Transcript from Epic of Evolution: Life, the Earth and the Cosmos (BEP 210A)
February 21, 2000 - Lecture by Michael Wysession

"Unwary readers should take warning that ordinary language undergoes modification to a high pressure form when applied to the interior of the Earth . . ." (F. Birch, 1952, p. 234)

I will shift the focus back down to our planet this week. I want to first give a disclaimer for this next part of the discussion. I tried very hard to figure out a way to talk about these next parts of the Earth's evolution as a continuous narrative, and found that it was almost impossible for me to do so. For one thing, there are just too many things that are going on at once, and they are all so interconnected -- the chemistry, the physics, the geology. This makes it very hard for me to describe a history, taking in all these factors together. Also, what was going on in the Earth 4 billion years ago is a lot like what's going on now. So what we have is the cumulative result of a set of inter-linked processes that have been operating on the Earth during most of its lifetime. Another reason is that very often it is the process that is more interesting to me than the particular random geological history that a plate or a continent has undergone. So sometimes the focus should be on the process, and not necessarily on the history. And lastly, so much of the geological record is missing. There are huge gaps in our knowledge of the past, for most of the Earth's history up until about 200 million years. We have bits and clues here and there, and I will mention some of them. So what I'm going to do is break up my next 3 weeks by process. I'm going to talk about Earth forces this week, Earth materials the following week and then water the last week. And you're going to see some of the same themes brought back again and again, but each time it will hopefully seem a little richer, and there will be a little bit more depth as to how these processes occur.

Let me start off with some something for Show and Tell. I have three pieces of limestone (and we will talk more about limestone in 3 weeks), which is a rock that forms at the bottom of oceans. It is a sedimentary rock. It largely forms from the precipitation of calcium carbonate in the ocean, but often incorporates the fossil shells of marine life like clams and corals. This one is found right here in St. Louis. It is from outside of the entrance to Santa's Village on Route 44, just west of Six Flags. It is a piece of limestone from a layer of rock called the Decorah Formation, which solidified about 450 million years old, and it contains within it a rich diversity of fossils. It contains shells, coral, crinoids, and I can even see pieces of two trilobites. The other two are a little fragile, and I won't pass around. These two rocks came from unusual parts of the world. This rock came from the top of the Andes in South America, and the other one came from near the top of the world. This was from near the base of Anapurna, in the Himalayas, not far from Mount Everest. And if you open this first one up, there is, contained within it, a very nice fossil shell of an ammonite. This relative of the nautilus lived several hundred million years ago. And inside of the rock from the Andes there is a fossil cast of a trilobite, also from several hundred million years ago. We are 1,000 miles from the ocean, here in St. Louis. Why are there ocean fossils here in a rock right outside of town? Let me take that question one step further. Go to the highest places on the Earth. Why are there ocean fossils at the tops of the Himalayas and the Andes? How did they get there? What sort of geological processes put them there? It turns out that the St. Louis limestone here and at the top of the Himalayas have some similarities, but also some real differences, as to how they formed. I will return to this later.

There are a couple of themes that I will return to several times. One is that events in the Earth happen both suddenly and continually, and for a long time geologists were really confused by this. It was almost like the Democrats and the Republicans -- there were two very different camps that had very violent arguments over how the Earth formed. One camp thought that the Earth formed through a process of catastrophic events, and they were called the Catastrophists. The other side viewed the Earth as being the result of a continual process of geological events, and they were called the Uniformitarians. Some geological features looked like they formed from continuous processes. Look, for instance, at Missouri River sediments. Every so often the Missouri River would flow over its natural levees and deposit a little more sediment in the surrounding flood plain, which would build up year after year. It looked very much like a continual process. On the other side, you can look at meteorite impacts, and come away with the sense that catastrophic events are very important. The Catastrophists originally based their ideas on the Bible, and the big catastrophe was Noah's flood, which they thought inundated the Earth and created all of the geological layers instantaneously. Later on, some geologists picked up the Catastrophist idea and proposed that the Earth really did form through a set of very sudden events. Interestingly, it turns out that both of these are not only correct, but they are both the same thing.

We've had meteorite impacts like the one that hit 65 million years ago in the Gulf of Mexico, which we believe killed off the dinosaurs. And if you look at floods, it is the case that most of the erosion from flooding occurs in the once a century or once a millennium catastrophic flood. The annual flow of the stream doesn't actually do very much, geologically speaking. But you get one giant flood, from several months of rain flooding down a river, and this will cause 99% of the geological change, carving out a valley with erosion, and redepositing the sand somewhere else. So there occasionally are really catastrophic events, but they are really just the far end of a spectrum of continuous events. In terms of the meteorite impacts, we are being hit everyday continuously by meteorites. Most of them are very small and we don't even notice them. The larger ones we see as little streaks in the sky, which we call *shooting stars*, or *meteors*. And the very large ones, the giant catastrophic collisions, do happen, and they cause most of the geological change. The idea here is that natural events occur with a certain fractal dimension. And when I say a fractal dimension I mean there is a spectrum of sizes of events from large to small, just like the branches of a tree. You may have a giant trunk that will split off into three larger branches, that will split off into a dozen smaller branches, that will split off into a 100 smaller twigs, and so forth. But the key is that there are many more of the smaller items than the larger ones. There is only one big tree trunk, but many, many twigs. There may be only one catastrophic meteor collision every 20 millions years or so, but that is one far end of a range of meteor sizes. At the other end are the tiny pieces of dust that are continuously streaking into the Earth's atmosphere.

We see this same thing happening with all geological events on the surface of the Earth. Earthquakes are another good example. Earthquakes are happening continuously. The Earth is constantly creaking and groaning at a small level. However, there is only about one magnitude 8 earthquake per year. There are about a dozen magnitude 7 earthquakes per year. There are about 120 magnitude 6 earthquakes per year, about 1,200 magnitude 5 earthquakes, so as I get to smaller and smaller earthquakes, I have got a lot more of them. You can think of this as the tree branching. And again, it is the biggest earthquake that does most of the total damage. The one giant earthquake per year releases much more energy than all the rest of the earthquakes in that given year combined. We've had some enormous earthquakes. There was one in Chile in 1960 where essentially 500 miles of ocean seafloor slid beneath South America for about 60 feet over a distance of about 200 miles in a couple seconds. And this one earthquake released more energy than if you took all of the nuclear bombs that were ever built, and detonated them all simultaneously. And that was just one earthquake. However, that earthquake was larger than the whole rest of the energy released by earthquakes that whole decade. The same thing happens with volcanoes. There are little volcanic eruptions around the world that continuously, but it's the few big ones at the far end of the spectrum that are most memorable – like the eruptions of Mount St. Helens or Krakatoa. So keep that in mind here that we are dealing with geological processes that are constantly occurring. What we remember are usually the very peak examples of these -- the biggest earthquake, the biggest volcano -- but they are part of continuous geological processes that have been operating for over 4 billion years.

Most of geology can be explained with these two words: *continents move*. Continents move slowly, but they move surely, and they move continuously. This idea first came to light at the beginning of the 20th century, and it went by the name of *Continental Drift*. Continental Drift was never abandoned by geologists in the southern hemisphere, in places like Australia and South Africa. For some reason, however, Americans and Europeans never took to the idea that continents could move about the surface, and it was not until the 1960's that this idea took hold here, with the new name of *Plate Tectonics*. The basic idea is that the surface of the Earth is broken up into a set of plates. Plates aren't really a good word, because it reminds you a flat dinner plate. Think instead of pieces of eggshell or orange peel, that are around a sphere. And the Earth's surface is broken up into about a dozen major plates, and these plates are about 100 kilometers thick, and they move. So again, imagine the pieces of your orange peel moving around the orange, and bumping into each other sometimes, and moving apart at other times. Plate Tectonics was able to give us a full understanding of almost all the geology that we see at the surface, and it was a remarkable shift in understanding. We previously had had a lot of disparate geological information that didn't make any sense, and then suddenly seen in the framework that the continents are moving about, all of this began to make a tremendous amount of sense. It was an inevitable shift in understanding. It didn't take an Einstein or a Niels Bohr to come up with Plate Tectonics. It came through a continuous accumulation of geological data, and eventually it became impossible to ignore the fact that the continents actually had been moving about. The continents move. They move anywhere from 0 to 15 centimeters per year. Okay, this is not so fast by our standards. We know this by the way from GPS systems, the same things that give you electronic directions in new cars. They use satellites to determine the positions, and geophysicists set out large numbers of GPS monitors around the world that actually let us monitor the movements of the continents. Ursula gave a good example 2 weeks ago about time and about scales of time, and I'm going to do that again in a slightly different way using the velocity of plates as an example. To understand the concept of time is probably the hardest thing to do in our field, and I think it is because there's nothing to compare it to. When you try to understand something new, the best way to learn it is to compare it to something else that you know. But if you're suddenly faced with the concept of 500 million years, there's nothing else in your life that's on that scale, and it's very hard to comprehend it. I was hiking in Switzerland once and hiked up to the base of the Jungfrau, which is a 2-mile high vertical face of rock. I stood at the bottom of it and looked up 2 miles and it was like I was looking at a poster. I could not believe it was real. I could not mentally comprehend what I was looking at, because I'd never seen anything anywhere like a 2-mile vertical wall of rock before, and it was a very strange experience. Time is like that.

For instance, think about the scales of time that you live by. Who are you going to have dinner with tonight? A scale of hours. Who's having a party this Saturday? A scale of days or weeks. Are you going anywhere for spring break? A scale of a month. Where are you going to live next year? Are you going to graduate or are you going through the housing lottery right now? That's a scale of a year, and a year is a long time to us. In a year, this blackboard will move 1 inch. North America is moving westward, away from Europe and Africa, at a rate of about 3 centimeters a year. So in a year, that's about an inch that this blackboard will have moved. Let's go to the next sort of power of 10 up from this. Let's talk about 10 years from now. How many kids are you going to have? Where are you going to be when you're 30? These are scary thoughts. This is a long ways away, 10 years. Already we're at a time scale beyond most of our thoughts and plans. Well, let's say we go back 10 years, maybe that's a little easier. You were in elementary school, and George Bush was President. If we go back 10 years, our blackboard was 1 foot away than where it is now. It was right over here. Let's go back 100 years and we're at 300 centimeters, or 3 meters. This is 10^2 years ago. 100 years ago the first cars were going into production, that's how old this is. There's a great story that of the first four cars that went into production, two of them were in St. Louis, and apparently they collided and had an accident. I don't know if the story is true or not. Let's go back 1,000 years, to the Middle Ages. The sun and planets are revolving around the Earth at this time. This blackboard was over in Goldfarb Hall, across the alleyway, so it's still not very far. Let's go back 10,000 years (10^4), the dawn of civilization. We've still got a lot of ice around from the Ice Age. No written language has evolved yet. Personal hygiene is not much to speak of. Our blackboard was then over in Givens Hall, in Art and Architecture, 300 meters away. Let's go back 100,000 years (10^5 years). The blackboard was then 3 kilometers away. 100,000 years ago, Neanderthals are still living with us, and this is the time of the rise of the dominance of Homo Sapiens, and the blackboard was over at the zoo someplace, 3 kilometers from here. A hundred thousand years is still nothing geologically. We have hardly moved at all. Let's go back a million years (10^6 years) - 30 kilometers. Now, we're really getting someplace. We're in East St. Louis. Humans weren't ever around – we had evolved as far as our ancestor, Australopithecus. We didn't even look anything like we currently do. If we go back 10 million years (10^7), we've moved 300 kilometers. Now, we're really getting places. We're in Terre Haute, Indiana, and our ancestors are swinging in trees somewhere. Okay, let's go back 100 million years (10^8 years). This blackboard has now moved back 3,000 kilometers to the east, and that is geologically significant. We're in the Atlantic Ocean, but that's a lot of powers of 10 that we've had to go through. And this is the scale that we want to talk about, geologically speaking. If I just double this number, and I go to 200 million years, this is when the breakup of Pangea occurred. Pangea was the name of the supercontinent that existed 200 to 300 million years ago, when all of the continents were together as one giant landmass. And it's over the scale of hundreds of millions of years that we get a significant amount of geological activity.

[Q: When you talked about the blackboard moving, are you . . .]

This whole room.

[Okay, the whole room . . .]

Right.

[But you're, it's not just the room itself but like the ground underneath . . .]

Right, this whole are, all of St. Louis, all of North America. That's an interesting point, and it leads to an interesting aspect of Plate Tectonics, that the plates are fairly rigid. So if we are moving in a particular direction, so is Chicago. For the most part this is true. We move together as a single entity, a single plate.

The concept of a supercontinent, Pangea, is geologically fascinating. You could have walked from New York to the Ivory Coast. There was no Atlantic Ocean at that point.

[Q: Is Pangea the name of the continent or the name of the time period?]

The name of the supercontinent.

[How did they come up with that?]

"Pan" means "all", "gea" is "Earth", so, all of the Earth.

The continents have moved apart since then, and something has moved them, and we're going to talk about why there was a supercontinent, and why the supercontinent broke apart, and how it moved. But even then, it is important to remember that 200 million years sounds like a lot of times, but it is still only a little more than 4 percent of the Earth's total. It is only a brief geological episode in Earth's history, and it turns out there have been lots of supercontinents as you go back in time, and they all looked different than Pangea. If you go back 300-400 million years ago, some of the continents were apart again, and if you go back 700 million years ago, some of them were together, and if you go back 900 million years ago they were broken apart. And 1.2 billion years ago seems to be an important time. There was a large supercontinent at that time as well. When we look back in time, we see evidence of these previous supercontinents, so there is a repeating cycle of continental activity over a very long time scale.

[Q: Are these, are the plates accelerating or are they slowing down? Are they moving at a constant speed? Even if they're different but are they, you know are they -- does it look like they're . . .]

Take a really hot cup of coffee and pour cold cream in it and watch what happens. Okay, the next time any of you go to Hilltop Bakery, try this. What happens is that for awhile all of the cream seems to roll over one way, and then it stops, and then it begins to roll back the other way, and then it stops and rolls back another way. There are cycles of great activity in the churning of the coffee, and times of stagnation, and this is what you get in the convection within a cup of coffee, and this is what you get in the convection of the Earth, and the physics are exactly the same. Because, again, Plate Tectonics *is* convection. I spent a lot of time in the last class talking about convection. Plate Tectonics is simply the surface expression of that convection. It is like the top of your coffee cup. Like the coffee and cream, the rock of the mantle moves one way, dragging the continents. It stops, the continents collide, roll back the other way, and so on. It is all due to the process of the Earth trying to cool down.

So now let's stop for a moment and look at a map of the plates that we actually have, and we will come back to this picture a couple more times in slightly different manners, in particular, with more information added to it. There are about a dozen major plates, and they don't necessarily fall in the locations that you might have thought. For instance, here's North America. The North American Plate stops at the western end at the Pacific but it extends halfway across the Atlantic, and it doesn't include the Caribbean, which is its own little plate. It turns out that parts of Siberia, and maybe even Japan, are actually part of North America. We aren't actually sure where the plate boundary is, as the relative motions are so small. Europe and Asia currently form a single large continent, Eurasia, and this also includes part of Southeast Asia, but not India, which is its own plate. India and Australia mostly behave as a single plate, though they move slightly differently, so we consider them to be two different plates. This map is about 10 years old, and it still has them as one plate, but now we know they are separate. The Arabian Plate is doing its own little thing, sliding into Eurasia. The African Plate includes some of both the Indian Ocean, the Antarctic Sea and the Atlantic Ocean. And the South American Plate is very similar to North American Plate. The plates are all moving, so go either back or ahead in time, and the configurations of the continents are all different. This will ensure employment for future map makers. We grow up looking at the maps of the continents over and over, learning the capitals of countries, and all of the political boundaries. However, not only are the political boundaries transient, changing over the years, but there's also nothing special about the current configuration of continents. If you go back 50 million years or you go forward 50 million years, the whole appearance of the continents is going to be very different.

[Q: What happens in these spaces where the arrows are pulling apart?]

These features are called mid-ocean ridges, such as the Mid-Atlantic Ridge, which runs from the North Pole straight down the Atlantic till it hits the Antarctic Plate. It then runs east through the Indian Ocean, through into the Pacific, and up through the East Pacific Rise until it runs into Mexico. You've got over 40,000 kilometers here of plate spreading, and these are the places where new oceanic plate is created. If you move plates apart you get a gap -- nature abhors a vacuum, and something comes up to fill its place. This is lava that flows up to the sea floor, and so there is essentially a 40,000 kilometer long continuous chain of volcanoes. They are underwater, so we don't see them for the most part. They do poke up occasionally. Iceland is one example where that ridge comes above the ocean surface, but for the rest of this large interlinked chain we have the plates spreading apart and creating new plate underwater.

[Do earthquakes only happen at the barrier between these plates or do they happen . . ., how do earthquakes get involved?]

That brings me right to my next slide. The plates behave such that the geological activity happens at their boundaries. One example of this geological activity is shown in this map, which shows the locations of earthquakes. Now, if I gave every one of you a dozen darts, and asked you to randomly throw them at this screen, the distribution of darts would not look like this map of earthquake locations. The reason is that the distribution of earthquakes is not random. You don't see the black dots covering most areas of this map. They primarily occur in narrow bands. They are occurring at the edges of the plates, at the plate boundaries, and we can see this all the way around the edge of South America, Central America, California, the Pacific Northwest, the Aleutian chain of Alaska, down through Japan, the Philippines, Indonesia, Tonga, and to New Zealand. This defines the edges of the plates that make up the Pacific Ocean: the Pacific, Nazca, Cocos, and Philippine plates. Here is India, and you can see all of these earthquakes that occur between India and China, and this is a big clue that India is not part of Asia, geologically speaking. There is a plate boundary that separates the two of them. There are earthquakes all around the Arabian Peninsula, but very few on the inside of it. Now, there are a lot of earthquakes that do seem to occur in the middle of plates in certain areas, and we will talk about that a little bit later on.

[So what are fault lines? Are those the same as plate boundaries? Are we really on top of one?]

Fault lines are places where earthquakes occur, and any plate boundary is made up of large numbers of faults, but not all faults are plate boundaries. There are many more faults than plate boundaries. And I'll give you a quick analogy now, and then I'll come back to it later on. Imagine that you have an old wooden ship sailing on a rocky ocean. The boards of that ship are going to creak and groan as that boat sails up and down over large waves. Those earthquakes that occur in the middle of plates are just like that wood creaking. When an earthquake occurs, it means that the rock of the earth has been stressed, bend, past its breaking point. This happens all the time at plate boundaries, but it also happens in the middle of plates. If I take this pencil and I begin to bend it, at some point it will snap. Okay, you just heard the sound of that snap because sound waves travel through the air to your ears. When the ground breaks along a fault line, and you can think of the crack here in this pencil as being the fault, there are sound waves that travel through the solid rock of the Earth. These waves are recorded as seismic waves on seismograms. The pencil was more likely to break along a pre-existing crack in the pencil, and it turns that intraplate earthquakes (earthquakes in the interiors of plates) are also more likely to form on pre-existing cracks. But we get earthquakes all over the continents because the continents are very old, and they are filled with billions of old faults. It turns out that one of these areas of pre-existing faults is just 150 kilometers south of here, in a region called the Reelfoot Rift. The large New Madrid earthquakes of 1811 and 1812 occurred there, but I will talk more about this later.

What else happens on plate boundaries? Well, if you look at a map of volcanic eruptions, you see pretty much the same pattern as earthquakes. Most volcanoes occur on plate boundaries. Volcanoes rim the Pacific Plate, where there are subduction zones, and of course, occur along the long mid-ocean spreading centers. There are also some volcanoes that don't occur on plate boundaries, however. Hawaii is not anywhere near a plate boundary. Yellowstone isn't near a plate boundary. There are other places where you get volcanoes occurring that aren't on a plate boundary. Most of these are associated with hot spots, and I'll talk about those soon.

It turns out that these pictures, which show the plate boundaries as being very sharp lines, are really over-simplifications. They aren't so good at describing what's actually happening with the plate boundaries. It turns out that many plate boundaries are actually very wide. If you were to look at a map of the earthquakes in California, you would not see all the dots fall on the San Andreas Fault as a sharp, well-defined line. In fact, you would see earthquakes spread out all over California. It turns out much of California, Nevada, Utah, Colorado, and many other western states, are part of a very complex set of faults, a system of faults with earthquakes occurring regularly, and the plate boundary is actually widely distributed. We also see this when we look at the motions of the plates using Global Positioning System (GPS) sensors. It's not exactly the situation that if you stand on one side of a fault you're going to be moving as part of North America, and on the other side of the fault, two feet away, you're part of the Pacific Plate. The plate boundary actually occurs over hundreds of kilometers, and the motions occur gradually across this region. The plates are kind of fuzzy, and this is an important aspect to Plate Tectonics. The plates are mostly rigid, but the plate boundary areas are on the order of up to 30 percent of the surface. This is a lot. After all, the total area of the continents is only about 30 percent of the Earth's surface. It turns out that most of Asia is actually considered to be the plate boundary between India and the rest of Asia. This is a very diffuse, broad boundary, and it is due to the fact that India is still rapidly colliding with Asia. In fact, India used to be attached to Antarctica, and not very long ago it moved rapidly northward, and this has caused a tremendous amount of deformation. Much of the western U.S. is actually part of this sort of diffuse plate boundary, and from the high level of intraplate earthquakes, we can see that much of Alaska is as well. There are places where the plate boundaries are very wide.

While plate boundaries are often fuzzy, there is no fuzziness when it comes to the difference between oceanic and continental crust. This is one thing in the Earth that does not have a broad spectrum. There aren't continent-like oceans or ocean-like continents. There's a real distinction between the rock of continents and the rock of ocean sea floors. The continental crust tends to be thicker than the ocean crust, and the continental crust sits high up on top of the mantle rock that with it makes up the continental lithosphere. The ocean crust sits on top of mantle rock to make the oceanic lithosphere, but the oceans are made of rock that is essentially the same as the mantle. The rock of ocean crust comes up from inside the Earth to fill the gaps as plates are moving apart at mid-ocean ridges. And these oceanic plates, which are all mantle rock, are heavier than continents, and will sink right down beneath the edges of these continents. Where one plate sinks beneath another we get an oceanic trench, and this whole region is known as a subduction zone. These are the places where oceanic plates (and I use plate and lithosphere interchangeably), sink back into the mantle. Now, you'll notice that continental mountains are often highest right next to the edge of a continent, and this is also very significant outcome of Plate Tectonics. If you look at a picture of the topography of the Earth, there are two things that are counterintuitive. The deepest parts of the oceans are not in the middle of the oceans, and the tallest parts of continents are usually not in the middle of the continents. This is reversed from the surfaces of other planets like Mars and Venus.

Where are the shallowest places in the ocean? They're in the middle of the ocean. Look at the mid-Atlantic ridge, exactly half-way in the middle of the ocean. For instance, where is the deepest part of a lake? The deepest part of the lake is usually in the middle of the lake. That's not what happens with the Earth. The deepest parts of oceans are usually not in the middle, because that's where the mid-ocean ridges are. When the rock from the mid-ocean ridges first forms, it is very hot and buoyant, and it sits higher on the ocean seafloor, so the ocean there is shallower. The deep ocean trenches, however, are at the edges of the oceans, where oceanic plates sink beneath the edges of continents. These trenches can be very deep, sinking to over ten kilometers.

[Q: You are talking about a subduction zone?]

Right.

[Q: What is it that goes down toward the mantle?]

The ocean lithosphere, the ocean plate, sinks back down into the mantle of the Earth.

You might think that mountains should be in the center of continents, and that elevation should decrease as you move toward the oceans, but look at places like South America. The Andes sit right adjacent to the Pacific Ocean, and the same holds with the coastal ranges in California, Oregon, and Washington. This is also true for the mountains in the southern part of Europe, where there is a continuous range of mountains that goes from the Alps to the Zagros Mountains, to the Tien Shan hills, to the Himalayas. This chain of mountains is along the southern border of Eurasia. Mountains are created when plates collide. Those collisions can take a couple different forms, and I'll talk more about this later this week. When you have two continents collide, you create a set of mountains like the Himalayas. When you have an ocean seafloor collide with the edge of a continent, however, you build up mountains through a very different process, through volcanism. Here's a schematic diagram of the different places on the Earth where you would find volcanoes. At the mid-ocean ridges, we have magma coming up, cooling, solidifying, and attaching itself to the existing oceanic plates. These oceanic plates eventually sink down into the mantle. We can think of this as the part of the Pacific Ocean seafloor (called the Nazca plate) that is sinking down beneath South America, creating the Andes mountains above the subduction zone. Or imagine that this is Oregon and Washington, and these volcanoes are Mount St. Helens, Mt. Rainier, Mt. Baker. Magma forms in the subduction zone, and it rises up, and erupts as lava at the tops of these volcanoes. We end up building up these mountains through the continual addition of magma coming up from below. This rock down in the subduction is not melting because it's hot. Far from it. We have cold rock that is being stuffed down into the mantle. One might think that this would be chilling this part of the Earth. The sinking plate, however, is bringing down a lot of water and a lot of sediments with it. The water seeps into the rock of the crust. Because the continents are being constantly eroded, sediments are washed by rivers from the continents into the oceans, where they settle on the sea floor. Some of those sediments come back down with the plate into the mantle. It turns out that those sediments of continent-type rock melt much more easily than mantle rock, and it turns out that when you take almost anything and add a little water to it, it melts much more easily.

So we have a situation where it's hot down in the mantle but the pressure is keeping it solid. Add a little bit of water and the rock melts, becomes buoyant, and comes up as a chain of volcanoes. The Andes are tall because there are volcanoes all along the rim of South America and Central America. There is nearly continuous volcanism there. On the other side of the Pacific, in one region, we also have an instance of ocean sinking beneath ocean. You can have ocean seafloor sink down beneath continents but you can also have one piece of ocean floor sink into the Earth beneath another piece of ocean floor. Here we create something that's known as a volcanic arc. If you have one bit of ocean lithosphere sinking beneath another, you still get volcanoes, and those volcanoes form new islands in the ocean. The Philippine Islands are a good example of a whole new set of land that has been created through this volcanic process. As a result, there are nearly continuous volcanic eruptions in the Philippines. The force of the sinking plate can create a force called *slab suction*, and this force can pull an island arc toward the subduction zone, creating a region of oceanic spreading behind it. This is called a back-arc basin, and it is just like a mid-ocean ridge – new ocean plate is being formed there. The reason that slab suction occurs is due to the way the sinking plate subducts. Gravity is pulling the whole plate down, and this force is called *slab pull*. But sometimes the bending point of the sinking slab moves backward as the whole plate is being pulled down. This is called *trench rollback*. This means that the plate boundary is actually moving in the opposite direction that the subducting plate is moving. This leaves a gap, and the volcanic arc gets sucked into it. This can also happen at continents. Japan has been pulled away from Asia by the sinking Pacific plate, creating a back-arc basin (the Japan Sea) between Japan and China. Next class I will continue talking about the forces that drive Plate Tectonics.