

Transcript from Epic of Evolution: Life, the Earth and the Cosmos (BEP 210A)
February 25, 2000 - Lecture by Michael Wysession

“In terms of observational facts alone the behaviour of the inner earth now appears even more fantastic than when we knew much less about it.” (A. Holmes, 1965)

Today I will wrap up the discussion of large-scale plate motions on the surface of the Earth. I will leave the actual structure of the plates and the continents until 3 weeks from now, because I will need to introduce concepts such as sedimentary, volcanic, and metamorphic rock. Only then can I talk about what happens to these materials when they undergo all of the collisions, rifting, subducting, and volcanic processes that I have talked about this week. But first I will give a few more highlights of the interactions between the continents at Earth’s surface. At the end, I will give a tour of our best current guesses for the history of our continents over the last 700 million years or so.

I ended last class showing a map of the ages of the oceans, determined from the pattern of magnetic field reversals frozen within the ocean crust. It is important to remember that not all of what we learn about the Earth is found in terms of nice scientific experiments where you go out looking for something, and you find it. Ironically, the geomagnetic stripes within the ocean crust were first discovered in order to hunt down German submarines. During World War II there was a very large effort to map out the oceans and the ocean seafloors in order to find ways to hide our own submarines, and to find ways of determining where German submarines might be hiding. This involved investigations of the bathymetry of the seafloor, and this was how we found that there was a ridge of underwater mountains running right down the middle of the Atlantic Ocean. We realized that the ocean seafloor is quite rough, covered with submerged islands called seamounts. Our submarines usually used sonar to determine the distance to the seafloor, and therefore avoid running aground. However, sonar is noisy, and would give away the location of our submarines to any nearby German boats or U-boats. We therefore looked for other ways of determining the locations of our submarines, and it was through this effort that we mapped as many other geophysical features that we could, such as horizontal variations in the gravitational and magnetic fields. This is how it was discovered that there were anomalous magnetic stripes running across the seafloor, parallel to the mid-ocean ridges. In fact, it was one of the American Navy captains, Harry Hess, who went on to head up Princeton’s geophysics program after WWII, and was one of the people who helped put together the idea of Plate Tectonics. Sometimes science works in very methodical and calculated ways, designing and testing experiments. But a lot of time it works out in inadvertent ways.

I talked previously about ocean plates colliding with continental plates, but I didn’t about what happens when continents collide. This is important because this is how continents like North America have grown. They grow through the collisions of lots of smaller plates. There’s a famous paper in our field called “The United Plates of America,” which talks about how lots of little pieces of continent have come together to make our continent, much like a patchwork quilt. Let’s start with the rock of the continental crust, which is the scum of the Earth. It’s so buoyant compared to mantle rock that you cannot sink it back down into the Earth. If you have a subduction zone where ocean crust is sinking back into the mantle, and you have a piece of continent embedded within that plate, if that continent gets dragged into the subduction zone, it

will clog up the subduction zone, and the subduction will stop at that location, and jump to a new one. If there is large-scale convergence occurring, you will often break the plate behind the continent, and start a new subduction zone behind it. The result is the creation of a larger continent than the one we started with. It now includes the continental fragment that was originally from someplace else. It may also include some ocean crust that got smashed up in the collision zone. We've made our continent larger by sticking on another piece of, and where they collide, we end up with mountains.

Anywhere that you see large regions of mountains on the continents, they are the result of collisions between continents. Some of the collisions are quite recent, or even going on currently. The Rockies, for example, are due to a fairly recent set of collisions. The Himalayas are still growing. The Alps are also quite young, geologically speaking. The Appalachians, in the Eastern U.S., however, are an example of an old mountain range. The Appalachian Mountains, which run from Maine to Georgia, used to be about 10 kilometers taller than they are now. They are about 300 million years old, and in that time they have mostly eroded away. Imagine having a nice sandcastle, and then drizzling rain on it. The sandcastle is eventually going to smooth out, and all that will be left will be a lump, with all of the original features gone. That's what happens over time to all mountain ranges. I will talk more about this in 6 weeks when I talk about water and erosion. Erosion works incredibly quickly on high places like mountains, so they just don't last very long.

When mountains first form, they can be quite dramatic. The normal thickness of a continental crust is on the order of 35 to 40 kilometers. When a new mountain range forms, that thickness can double. For instance, beneath the Himalayas, the crust is up to 80 kilometers thick from the top of the mountain to the bottom of the crust. This is because the rock of the crust gets horizontally squeezed. It's got to go somewhere, so it goes up and it goes down. The result is that it thickens, and it thickens through the processes of both folding and faulting. The rock is solid, but we determined previously that it flows like a liquid over long time scales. This is also what happens with mountains. Large folds in the rock develop when the crust is compressed, and when the crust is pulled apart, it stretches like taffy and thins. Sometimes the stresses do break the strength of the rock, and results are earthquakes that occur on faults. But if the process of deformation occurs slow enough, then you just slowly twist up the rock. The resulting process can be quite dramatic over long times. In places like the Alps giant folds within the rock can actually flip over, so that the older rock is now on top, and the younger rock is on the bottom. Suppose we compress the crust between two plates that are colliding. We cause that rock to buckle up, and sometimes fold right over. Sometimes those folds then get twisted up again later on. Geologists have looked at the geology of mountain regions around the world, and have come up with reconstructions of what the rock structure used to be before it was eroded away. Erosion wears away the mountains quickly, so it is as if a knife has cut off the tops of the mountains. The reconstructions show, however, that there were once giant folds that extended much higher at mountain ranges like the Alps and Appalachians. Our continents are made of tortured rock. They've been around for a long time. They've been battered and beaten, broken apart, twisted, and they get a break every now and then, but they keep slamming back into each other, and more things keep happening to them. Like 4 billion years of professional wrestling. The result is that the actual structure of the rock down beneath us is very complicated.

The basic idea for America and for other continents is that the oldest continental rock is found at the center of the continent, and through these collisions over time, we've tacked on younger pieces of rock at the edges. The oldest fragments of continental crust are called cratons, and we have some of these that go back 4 billion years. They tend to have very deep roots in the mantle. Their roots go down about 300 kilometers, and that's why it's very hard to drag them along in plate movements. When these cratons collided, they got glued together, and the places they got glued or sutured on are called orogens. These orogenic belts exist between all of the fragments of cratons. This means that 1.8 billion years ago, North America extended from Canada down to about Chicago, and there wasn't yet anything south of Chicago. There was nothing there – the crust we are now on here in St. Louis had not yet been made. As you go to younger times, other areas in the middle of the continent here came on between 1.8 and 1.6 billion years ago. A later set of collisions, largely with South America, formed a stretch of crust from Canada to the Gulf of Mexico called the Grenville Terrane. Lastly we have the crust east of the Appalachians that was stuck on during the collision with Africa that closed up the ancient Atlantic Ocean. The Grenville Terrane used to have a mountain range that ran through the middle of Ohio, but there are no mountains in Ohio now. They're all long since eroded away. And then the Appalachian mountains were formed, and we still see evidence of them, but they are rarely higher than a mile, and those too will eventually level out. The Ouachita Mountains, south of Missouri, used to be like the Rockies. Antarctica had collided with North America about 1.2 billion years ago, and there was a dramatic mountain front just south of here. But the Ouachitas are now just rolling hills compared to the current Rockies.

[Q: Is that the same as the Ozarks?]

Right, they are the same.

If you look at the Western U.S., all of the continental rock is actually much younger. Everything west of Colorado has been tacked on in the last couple hundred million years, practically yesterday, geologically speaking. What's more, the western part of our continent is filled with different fragments of crust that came from many different places. We know they came from different places because of their paleomagnetism – the magnetic fields that were frozen in when they were formed. We can go there and drill out pieces of rock and take them to a laboratory, and the magnetic fields that they have frozen in all point in different directions. This means they came from different places. These crustal fragments were brought in through subduction. The continental fragment would get stuck onto North America, and clog up the subduction zone, which would then jump westward to allow subduction to occur beneath the new continental addition. Some other crustal fragment or island arc would then get pulled to North America, clog up the subduction zone, and become the next continental addition. Piece after piece of separate continental fragments came in through this way to build up the Western U.S. Geologically, this all happened quite recently.

If we go back to 1.2 billion years ago, there was another supercontinent that contained most of the continents. South America was wedged in between North America and Africa, and you could have walked from New York to Chile. Much of the southern part of North America didn't exist at that time. Most of Asia had not even formed yet. Eurasia existed only as far as the Ural Mountains.

The basic idea is that continental crustal rock has been around a long time, even if it has been reworked in many ways. The continents grow and shrink, but the rock of the crust stays at the surface. Continents grow by two means, by accreting continental fragments, and by platform deposition. Continental accretion is when you bring in a continental fragment and stick it onto the edge of your plate. Platform deposition is how we got our limestone here in St. Louis. At a time when the sea level was high, and you wash over the continents with the oceans and you deposit ocean sediments onto the seafloor (now the former land of the continent), and this compacts to form sedimentary rock. We haven't talked about sedimentary rock yet, so more on this later. You can add stuff at the sides, or you can pile it up on top. Continents shrink by lateral compression and by erosion. During plate collisions the continent gets squeezed. Mountains get pushed up, but the lateral length of the continent gets reduced. Once the rock goes up as mountains, it gets subject to more rapid erosion, which washes it back into the sea. So we actually lose continental material whenever we accrete continental fragments because the mountains are very quickly eroded. The rock gets squeezed up, it gets eroded, and then pulled back down. There is a battle that goes on between these two effects, and the prevailing thought is that the amount of continents that we currently have is the same amount that we've always had. It is not like we started with a few tiny continents, and then they just kept growing and getting larger and larger. It looks this way for North America, but in reality we probably have always had roughly the same volume of continents, but they have just been constantly reworked. Rock has been tacked on, pulled apart, sediments piled up on top, sediments eroded away, so the appearances of the continents have changed tremendously, but the total volume of the continents has probably changed very little.

Let me take the most dramatic example of plate motions that is currently going on, and that is the collision of India into Asia. Notice that from the Himalayas northward there is a lot of mountainous land, but India is quite flat in comparison. India is one of the fastest moving plates, and only 150 million years ago India wasn't anywhere near Asia. In fact, it was nestled quite nicely between Africa, Australia and Antarctica. For some reason that we don't really understand this part of the southern supercontinent got torn off and pulled northward. There were several island arcs and continental fragments that were between India and Asia, and they all just got swept up and piled onto Asia as the two collided and got glued together. 140 million years ago, India is some long ways away from Asia, but we've got subduction occurring beneath Asia, and this is like a conveyor belt that will drag everything here in towards Asia. The first things that are going to hit are any volcanic islands that may be on the seafloor, and they stick onto Asia. And there also a separate microcontinent that got swept in 40 million years ago, and this became Tibet. This small terrane is just like the terranes that recently came together to form the western U.S. India then collided with Asia, and was thrust under it. There are very long, large faults where India is sliding beneath Tibet. When you slide these two pieces of continental crust on top of each other, the result is a single crust that is much thicker. The Indian crust itself will never be able to sink down into the mantle, though the mantle part of the Indian plate does peel off from the crust and sink into the mantle.

[Q: Okay, so when two plates collide they form mountains. So I guess wherever there are mountains there is a separation of two different plates, right?]

Right, you're going to get different material on either side.

[Okay, so they don't ever merge into like one plate? Could they like split apart again?]

There's a very profound question there. Yes, they do become one plate, at least for a while. It turns out that when continents break apart, they often do so along the former suture lines where the continents were attached. It doesn't always happen this way. For instance, Rhode Island used to be part of Africa, and it's now very much part of North American Plate. But there is a zone of weakness that exists down the line of the Appalachian Mountains, and if North America ever breaks in two pieces, it would not be surprising if it split along the line of the Appalachians. India is part of Asia for now, but if the two get split apart, they'll probably split right along Tibet.

Here's what's happening in a physical sense. We're taking India and thrusting it up into Asia, and what we find is that there are all these little slivers of crust that are being squeezed out the sides in order to make way for it. Indochina (Southeast Asia) sticks out somewhat from the rest of the continent. Well, it didn't used to do that. It was pushed out of the way, and is actively moving away by the force of India's northward motion. All of these different little segments of crust are being pushed aside in order to make way for India. Geologists have done experiments where they have made models of these interactions by slamming a block of wood into plasticine, and they see the same process whereby pieces of the plasticine will sliver off and squirt out the sides. This process creates many mountain ranges, and large numbers of earthquakes. Earthquakes in China regularly kill hundreds of thousands of people, and it is all India's fault.

Looking at the history of plate motions more than 200 million years ago requires the use of paleomagnetism on continents. We have no ocean seafloor that's older than 200 million years. We have a record of what the continents have done going back a long ways, but we have no record of what the oceans did. We don't know where the trenches were, where the mid-ocean ridges were. We have to guess that there were a lot of subduction zones, a lot of ridges, a lot of crust being created and subducted. We don't have any idea what form this actually took, but we do have some interesting current examples. Just off the coast of California there used to be subductions. There was once a plate that took up most of the Pacific seafloor called the Farallon Plate. It was moving eastward, and was subducting beneath the entire western edge of North and South America when Pangea was opening up. When Pangea broke open, North America was moving away from Europe and Africa, and as it moved westward, the Pacific seafloor sank beneath it, and that plate was called the Farallon Plate. New crust of the Farallon plate was being created at a mid-Pacific ocean spreading center, but North America was moving westward faster than the Farallon plate was being created, so North America has begun to ride right over the ridge. From Mexico to Cape Mendocino, California, the Farallon ridge has sunk beneath the U.S. From just north of Vancouver to Alaska, Canada has ridden over the Farallon ridge. The Farallon oceanic plate is now almost entirely gone. It just exists as two pieces, one that is subducting beneath Oregon and Washington (the Juan de Fuca plate), and one that is subducting beneath Mexico (the Cocos plate). Eventually, these plate segments will be gone as well. There used to be subduction beneath all of California, but the Farallon plate out the way, there is only transform plate motion between the Pacific and North American plates, allowing them to slide past each other. This turned off all of the volcanoes in central California, though they are still

warm, and could still erupt. Once the Juan de Fuca and Cocos plates fully subduct, the San Andreas will grow to be one giant transform fault system, stretching from Mexico to Alaska.

As I said, we don't have any record of these sorts of oceanic plate motions going beyond 200 million years ago. We only have a record of what the continents have done, but that has told us some interesting stories. Let's take the case of the Atlantic Ocean. If we go back 200 million years ago, the Atlantic was closed up. This is the time that the modern Atlantic Ocean was born. Before then we had the supercontinent Pangea (300 to 200 million years ago), and there was no Atlantic Ocean. But if you go back to earlier times, there was an ocean there. This proto-Atlantic is often called *Iapetus*. 600 million years ago, North America and Africa were far apart from each other, with several continental fragments and island arcs stuck in between. *Iapetus* was already a mature ocean by that time. It had already been around for a very long time, and was closing up. Between 600 and 300 million years ago, Africa and North America were moving toward each other. A large piece of Eastern U.S. was formed from an accreted crustal fragment, and this became known as the Piedmont Terrane. And then we have the Carolina Slate Belt, which was likely an island arc that got stuck on. The Appalachian Mountains formed from that collision with Africa. When Pangea broke up, a remnant of Africa remained stuck along the eastern seaboard of North America. We have found that the plate motions go through this continuous cycle of back and forth motions that occurs over and over.

New Jersey is vitally important for the future of North America. I'm from New Jersey. I just like to say that. Actually, the whole passive margin along the east coast, from Maine to Florida, is important for the future of our plate. I previously mentioned that this was a continental rift basin at the time that Africa rifted away. The rock beneath the coastal margin is filled with faults. At some point, we are going to dump enough sediment out of the Hudson River and the Connecticut River and Chesapeake Bay and all the other rivers, that the weight of the sediments will be too much for the edge of this crust. Remember, the ocean plate that is next to the continents, on both sides of the Atlantic, is the oldest. It's 200 million years old. That means it's cold and it's heavier than the mantle beneath it. The only thing that's keeping it from sinking is the fact that it's stuck on to the continents, but it's not stuck on very well because the passive margin was all rifted up when the Atlantic first opened up. At some point we're going to build up enough sediment that the plate will break from the weight, and the ocean floor will begin going under America, and the next subduction zone will go right through New Jersey, complete with giant earthquakes and explosive volcanoes. We don't know when this will be. This could be tomorrow. This could be 400-500 million years from now. But it will inevitably occur.

Let me finish with a historical tour of our continents. [slide 1] Let's go back to 650 million years. This doesn't look anything like our current distribution of continents. Remember, there is nothing special about our current distribution of continents. They are just a snapshot in time. 650 million years ago is still only 15% of the way back to the formation of the Earth. There is a lot of geological history that we still haven't been able to piece together. Most of China had not formed yet, so we see little fragments that will become South China and North China. This also doesn't look a lot like the other picture that I showed you from a little bit older, partly because this is more recent. That was 1.2 billion years ago and this is 600 million years ago, but also because this whole process of piecing together the history of the continents is highly speculative,

and every version I see of this from a different scientist looks different. Things were fairly spread out, and there were a few large oceans that spanned much of the Earth's surface.

[slide 2] If we go to 500 million years ago, we see that North America has a different name, Laurentia, and it contained mostly Canada and Greenland. We're missing the bottom part of our continent. Notice that what will become Florida is way over here. The New England fragment is way over there. Most of the southern continents were together in one supercontinent called Gondwana.

[slide 3] Going a little ahead in time, we see that the Baltic region is heading in, and North America is having a little collision with Scandinavia. Some of pieces like New England are coming in.

[slide 4] Now the Baltic area is now stuck on with Greenland, and Florida is going to come in. The ancient version of the Atlantic Ocean, Iapetus, is closing up. South China and North China are still a bunch of little continental fragments. Gondwana is still pretty well stuck together: Antarctica, Arabia, Africa, South America, and Australia

[slide 5] We're working towards closing up everything to form Pangea. Kazakhstania and Malayia are coming in to form Asia, but there's still not much to speak of yet. Europe has now stuck on to Laurentia and the Baltics. The Appalachian Mountains are now actively forming. Much of Africa is under water, but Africa is colliding (though it's submerged) with North America.

[slide 6] There was a former ocean that separated India and Siberia called the Tethys Ocean. This is the ocean that India is going to end up crossing when it moves north. We are closing things up.

[slide 7] Now we've got Africa connected directly with North America. At this point Pangea is a combination of both Laurentia in the north and Gondwana in the south. Things are still adding things on with subduction Asia, but there is also subduction occurring all along the west side of Pangea. This is called the Panthalassic Ocean, and much of the ocean seafloor here is the Farallon Plate I talked about earlier, which is actively sinking beneath western North America.

[slide 8] 255 million years ago. We've now got a big supercontinent, and the Earth at this point is fairly lopsided in its rotation because we've got continents with greater elevation are in one spot, and all the rest of the Earth is ocean. In terms of climate, this does some really bizarre things. When you have very large supercontinents, you create very different weather patterns, with terrible monsoons and very severe changes in weather. This is probably what was going on at the time. It totally disrupted the whole ocean current system, which used to be able to run right through the equator, but now is blocked off. Ocean life would have been tremendously affected by having this supercontinent essentially block off the flow of water around the world. It would have been much more subject to large tides along the shores. India is still nicely nestled here between Africa and Antarctica and Australia. What will become Tibet is still a long ways away from a unified Asia.

[slide 9] We still have Pangea, and are closing up the Tethys Ocean. Turkey, Iran, Tibet are only fragments. They don't exist as part of a continent yet.

[slide 10] 195 million years ago. Things are still fine as far as Pangea occurs. We are now sticking on Tibet, and tacking together all the various pieces of Asia. Still not much is going on in the rest of the world.

[slide 11] The modern Atlantic Ocean has been born, and we now have an open seaway again along the equator that forms the Tethys Ocean. North America is breaking away from Africa and South America, which are still together. They don't break apart until later. Europe and Greenland and North America are all one continent still.

[slide 12] We are beginning to break Greenland away from North America. The Atlantic is now cracking its way up towards the North Pole, and we've begun to break South America away from Africa. North America and South America are far away from each other, but notice that we've also begun to break India away, and it is going to very quickly veer northward.

[slide 13] 70 million years ago. The Atlantic Ocean is growing, and India is halfway towards Asia.

[slide 14] Continents are moving apart, spreading back open. Things are opening up. Greenland is no longer moving away from North America. The Iceland Hot Spot caused the rifting to jump from between Greenland and North America to between Greenland and Europe. The Atlantic Ocean has changed its mind, and is now opening up between Greenland and North America. The Atlantic is also opening up in the south. India is now beginning to collide into Asia.

[slide 15] Australia is doing its own thing as well. It has broken away from Antarctica, so now Gondwana has totally split apart. Africa, South America, Antarctica and India were all together, but are now broken apart. North America and South America are actually swinging together a little bit and we've now closed up the equatorial seaway passage again. Africa is swinging in toward Europe, and the Tethys Sea (including the Mediterranean) is being closed up.

[slide 16] And this is what we have today, which I have already shown in several versions.

[slide 17] This is what we might expect a 150 million years in the future, and then 250 million years in the future. Things look very different. Here is the subduction zone I talked about along the coast of Eastern North America. The Atlantic Ocean is going to reach some maximum level. It is then going to begin to close up again, and Africa will eventually collide back together with North America, perhaps in a different place. Australia is actually moving up into Asia, and will probably become part of Eurasia. Sometime in the future there will be another supercontinent. The continents will come back together in some new form. This is total speculation. We don't have any idea what distribution the continents will take when they come together. But it will happen in one form or another.