depression and the larger Qattara Depression to the north below sea level? (Hint: Why doesn't this happen more often in other parts of the world?)

2. The date palm tree has evolved to extract fresh water out of salty water. What are the implications of this adaptation for agriculture and soil quality?

Auroras—Light Shows on the Edge of Space

Lecture 33

So far in this course, we've looked at wonders that are tied to the geosphere—the land and the water and ice that are on it. But of course, the atmosphere also contains wonders: clouds in amazing shapes; severe weather, such as tornadoes and hurricanes; and fascinating light effects associated with weather, such as rainbows. In this lecture, we'll talk about a phenomenon of space weather: the Aurora Borealis, or northern lights. To witness the auroras is a truly remarkable experience; they form a dancing, shimmering curtain of green and pink fire in the sky. To explain this phenomenon, we'll look at the workings of Earth's core and the Sun and even some quantum mechanical behavior of atoms themselves.

The Earth's Magnetic Field

- The Aurora Borealis is most likely to be seen in northern Canada, Alaska, Scandinavia, and other places at very high latitudes. An auroral zone that is a few hundred kilometers wide tends to run in an east-west band around the north magnetic pole. A similar zone runs around the southern magnetic pole for the southern lights.

- Earth's magnetic field looks roughly like the dipolar field of a bar magnet. Field lines run from the North Pole to the South Pole. In terms of magnetism, the Earth's South Pole is the North Pole, and the field lines run all the way up to the northern latitudes.

- The field is much more complex, however, than a bar magnet. Inside the Earth is liquid iron at a temperature of more than 5000°C. This iron is constantly convecting and churning, just like the mantle but much faster because the viscosity of the liquid iron is low; it probably has a similar thickness to honey. It's not entirely clear what drives the convection, though there are probably three factors at work.

- As the heat from the outer core passes into the mantle above, the iron becomes a little colder and sinks, helping to drive the convection.

- Heat is also probably generated by the radioactive decay of certain isotopes, such as potassium 40.

- Further, the inner core tends to crystallize more pure iron and nickel, leaving a chemically lighter, more buoyant fluid. This, too, may help drive the convection.

- These three factors, however, are not sufficient. It seems that the Coriolis effect, caused by Earth's rotation, is also important. Because of the Earth's rotation, the convecting iron becomes spiraling columns that are parallel to the axis of the Earth and are lined up surrounding the inner core.

- The locations and shapes of these spiraling columns tend to shift over time. As a result, the locations of the magnetic north and south poles changes, as well.

The Solar Wind

- The northern lights themselves aren't in any one location. At certain times, they extend in a wider band and come down to lower latitudes. The times of active auroras on Earth are times of increased solar activity, which produces the solar wind, a stream of ionized particles that blasts through the solar system away from the surface of the Sun.
  - The Sun is 99.85 percent of the mass of our solar system. It contains a mixture of all the elements, but it's dominated by hydrogen and helium. Nuclear fusion in the core powers a layered structure inside the Sun. Away from the core is a radiative zone, which then powers a convecting layer; the top of that layer is called the photosphere. At the top of the photosphere, the temperature is about 5700°C.

- Hydrogen and helium exist in a special state called plasma, a condition so hot that the electrons are stripped off the nuclei of the atoms. It's essentially an incredibly high-temperature soup of atomic particles.

- The outer layers of the Sun, the corona, are much hotter, even though they are much less dense. High-temperature ionized particles are thrown off the layers of the Sun at great speeds.

- During times of increased solar activity, the Sun may experience a coronal mass ejection, in which hydrogen is thrown off the surface of the Sun. Some of these ejections create giant magnetic loops that leave the Sun and return, causing a much stronger solar wind.

- The solar wind doesn't arrive at all locations on Earth's surface. The Earth's magnetic field is warped by the incoming solar wind, creating a shape called the magnetosphere. The boundary between the magnetosphere and the incoming solar wind is the magnetosheath.
    - The magnetosheath presents a significant barrier to the solar wind and protects our atmosphere. If we didn't have a magnetic field, the solar wind would strip away our atmosphere over time.

    - The high-energy particles of the solar wind are extremely damaging to living tissue and cause problems for radio telecommunications.

    - When the particles of the solar wind reach the Earth, they tend to follow Earth's magnetic field lines, which are concentrated closer to the poles.

- Interestingly, the ionized particles of the solar wind can't punch through the Earth's magnetosphere. They actually travel far past Earth and then double back when the magnetic field lines become so deformed that they snap. This process is called magnetic reconnection. The magnetic field lines get stretched, and when they stretch too far, they suddenly snap back to a new shape. At that point, large numbers of solar wind particles come to the Earth in shimmering bands that circle the northern and southern poles.

The Colors of the Auroras

- The auroras occur high in the thermosphere, more than 50 miles above the Earth, where there are very few atoms; the thermosphere is close to a vacuum. The particles there have very high energy from the sunlight constantly hitting them.

- Earth's atmosphere is primarily made of two materials, nitrogen and oxygen. Like all atoms, the electrons of these materials can exist at discrete energy levels, called quantum energy levels. These electrons are at their lowest energy state, but they can be knocked into a higher energy state by any source of added energy, such as interactions with the solar wind particles.

- The electrons don't stay at higher energy levels for long, however; they drop back down quickly to their lowest energy levels. Because the energy has to go somewhere—energy is always conserved in any interaction—it goes into photons, light.

- Because the quantum levels are discrete amounts of energy, they correspond to discrete, specific frequencies of the light emitted. When the electrons of oxygen atoms return to their lowest energy levels—the ground state—they tend to release a green or brownish-red light, depending on the amount of energy absorbed. For nitrogen atoms, the light tends to be blue or red.

- Oxygen is unusual in terms of its return to the ground state. It can take up to 3/4 of a second for green light to be emitted and then jump to the lower energy level and up to 2 minutes to emit red light.
    - If there are any collisions with other atoms or molecules in the atmosphere during that time, the collision will absorb the added energy and prevent the emission of light, and we won't get an aurora. But because the very top of the atmosphere is so close to a vacuum, such collisions are infrequent—

infrequent enough to allow the 2 minutes needed for oxygen to emit red light.

- o The collisions become more frequent further down in the atmosphere, so that red emissions don't have time to occur, and the oxygen atoms primarily release green light. Eventually, the atmosphere becomes dense enough that collisions between atoms happen frequently, and even green light emissions are prevented.

- o This explains why different auroras release different colors. At high altitude, oxygen red dominates, then oxygen green and nitrogen blue or red, and finally, nitrogen blue or red.

Flipping the Magnetic Field

- Auroras don't usually occur in the continental 48 states, but there are times when auroras are centered over the United States. The last time this occurred was about 780,000 years ago.

- For reasons that are still not fully understood, Earth's magnetic field randomly reverses itself. This reversal takes about 1000 years, and in the process, the magnetic north pole wanders down to the south.

- When the magnetic field reverses, the total strength of the dipole field drops by about 90 percent. That means that the Earth's magnetosphere is much weaker, and many more solar particles reach Earth during this time.

- These reversals usually happen every few 100,000 years, which means we are overdue for one now. Over the past century, the strength of the Earth's geomagnetic field has dropped by 10 percent. It's not inconceivable that in 200 years, we could see large auroral displays overhead in the middle of the United States.

Top Atmospheric Phenomena

- Sun dogs represent an interesting refraction occurrence that happens as a result of the presence of hexagonal ice crystals in high, cold

Processes that take place inside the Sun, the Earth's core, and atoms themselves contribute to the auroras—the greatest light shows on our planet.

cirrus clouds. As we know, rainbows form from refraction through water droplets. With sun dogs, the light from the Sun is refracted by ice crystals, usually at an angle of about 22 degrees from the Sun. If the ice crystals are randomly aligned through the atmosphere, the appearance is a stunning circular halo of light around the Sun.

- A variety of phenomena can cause a green flash, an optical effect that can be observed at the last moment of a sunset or the first moment of a sunrise. Because of the refraction of sunlight, the very top of the setting Sun actually has a faint green rim; it's present all the time, but it's usually too small to see directly. Under certain conditions, the green light will get bent around the Earth's surface and appear as a sudden green flash.

- A Fata Morgana is a mirage that seems to show land up in the air or above the horizon. This kind of mirage can be seen when a temperature inversion—a layer of warm air on top of cold air—

occurs in the atmosphere. This warm air causes light rays to be bent more than the curvature of the Earth. One result is that islands that are actually below the horizon become visible. Light from the ocean surface may also be bent so much that it appears as if land is floating in the air.

- Under just the right conditions—just after sunset or before sunrise, during the spring or fall—it's possible to see sunlight reflected off microscopic dust particles floating in the solar system. This phenomenon is known as zodiacal light. The particles appear as a weak, triangle-shaped cone of diffused light, extending a little way above the horizon. This dust is largely the remains of comets, which slowly drifts into the inner solar system.

Suggested Reading

Davis, *Aurora Watcher's Handbook*.

Hall, Pederson, and Bryson, *Northern Lights*.

Questions to Consider

1. Why don't we see auroras in the part of the atmosphere that is close to the ground?

2. Every few 100,000 years, Earth's magnetic field reverses. When this happens, the magnetic field drops to about 10 percent of its current strength and the poles wander across the Earth, the magnetic north pole moving to be near the South Pole, and the magnetic south pole moving to be near the North Pole. What do you think auroras would be like during this time?

Arizona Meteor Crater—Visitors from Outer Space

Lecture 34

In the last lecture, we saw auroras, spectacular colors that appear in the troposphere as a result of particles of the solar wind bombarding Earth's magnetosphere. In this lecture, we'll look at the arrival on Earth of slightly larger particles: meteoroids that create craters on the surface of our planet. We'll start by visiting Meteor Crater in Arizona. This crater is only about 1.2 kilometers across, but it's 170 meters deep and makes a stunning impression. For scientists, a "meteor" is defined as the streak of light in the sky produced by a meteoroid; a "meteoroid" is the rock that produces the streak; and a "meteorite" is a meteoroid that has hit the Earth.

Description of the Meteoroid

- Meteor Crater formed less than 50,000 years ago. At that time, the climate on the Colorado Plateau was much cooler and damper than it is now. This part of Arizona was open grassland with occasional woodlands and was inhabited by creatures that are now extinct, such as woolly mammoths and giant ground sloths.

- The meteoroid that formed the crater in Arizona was perhaps only 40 meters across and was made of nickel and iron. This size doesn't seem very large, but the energy of a moving object is proportional to the square of its speed, and this meteoroid was moving fast.
  - The formula for kinetic energy is simple: $1/2mv^2$, where m is the mass of an object and v is its speed. The meteoroid that made Meteor Crater was probably traveling at a speed of slightly more than 11 kilometers per second (25,000 miles per hour).

  - We know the speed had to be at least 11 kilometers per second because that's the escape velocity of Earth—the speed an object has to have to escape Earth's gravity, not taking into account air pressure. It's also the speed of an object that falls to Earth from far out in space. Earth's atmosphere significantly slows down smaller meteoroids, but the effect of the atmosphere is much less for larger meteoroids.

- The initial nickel-iron meteoroid that produced Meteor Crater was probably on the order of about 300,000 metric tons. Half of it may have been broken off during its passage through the Earth's atmosphere, making a pancake-shaped cloud of iron fragments. Most of the rest of it would have vaporized when it hit the ground.

- Meteoroid craters are always circular; they don't show any preferential indication of direction. The reason for this is that the intense energy of the impact causes much of the impactor to vaporize and then explode outward with an intense shock wave. That shock wave gradually converts into a seismic wave that propagates out in all directions from the impact across the planet.

- This explains why Meteor Crater could be formed by a relatively small impactor. The 40-meter chunk of iron was compressed, vaporized, and then exploded outward. In fact, pound for pound, the energy released by an impacting meteoroid is about 25 times greater than that released by the same mass of TNT.

Identifying the Crater's Cause

- At one point, there was significant debate about whether or not Meteor Crater was actually caused by a meteor. In 1891, G. K. Gilbert, the brilliant chief geologist for the U.S. Geological Survey, concluded that the crater was the result of a volcanic steam explosion.
    - Gilbert assumed that if it were an impact crater, then the volume of the crater plus the meteoritic material should be present on the rim, which it roughly is. His calculations showed that the volume of the crater and the debris on the rim were roughly equivalent, and he thought that the mass of the hypothetical impactor was missing. What he didn't know is that a huge meteoroid isn't needed to create a large crater.

    - Gilbert also assumed that a large portion of the iron meteorite should be buried under the crater and would generate a large magnetic anomaly, but none was present. Impact physics was poorly understood at the time, and Gilbert was unaware that most of the meteorite vaporized on impact. He argued that the iron meteorite fragments found on the rim were coincidental.

- In 1903, a mining engineer and businessman named Daniel Barringer suggested that the crater had been produced by the impact of a large iron-metallic meteorite. His company, the Standard Iron Company, received a patent signed by Teddy Roosevelt in 1903 for mining the 640 acres around the center of the crater. In 1906, Roosevelt also authorized the establishment of a newly named post office at Meteor, Arizona.
    - Barringer, like G. K. Gilbert, believed that the bulk of the impactor could still be found under the crater floor. He spent 27 years trying to trying to find the large deposit of meteoritic iron that never existed.

    - Barringer estimated, incorrectly, from the size of the crater that the meteorite should have had a mass of 100 million tons. The current estimate of 150,000 tons or so for the impactor is less than 0.02 percent of Barringer's estimate.

Meteorite Crater Structures

- Meteorite craters have specific structures, usually an excavated crater with the material (impact ejecta) ejected out on a rim. At the bottom is a combination of rock that has been melted (impact melt) and rock that has been fractured or shattered (breccia). In certain cases, especially for larger craters, material may stick up as a central peak in the middle.

- We have learned about the structure of impact craters by looking at craters on the surface of the Moon, where there is no weathering or erosion. Craters on the Moon remain perfectly preserved, allowing us to see the ejecta blanket and the details of the inner peak in the center of the crater.

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A combination of impact melt and breccia at the bottom of a crater is a good indication that it was caused by an impact from outer space.

- Meteor Crater has the same raised rim as craters on the Moon, materials thrown outward, and a significant amount of rubble lying at the center of the crater. The rim is 45 meters above the surrounding plain.

- An added clue that the crater was created by an impact is the upside-down layering of the rock around the rim. In fact, the oldest rock, the Coconino Sandstone, which is about 265 million years old, is now found at the top. The Moenkopi Formation, which is 200 million years old, is near the outer foot of the rim. Inside the crater, however, all the layers are in their expected order.

Behavior of Quartz

- In 1960, a geophysicist named Gene Shoemaker conducted experiments in which he subjected various materials to very high pressures. In the process, he discovered a particular phase of quartz called stishovite.

- A phase diagram shows that raising the temperature of quartz changes its phase. It first becomes tridymite, then cristobalite; if it is heated more, it will melt and become liquid.

- If the quartz is subjected to high pressure, the atoms rearrange to form the mineral coesite. At very high pressures, quartz becomes stishovite, which is found in the rocks at Meteor Crater. The only other place stishovite can be found is deep in the interior of the Earth. Finding it at the surface indicates that the rock has been suddenly and intensely compressed.

Disappearance of Craters

- Three factors explain why craters on Earth don't last long.
  - First of all, the seafloor is 60 percent of Earth's surface, but the oldest seafloor anywhere on the planet is 200 million years old; that's only 4 percent of the age of the Earth. Almost any impact crater that has formed on the ocean seafloor has long since subducted into the mantle at an ocean trench.
  - Further, tectonic collisions on land have deformed the Earth's surface beyond recognition; thus, any feature on the surface is likely to be gone, as well.
  - Most important, of course, erosion due to water, ice, and wind constantly removes and alters the top layers of the rock on land, making it difficult to identify impact craters on Earth.
- As mentioned earlier, the lack of erosion on the Moon allows us to understand the details of the cratering process. Both the surface of the Moon and the surface of Mercury, which is also intensely covered with craters, have been essentially unchanged for billions of years.

Top Impact Craters

- The Vredefort Dome in South Africa is the largest confirmed impact basin in the world, at about 300 kilometers in diameter. The impact here occurred 2 billion years ago, which means that much of the detail has disappeared, but it was large enough that the shape of the circular crater is still clearly visible in the surrounding lands. The object that formed this crater might have been about 10 kilometers across.
- Sudbury Basin in Ontario, Canada, is the second largest confirmed impact basin, at 250 kilometers across. This crater is also extremely

old, about 1.8 billion years. It has been deformed by several tectonic events in North America, but it also was big enough to retain characteristics that allow it to be identified.

- Three craters—Manicouagan in Quebec, Saint Martin in Manitoba, and Rochechouart in France—form an interesting triplet. All of them are 214 million years old. If we move North America and Europe back to their positions in Pangaea at that time, they all three align. It seems likely that they were all part of one asteroid that broke up during arrival.

- The Chicxulub Crater in the Yucatan Peninsula in Mexico is certainly the most famous of the impacts and potentially the most important from our perspective as humans. At 170 kilometers in diameter, this crater is the third largest verified impact crater on Earth.
    - This impact occurred 65 million years ago and would have triggered an environmental catastrophe, ejecting so much debris into the atmosphere that the skies would have gone black and global temperatures would have plummeted. The impact likely played a major role in the extinction of the dinosaurs and many other species. The severity of this impact and of its consequences brings up an interesting point.

    - Meteoroid impacts are part of a continuous process, similar to the flow of a river. Several tons of cosmic debris reach Earth each day, mostly tiny particles that burn up in the upper atmosphere. Sometimes, this debris is large enough to make it to the ground and survive as rocks, but every few tens of millions of years, a very large meteoroid hits, and the results can be catastrophic.

    - This fact presents the history of life on our planet from the perspective of a few chance events, any one of which can have great consequences for the course of evolution and the future of life on Earth.

Suggested Reading

Mark, *Meteorite Craters*.

Norton and Chitwood, *Field Guide to Meteors and Meteorites*.

Questions to Consider

1. You buy land in a remote area, and the seller tells you that there was once a meteor impact there. How can you tell if this claim might be true or not?

2. Jupiter acts as a good shepherd, gravitationally diverting out of the solar system most of the large rogue objects that might otherwise one day strike Earth. How do you think the course of evolution of life on Earth would have progressed if large impacts were much more frequent? How about much less frequent?

A Montage of Geologic Mini-Wonders

Lecture 35

We've almost reached the end of our course, but there are still many wondrous places that we have not seen. This lecture takes a brief look at 10 geologic wonders that don't fit into any neat categories but still deserve mention. These sites are quite varied, but they still span the range of what we might consider geologic wonders. They aren't presented in any particular order, except that toward the end of the list, the explanations for why they occur become a bit more uncertain. As we have said, science is a process, and we still haven't completely explained all the wonders on Earth.

White Cliffs of Dover

- The White Cliffs along England's southeastern coast rise as much as 350 feet from the ocean. They are made of a soft, crumbly, nearly pure white chalk—almost pure calcium carbonate—with occasional black specks of flint.

- The geologic wonder of these beautiful, iconic cliffs is in their formation. They are made almost entirely of the tiny, fossilized skeletons of ancient single-celled ocean creatures, a type of plankton called coccolithophores.

- The presence of the coccolithophores explains why the cliffs are so white. Unlike other limestone, which is often gray or mottled from impurities washed into the ocean from the land, the chalk of these cliffs formed at a time when the sea level was so high that there was no land nearby. Pure plankton skeletons slowly accumulated on the shallow seafloor for millions of years, not contaminated by any other sediment.

Eisriesenwelt Ice Caves

- The Eisriesenwelt Ice Caves, in Austria, are a 40-kilometer-long system of caves in the Alps. These are the largest ice caves anywhere in the world, and they are the result of an unusual pattern of airflow that reverses direction between winter and summer.

- The cave system has two entrances, one at the top of the mountain and one at the bottom. In the wintertime, when the outside air is below freezing, the relatively warm temperature inside the cave causes an updraft through the cave system. This leads to extreme cooling at the bottom of the cave as a result of cold air being sucked in from the outside at the bottom entrance.

- During the summer months, the outside temperature is much warmer than inside, and the opposite flow happens.
    - The relatively cold air inside the cave, usually about 8°C, causes a downward draft; fairly warm outside air gets sucked in at the top opening. But on its way down, this air is cooled so much that it can no longer warm up the hollow areas in the lower sections. As a result, there's a fairly constant temperature right around the freezing point in the area around the lower entrance.

    - Water that seeps down into the cave freezes over when it reaches the bottom, allowing spectacular ice formations to build up over time.

Moeraki Boulders

- The Moeraki Boulders are huge, almost perfectly round rocks than can be up to 1 to 2 meters in diameter. These rocks fall from the cliffs along the east coast of New Zealand, just north of the city of Dunedin.

- These giant, nearly spherical rocks are called cannonball concretions. They form by the growth of minerals within sedimentary rock that cement the sediment together, making it more resistant to weathering.

- In the case of the Moeraki Boulders, these concretions have formed over millions of years inside a layer of mudstone. The mineral calcite has grown outward from points of nucleation, causing the boulders to slowly grow underground. As the shoreline erodes and cuts into the cliff, the boulders become exposed and simply fall and roll down the shore.

Spotted Lake

- Spotted Lake is in Osoyoos in British Columbia, just a mile north of the U.S./Canadian border from central Washington State. Osoyoos is a warm, dry region, and as a result, the Spotted Lake doesn't drain out; it's a closed basin that fills from rains during the winter months. During the summer, when the water evaporates, it leaves a set of smooth and strangely colored oval-shaped pools.

- The pools are extremely alkaline and are filled with high concentrations of sulfate salts, including magnesium sulfate (Epsom salts) and calcium and sodium sulfates. The water also contains large amounts of many other minerals, such as silver and titanium.

- As the water evaporates, the minerals begin to precipitate in individual pools, which then become cut off from one another. Depending on the exact minerals that are precipitating, the pools can appear yellow, white, green, blue, or other colors.

Nieves Penitentes

- In Mendoza, Argentina, at the foot of Mount Aconcagua, we find strange patterns of ice along the sides of the mountain. The ice looks like a giant bed of knives, with sharp peaks placed one after another. These formations are called *nieves penitentes*.

- The clue to how these peaks form is first seen in the orientation of the blades, which face north, toward the Sun. Because it's so cold here, the ice doesn't melt. It sublimates directly into a water vapor phase.

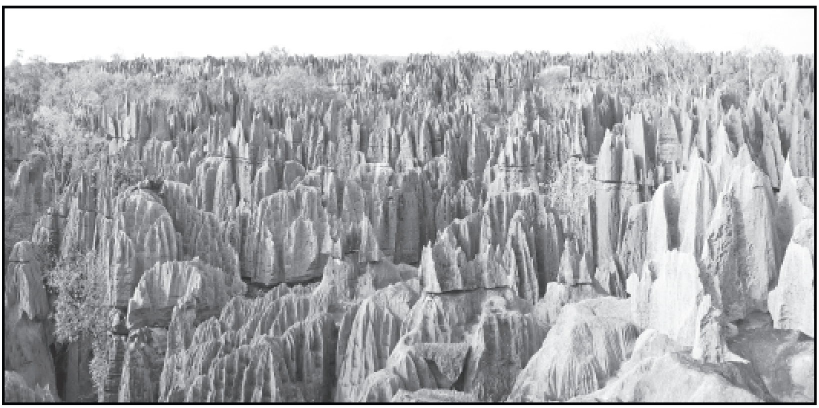
- Once the ice surface initially becomes even slightly pitted, sunlight begins to reflect back and forth in between the pits, which causes melting in between the peaks, while the tops of the peaks remain frozen. The troughs between the peaks continue to melt downward as sunlight gets trapped within them, bouncing back and forth. Eventually, they will melt all the way to the ground.

Tsingy

- An unusual formation of rocks called *tsingy* occurs in the Bemaraha plateau of western Madagascar. Here is a 1500-square-kilometer park that is covered with jagged, bluish limestone peaks.

- Unlike the icy *penitentes*, which are only years old, the *tsingy* form over tens of millions of years. The limestone was once a coral reef in a large Jurassic lagoon. When Africa was flooded, the lagoon was buried by more sediment and slowly turned to rock. The rock became fractured into a large set of parallel joints when Madagascar rifted away from the rest of Africa, about 135 million years ago.

- The resulting joints became channels for water, and when the surface eroded down to the layer of limestone, the water kept percolating downward. Groundwater dissolved away the limestone and made parallel sets of caves. Rainwater percolated down and widened them out until the peaks intersected at sharp ridges.



The name *tsingy* in the local language of the Bemaraha plateau in Madagascar means "place where one cannot walk barefoot."

Salt Glaciers

- Most salt glaciers are found in one part of the world, the Zagros Mountains of Iran. Here, we find more than 160 separate outpourings of salt.

- Water ice is technically a mineral, although it is able to flow—slowly by our standards but very quickly by geologic standards. Salt can also flow relatively quickly over geologic time, and both of these flow within glaciers.

- Because salt is much lighter than other rocks, if there is a layer of salt underground, the pressure of the overlying rocks will push the salt up. In Iran, the salt layers were folded and deformed underground during the current movement of the Arabian Plate north into Asia.

- In certain places, windows to these salt layers are exposed at the surface, and the salt slowly oozes its way out, flowing downhill, just like an ice glacier. The salt erodes slowly because the climate is very dry. Any rain wears away the salt glacier into fascinating pitted and grooved formations.

Blood Falls

- Blood Falls occurs in the Taylor Glacier, which flows onto the ice-covered surface of West Lake Bonney in the Taylor Valley in Antarctica, not far from McMurdo Base. The snow flowing out from the bottom of the Taylor Glacier is a rusty red color that looks like drying blood.

- The color was initially thought to be due to the presence of red algae, but it now seems to be the result of oxidizing iron in the water. Blood Falls is actually a plume of salty water, rich in sulfates and iron, coming from a liquid saltwater lake beneath the glacier.

- It's possible that this saltwater formed by the evaporation of water from a salt pond. It's also possible that this is an ancient pocket of ocean water that got trapped here a few million years ago when sea levels rose and the continents were flooded. The high level of sulfates is expected for ancient seawater, but the iron is a bit of a mystery.

- Perhaps the most interesting part of this geologic wonder is the fact that the reddish saltwater is filled with life, even though it has been trapped under a glacier for at least 2 million years. Salt-loving bacteria may have survived underground during this time, feeding on the sulfates and iron and evolving along their own isolated paths of evolution.

Morning Glory Cloud

- The Morning Glory cloud is a meteorological phenomenon that forms over the Gulf of Carpentaria on the north coast of Australia. This cloud formation can extend for up to 1000 kilometers in a remarkably straight and sharp line. Each year, between September and October, these clouds roll across the gulf and over land.

- The exact cause of this cloud is not known, but one idea is that it's a result of sea breezes. Sea breezes occur because sunshine heats up the surface of the land much faster than the ocean; thus, warm air rises above the land and pulls the cooler sea-surface air in toward the land to take its place.

- From September to October, conditions of the air and water temperatures at night are just right to create an inversion layer over the Gulf of Carpentaria.

Racetrack Playa

- Racetrack Playa, in Death Valley, California, is the site of one of the greatest geologic mysteries on the planet. The playa is a closed basin that becomes a shallow lake during the infrequent rains, but the water quickly evaporates to leave a dry, flat surface the rest of the year. For most of the year, Racetrack Playa is covered with a layer of cracked, dry mud.

- The playa is also dotted with large boulders, called sailing stones, that have tracks that seem to suggest they have been dragged across the surface of the lakebed. Some of these boulders are extremely heavy, yet they seem to drift across the surface, usually in roughly straight lines but sometimes abruptly changing direction.

- The stones have never been observed moving, but scientists have come up with at least two hypotheses to explain the appearance of the tracks. The rocks may slip or be blown across the muddy floor of the lake in the wintertime, or they may sail across the flat on ice floats. Until someone sees the rocks move, the Racetrack Playa will remain a geologic mystery.

Suggested Reading

Bright, ed., *1001 Natural Wonders You Must See Before You Die*.

Brown, Brown, and Findlay, *501 Must-Visit Natural Wonders*.

Questions to Consider

1. How would you say that the *tsingy* of Madagascar and the Matterhorn in the Alps are similar in the manner in which they were formed?

2. What is the strangest thing you have ever seen in nature? Do you feel as if you have a better sense now of what might have caused it?

Planetary Wonders—Out of This World

Lecture 36

Over the past 35 lectures, we have seen mountains, sinkholes, glaciers, canyons, fjords, volcanoes, geysers, caves, crystals in caves, lava lakes, salt lakes, and acid lakes—more than 200 different locations of geologic wonders of many different types in almost 120 different countries. In this final lecture, we'll look at some of the remarkable geologic wonders that have been discovered on other planetary bodies in the solar system. Thanks to the remarkable robotic probes of NASA and other space agencies, we can now take virtual trips into space and explore some of the truly incredible features found there, some similar to features we have on Earth and some unlike anything seen on our planet.

Venus

- As we have seen, in Hawaii, lava can flow for tens of kilometers across the ground, but on Venus, lava flows can extend for many hundreds of kilometers. The lava is basalt, the same material as lava on Earth, but the surface of Venus is so hot—460°C—that the lava flows easily.

- Venus is covered with volcanoes—hundreds of thousands or even millions of volcanoes. We can't determine a number because we can't see the surface. Venus is covered by such thick clouds, made of sulfur dioxide and sulfuric acid aerosols, that light can't penetrate them. However, satellite information on elevation and the surface roughness of the ground enables us to make images of the surface of Venus.

- We've seen some places on Earth where the crust has been fractured into large numbers of parallel sets of faults called joints. On Venus, large expanses of the surface are densely covered with these parallel fractures. Venus's surface also shows evidence of extreme stretching and compression. There is mantle convection here—the rock of the mantle is flowing—but because there are no tectonic plates, the surface doesn't have anywhere to go. It is just repeatedly stretched and cracked and fractured.

- Volcanism is not currently active on Venus, but the planet appears to undergo a process of catastrophic resurfacing every 300 to 500 million years, when the heat in the mantle builds up to a critical level.

Earth's Moon

- A few lectures ago, we saw the largest impact crater on Earth, the Vredefort Dome in South Africa, at 300 kilometers across. The largest crater in the solar system is on the Moon, the South Pole–Aitkin Basin. It is more than 2500 kilometers in diameter and up to 13 kilometers deep.

- This crater was formed at a time of extreme violence in our solar system known as the Late Heavy Bombardment period.
  - At this time, the planets Jupiter and Saturn drifted into a 2:1 resonant orbit that caused their own elliptical orbits to become eccentric and destabilized the entire solar system.

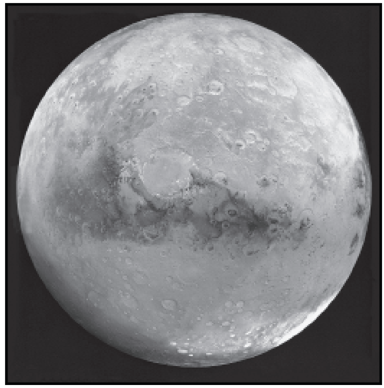
  - Neptune and Uranus were flung to the farther parts of the solar system, and many large icy objects were thrown into the inner solar system.

Mars

- Mars is a place of extreme geologic features. It has many similarities to Earth, including deserts and glaciers, polar icecaps, long-term climate change, and enormous volcanoes and canyons.

- As we saw, the Big Island of Hawaii itself is a volcano, 100 kilometers wide and rising 10 kilometers off the seafloor. At Olympus Mons on Mars, which is the largest single volcano in the solar system, we see something almost an order of magnitude larger. The central caldera sits 27 kilometers above the mean surface level; that's three times the elevation of Mount Everest above sea level. The top sits 22 kilometers above the surrounding plains.

- Hawaii is also the location of the largest hotspot on Earth, but because the Pacific Plate on which it sits is moving westward, all the lava is spread out over a long chain of islands and seamounts. Mars has the largest hotspot in the solar system, a region known as the Tharsis Rise. The area of the Tharsis Rise sits about 7 kilometers above the surrounding plains and is about 30 million square kilometers.



Mars has numerous extreme geologic features, including the largest volcano, largest hotspot, and largest canyon in the solar system, along with giant sand seas and complex icecaps.

- In earlier lectures, we saw large canyons that cut through the Himalayas; these can be 5 kilometers deep and extend for 240 kilometers. On Mars, we find the largest canyon in the solar system, the Valles Marineris, at about 4000 kilometers long, 200 kilometers across in places, and more than 7 kilometers deep. This canyon may have both tectonic and erosional origins.

- Mars also has deserts and some giant sand seas. One of these giant ergs, the Olympia Undae, covers 0.5 million square kilometers. The dunes here can be as much as 0.5 kilometers apart and rise up to 25 meters above the plain.

- In dry areas on Earth, we sometimes see dust devils, or small whirlwinds. Dust devils constantly zip across the surface of Mars and are responsible for all the dust in the planet's atmosphere. The dust devils have also served as windshield wipers for the solar panels of two Mars rovers that have been operating there since 2004.

- Larger dust storms on Earth can be a significant hazard, but nothing here compares with the dust storms on Mars. A dust storm may begin in one area, and when sunlight hits the dust, it warms that part of the atmosphere. Temperature differences in the atmosphere are what drive winds. The strong winds pick up more dust, and the dust storm grows; after a couple of weeks, it can cover the entire planet. Once the whole planet is dusty, there are no more variations in temperature, the winds die down, and the dust slowly settles.

- Mars also has the most complex icecaps in the solar system. The ground on Mars is filled with ice, similar to permafrost on Earth. Huge glaciers come out of mountains and gullies on Mars and deposit rock at terminal moraines. In many places on the surface of Mars, we see areas that look like flat soil, but these areas are actually ice covered with a layer of dust—glaciers flowing across the surface of Mars.

- The most unusual ice surfaces on Mars are the giant icecaps at the north and south poles. The icecaps here are two compounds: a thick, permanent, water icecap and a thin, variable, carbon dioxide icecap. The solid-water icecaps are huge, larger than Texas, and have repeating layers that seem to be caused by climate swings.

- Mars shows evidence of a period between 4 to 3 billion years ago when a vast amount of water carved away large portions of the land. Some of this water might have come from impacts of ice-rich planetoids during the Late Heavy Bombardment period. It may also have come as water vapor during an extremely active volcanic phase. In any case, the water is long since gone.

Asteroids

- The asteroids are a belt of rocky, icy objects that revolve around the Sun in between the orbits of Mars and Jupiter.

- A small asteroid named Vesta has unusual craters, including three in a row that look like the outline of a snowman. Vesta also has the tallest nonvolcanic mountain anywhere in the solar system, 21 kilometers high, found within a giant impact basin.

- Another asteroid, Kleopatra, is perhaps the strangest-looking object in the solar system. It looks like a giant dog bone, 200 kilometers long, spinning in space. Kleopatra formed from the loose connection of two smaller piles of rock and dust.

The Gas Giants and Their Moons

- If we go farther out into the solar system, we reach the gas giants, Jupiter and Saturn. The recent Cassini satellite mission sent back amazing images of a variety of remarkable geologic features from these planets.

- The northern and southern lights we saw earlier pale in comparison to the auroras found near the poles of Jupiter and Saturn. These auroras can be hundreds of kilometers across, 250 kilometers above the planet. They form by the same mechanism as auroras on Earth.

- The fast rotations of Jupiter and Saturn cause their atmospheres to break up into many separate bands, and where these bands intersect, there are enormous storm systems. The largest of these is the Great Red Spot on Jupiter, a 23,000-kilometer-long hurricane that has been present for at least 180 years.

- Jupiter's moon Io has hundreds of volcanoes erupting at any given time. Io also has the hottest lavas anywhere in the solar system, at more than 1500°C. The volcanism on Io is generated by its resonant orbit with Europa and Ganymede, two other moons of Jupiter.

- Europa has a liquid saltwater ocean, perhaps 150 kilometers thick, covered with a thin sheet of ice. The ice crust of Europa resembles a giant jigsaw puzzle, with pieces breaking up and drifting around over time. The presence of the liquid saltwater ocean makes Europa a likely candidate for life.

- All of the large planets—Jupiter, Saturn, Uranus, and Neptune—have rings, but the rings of Saturn are by far the largest. They look substantial, but they are actually thin layers of small particles of rock and ice.

- At Saturn's south pole is a vortex, the giant eye of a hurricane that is 8000 kilometers across. At the north pole of Saturn, the atmosphere flow takes the shape of a hexagon. Saturn's atmosphere has been modeled by scientists as a particular jet stream of gas moving at different speeds than the surrounding atmosphere, which causes the flow to break up into six separate eddies.

- Saturn's moon Enceladus has ice geysers that eject ice more than 500 kilometers off the surface. These geysers come out of a region of Enceladus where rifting occurs. The microscopic ice particles from the surface of Enceladus are the source of one of Saturn's rings.

- Saturn's moon Titan has perhaps the strangest surface of any of the planetary moons, with hydrocarbon lakes. These lakes are made of liquid methane and ethane, and the largest is 1200 kilometers across.

Life in the Solar System

- We have some evidence for the possibility of life elsewhere in the solar system, but no confirmations yet. For example, methane is emitted from some regions of Mars, and methane on Earth is often created by biologic activity. The saltwater oceans on Europa, Enceladus, and Ganymede might also support life.

- Keep in mind that we have looked only at the planets of one star. There are hundreds of billions of stars in just the Milky Way galaxy and hundreds of billions of galaxies in the universe. As of 2012, NASA scientists had identified more than 2000 planets around other stars that might be at the right distance from the star to support life.

- It might be impossible for us to ever reach those planets and see what geological wonders they have, but perhaps we can someday see pictures of them. Until then, there is no shortage of amazing geologic wonders on our own planet.

Suggested Reading

Hodge, *Higher Than Everest*.

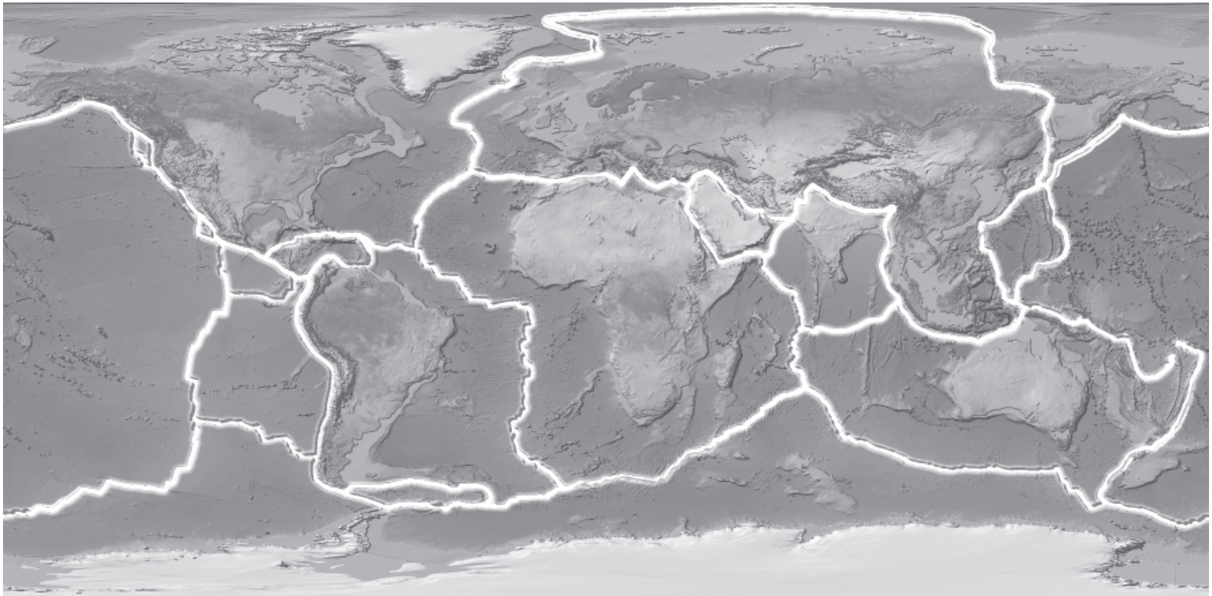
Lang, *The Cambridge Guide to the Solar System*.

Questions to Consider

1. Venus is much more similar to Earth in size than Mars, but Mars is much more likely to possess life. Why is this?

2. How is it that we can find out about Earth's past by visiting the Moon?

Earth’s Tectonic Plates



Pangaea


Eurasia
North America
Africa
South America
India
Antarctica
Australia

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