

Changing Planet: Past, Present, Future
Lecture 2 – Building Scientific Knowledge: The Story of Plate Tectonics
Naomi Oreskes, PhD

1. Beginning of Lecture 2 (0:16)

[ANNOUNCER:] From the Howard Hughes Medical Institute...The 2012 Holiday Lectures on Science. This year's lectures: "Changing Planet: Past, Present, Future," will be given by Dr. Andrew Knoll, Professor of Organismic and Evolutionary Biology at Harvard University; Dr. Naomi Oreskes, Professor of History and Science Studies at the University of California, San Diego; and Dr. Daniel Schrag, Professor of Earth and Planetary Sciences at Harvard University. The second lecture is titled: Building Scientific Knowledge: The Story of Plate Tectonics. And now, a brief video to introduce our lecturer, Dr. Naomi Oreskes.

2. Profile of Dr. Naomi Oreskes (1:14)

[DR. ORESKES:] Because I am a historian, and because part of the craft of history is not just finding the facts but telling a compelling and convincing story about them, narrative, the craft of narrative is really important in history. When you're a scientist you really don't have that freedom. There's not much creative license, there's not much style in most scientific work, right? So it's kind of fun to break out a little bit from that mode and write in a way that's a little...a little more fun, a little more interesting for my readers to read. And the irony is that the people who attack science understand this very well. They have some very compelling stories to tell about why they don't think we should believe scientific data, and the scientific community by and large has rather weak stories, and so one of the challenges of being in this interesting middle ground between science, history of science, and science communication, is thinking about how to tell the stories in ways that are compelling and convincing but still honor the fact, still honor the facts in a very, very rigorous way.

[LECTURING:] But even political actors respected the boundaries...

[DR. ORESKES:] I'm interested in talking about my work to anyone who is interested in listening, I mean I'm not shy. But I'm especially interested in school teachers because we know that most Americans end their scientific education with high school chemistry, so if we want people to understand science, we have to bring it into the high schools, so high school science teachers are hugely important. And it's important both because high school is the point at which many students will decide whether or not to continue their scientific educations, but even if they don't, high school then becomes the point at which they have the foundation for judging scientific evidence, for judging scientific claims on questions that will be relevant to their own lives.

3. Science as a process, not a body of knowledge (2:57)

[DR. ORESKES:] Well, good morning. It's very nice to be here with you today. And thank you all for coming and thank you to Howard Hughes for inviting me to give this lecture. As you

heard there my name is Naomi Oreskes and I'm a historian of science. The work I do is a little bit different from some of the other kind of work that you'll be hearing about today and tomorrow. I don't do primary scientific research, although my original training is in earth science. I study the development of scientific knowledge. I study how scientists learn about the natural world, how they judge and evaluate evidence, and how they decide whether or not a claim can be justified by that evidence. So one of the things I'm interested in is a kind of paradox in science education or an irony about scientific education, and that is that when we teach science to our students we tend to teach it as a body of factual knowledge. We give exams, examinations that have definite right and wrong answers. But in reality science is much more complicated than that. And in fact the word science, the word we use, science, describes really two rather different things. We use the word science to describe a body of knowledge-- facts, theories, hypotheses-- that we believe are known to be true but we also use the word science to describe a process, a process of investigation and discovery. And one of the things we know from the history of science is that science on the right, the process of investigation, can alter, change, and in some cases, even refute science on the left. That is to say new investigation can lead us to realize that things that we used to think were true, maybe now we need to rethink. And so as a historian of science I'm interested in that process and I'm interested in how we learn new things that in some cases displace what we previously thought was true.

4. Building scientific knowledge is a community effort (4:49)

Now we also often teach history of science as a story of great scientists but great scientists are not the whole story. In fact, as a historian I would argue that they're not even the most important part of the story. So we can respect great scientists like Marie Curie and Charles Darwin and E.E. Just-- it's interesting to learn about them as individuals, to understand their lives-- but it doesn't actually tell us very much about how and why we believe the things we believe about the natural world. For that we have to expand our scope and look at the scientific community as a whole, because building scientific knowledge is a community effort. An individual can make a claim, they can suggest a hypothesis, but it doesn't become knowledge. It doesn't become scientific knowledge until it's accepted by a community of scientific experts.

5. Scientific methods come in many forms (5:40)

Now we also talk a lot about what some people will call the scientific method. As a historian I would say that that's a misconception, that there is no scientific method, and there is no recipe that scientists generally and routinely follow to do scientific work. Rather, we would say, historians would say, there are many different scientific methods, and some of those methods have changed over time. Now you have probably learned about hypothesis testing and experimental design and for sure, some scientists do follow that method, but there are many other things that scientists do. And in the earth sciences which we're talking about today and tomorrow, and in which I was trained, scientists don't really do a lot of hypothesis testing most of the time. In general they tend to make observations of the natural world and try to make sense of what they see.

6. Scientific knowledge requires consensus building (6:34)

So what we call knowledge is really the consensus of the scientific community. Scientific knowledge emerges when you, as a scientist, convince your peers, your fellow scientists that your claims are convincing. And so if we really want to understand scientific knowledge and especially if we want to understand scientific knowledge as a basis for decision making about complex social questions, we need to understand the process by which scientists come to consensus.

7. Animation: Plate tectonics: The unifying theory of modern earth science (7:03)

In earth science, the unifying theory of earth science is the theory of plate tectonics. Virtually every earth scientist working on the planet today accepts the theory of plate tectonics as the unifying theory that explains many of the major features of how our planet operates. So in a moment I'm going to show you a video that explains some of the basic features of contemporary plate tectonic theory as you may have already learned in school or you will learn if you take university-level earth science courses. So the basic concept is that heat inside the Earth drives motions. We have convection currents through which heat is dissipated from the interior of the Earth. Those convection currents then have an impact on what happens at the surface. So as the convection currents rise, the surface of the Earth is actually fractured or ruptured, and portions of the Earth's surface spread away from the rising convection current. That spreading drags the surface of the Earth along and eventually back down into the interior of the Earth in what we call subduction zones. And this also drives the motion of the continents, what is sometimes referred to as continental drifts. Sediments can accumulate on the continental margins, they get incorporated into mountain belts, and then melting of the slab or of the mantle above it can lead to volcanoes, such as we find in the Andes in Chile or Mount St. Helens on the west coast of the United States. If we back off and look at what this looks like on a planetary scale we see that the whole planet can be divided into a series of fragments which we call plates and it's the motion of those fragments, those plates, that explains earthquakes, volcanoes, and a host of other features about the planet that we live on. So that's the essential theory. It's completely accepted by earth scientists today. It's considered entirely non-controversial. You would be very, very hard pressed to find any working active researching earth scientist who would tell you that that's not a basically correct account of the Earth's processes. So we call it the unifying theory of earth science. It accounts for Earth's history in many respects, including the distribution of life and past climate change. I'll say more about that in a moment. It explains the distribution of geologic hazards like earthquakes and volcanoes and it also tells us where to look for valuable resources like coal, minerals, oil, and gas.

8. Historically, continents were thought to be fixed in position (9:30)

So how did the theory of plate tectonics develop and become accepted, because scientists didn't always think this about our Earth. In fact, prior to plate tectonic theory, if we go back 80 or 90 years, there was no consensus in earth science about how the major features of the Earth developed. There was no generally accepted, unifying theory. However, it is the case that most people, most earth scientists, geologists, and geophysicists did not think that continents could move long distance. Yet today, we not only accept it, we accept it as an established fact that

continents move. So what was this process by which this change in thinking came about? What is the process by which scientific knowledge was built leading to the theory of plate tectonics? Well, if we go back to the early 20th century we find that most American scientists believe that continents were fixed in their lateral positions; that they did not move horizontally. And mountain belts were thought to result from the differential cooling of the Earth. So it was thought that the Earth did move but not horizontally, it was thought that the Earth moved vertically. The Earth was cooling as it contracted it shrunk, and the parts that shrunk the most formed the ocean basins, and the parts that had shrunk less would form the high mountain ranges. So people imagined there might be small amounts of horizontal displacement along the boundaries but mostly people thought that horizontal displacement was minimal compared with vertical displacement.

9. Demo: Principle of Isostasy (11:04)

Now, there was one complication in the story that came from some observations made in Scandinavia. It was evidence that the area of the Earth beneath the crust, what today we call the mantle, was plastic. And the evidence came from an area in Scandinavia known as the Fennoscandian shield, where geologists mapping geological features, such as old fossil beaches, had found evidence that the entire area of Fennoscandia had been rising upward since the end of the Pleistocene glacial period. And the question was, how was that possible? So they developed a theory, known as the theory of isostasy, to help explain how that could be. So the basic idea was to imagine that the mantle beneath the crust was not rigid; it wasn't hard as rock but it was actually soft or plastic. So if you pressed on it, if you deformed it, if you loaded it somehow, it would deform and then you would see that deformation, and then over time the mantle would gradually recover, like this memory foam. So now imagine an ice age. Imagine this is the Earth, this is the solid Earth and the continents, here's the ocean next to it, and now here's a slab of ice. And I'm going to start loading the continent with ice, and you'll see that as I load the continent with the weight of ice, the continent begins to sink underneath this weight of ice. And as I add more and more ice, as we reach the peak of the glacial maximum, the continent deforms more. So those of you in the front can certainly see it but I think you can see it on the sides too; the continent is actually sinking down under the weight of the glacial ice. So even though it's rock, even though it's hard as rock, it's not actually that hard. It's actually somewhat soft and plastic. Now imagine the glacial period is coming to an end. The ice begins to melt. It's as if I am removing the ice--the weight of the ice is being removed from Fennoscandia and watch what happens to the mantle beneath the crust as I remove the weight of the glacial ice. I'm also getting a little bit of good arm exercise today. So here we go and now you see that the mantle has rebounded. So Fennoscandia gradually returns to the former level that it had before we weighed it down with ice. Well, that was important because it told people that their intuitions about the interior of the Earth might be wrong. We think of rocks as being very hard and solid, but in fact they can be soft, malleable, and plastic, rather like this memory foam.

10. Wegener's evidence for continental drift (13:44)

So one of the people who was quite impressed by this evidence and was thinking a lot about what it meant, was a German meteorologist and geophysicist named Alfred Wegener. And

Alfred Wegener in 1912, exactly 100 years ago this year, first proposed the theory of continental drift. He argued that if you looked at geological evidence from around the globe it supported the idea that some time ago, maybe 200 or 250 million years ago, all of the Earth's continents were united in one supercontinent called Pangaea and that gradually over time Pangaea had broken up and the continents had drifted into their present position. So the hypothesis was that there was this supercontinent and it had broken up. If you asked yourself, well, what would the consequences of that hypothesis be, Wegener said, well, in fact, we see a lot of evidence that those consequences are in fact correct. For example, geologists who had mapped the distribution of fossils around the globe, had noticed that extremely similar fossils, in some cases identical fossils, had been found in totally different places around the globe. So there were fossils in Australia that were identical with fossils in South Africa or South America, even though they were thousands of miles away. But Wegener said, well, if the continents had all been united once upon a time, that would explain why the fossils were the same, because the animals and the plants could have migrated easily around this supercontinent, and then subsequently when the continents broke up they would have been separated. And similarly geologists had noted that very similar, in some cases almost identical, rocks were also found in widely separated continents. For example, certain coal beds in the Permian across the globe. And again, Wegener said this could be explained if the continents had previously been united. Finally, the evidence that Wegener liked the best had to do with glaciations, had to do with ice. Wegener was a meteorologist. He had a great interest in the question of paleoclimate change and he also noticed that glacial deposits were found in various places around the globe including places that today are equatorial, where we would never expect there to be glacial ice. And again, he said we could make sense of those glacial deposits if the continents were previously connected, and some places that are today equatorial were, in fact, at high latitudes in the past.

11. Animation: Continental Movement Over the Last 200 Million Years (16:20)

So here's a video to illustrate what this could look like. So here we see the supercontinent about 200 million years ago and then it begins to break up. And as it breaks up you see the continents begin to be separated. You can see Africa separating from South America, and gradually over the course of about 150 or 200 million years the continents come to their present configuration. Now I want to roll that video again in just a moment but this time put your eye on some spot, some place on Earth, it doesn't really matter where it is, but maybe someplace that's near the equator 200 million years ago and then let's watch and see where that spot ends up. So here we are again, so just find a spot to watch, any spot you like, and now watch as it moves across the face of the Earth. And you can see that many places are really changing their position with respect to latitude, so things that were previously equatorial can become high latitude and vice versa.

12. Demo: Isostasy Is Key to Understanding Continental Drift (17:22)

So Wegener's argument then was that this hypothesis could explain an enormous amount of diverse geological evidence, evidence that geologists around the globe had collected over a long period of time. Moreover, if we return to our idea of isostasy, he says, an isostasy can explain how it happens, because in fact, if the mantle is plastic, if it's malleable, if it deforms under

pressure, and I can squeeze it and move it around and do different things with it, well, then imagine a continent. A continent could actually move if the mantle on which it's sitting we'll put it more on top because it's more like this really-- that continent could begin to move because the mantle underneath it is not actually rigid. And so those were the essential features of the argument that he made in 1912.

13. Despite evidence, continental drift was initially rejected (18:13)

He developed it then over the next eight or ten years, so by 1920, Alfred Wegener had provided and summarized extensive evidence to support the theory. He had a mechanistic explanation for how it could happen, drawing on the principle of isostasy. He communicated his theory very well-- his book was translated into several different languages including English-- and it was widely discussed around the globe. But it was mostly rejected, particularly here in the United States. And so even though it was first proposed in 1912, it was not broadly accepted until about 60 years later, 50 to 60 years later. Today we would say that Alfred Wegener was a visionary, and indeed, as you saw, he has a postage stamp made with his likeness on it. We might even say that he's a scientific hero. So why was continental drift rejected and what did it take scientists to convince them that the idea was correct?

14. Q&A: Why was all of early Earth's land in one place? (19:13)

I'm going to stop here now and take a few questions. Yes, in the front.

[STUDENT:] When Earth first started to form mountains why was all the land in one area?

[DR. ORESKES:] Okay so it's not when the Earth first formed. So Wegener's theory only goes back about 250 or 300 million years, which is the period for which he had abundant geological evidence. He doesn't really address what happened in the early history of the Earth and maybe Andy will say more about this in his next lecture. But the early history of the Earth is more complicated and so the initial theory doesn't really try to address that. Yes?

15. Q&A: Why do the continents changes shape as they move? (19:49)

[STUDENT:] You said that the land can move but how do you explain that change in shape, like, the United States if you look at it as it moves, it turns into a whole different shape...

[DR. ORESKES:] It doesn't actually change shape. One of the basic concepts of both Wegener's idea and later plate tectonic theory, is that the plates themselves are rigid and don't change shape. In that video we saw, they appear to be changing shape, because at the same time that they're moving, sea level is also changing. So the outlines of the continents can vary depending on how high sea level is, so they can appear to look quite different, but the basic outline of the continent, the basic configuration, actually the shape is not really changing at all. Yes?

16. Q&A: Is the mantle solid or liquid? (20:31)

[STUDENT:] Would you argue that the mantle is closer to a liquid or a solid?

[DR. ORESKES:] Ah, well, that's a great question. Of course, this was a topic of great argumentation in the 1920s, because some people thought that Alfred Wegener was saying that the mantle was liquid. And they argued against that because there was early evidence from seismology that that was not correct, because seismic waves were being propagated through the mantle, and if it was entirely liquid then you wouldn't have seismic wave propagation of the type that you did. But that was not actually his argument. Wegener never argued that the mantle was entirely liquid. What he argued was that it was plastic. That it had some kind of malleability and exactly what that malleability was and exactly how it was created, he didn't really know and no one did, he and others discussed the possibility that it was partially molten, which is what we would say today, but his basic argument is essentially an empirical one. He says we know that it's malleable because of the evidence from the Fennoscandian uplift, right? Because there's no way to explain why Fennoscandia would be depressed and then come back up if it weren't malleable. So the word that he used and it was widely used at that time was plastic and he talked about the plastic substrate. It's not until quite a bit later in the 1950s and '60s that we begin to get more seismic evidence about the composition of the mantle and even today, there are aspects of it that are still not fully understood, but today we would say that the mantle is partial molten, so it's actually a mixture of solid... soft solids that are close to their melting temperature and then some degree of actual molten rock. Yeah, in the back?

17. Q&A: Can we predict future locations of the continents? (22:08)

[STUDENT:] Can we use our observations of the last hundreds of millions of years to predict how the continents are going to shift in the next million or hundred million years?

[DR. ORESKES:] Yeah, some scientists have done it. There's actually an atlas that's been produced which is a very strange thing for a geologist to do because, you know, I was trained as a geologist; we don't make predictions. We just study the past and of course, historians would say the same thing. I'm always asked as a historian what I think is going to happen in the future about various issues, and I always say I'm an historian, I don't predict the future. But actually there are geologists and geophysicists who have taken the present plate motions and their orientations and projected them out in time, into the future, to make maps of what the world might look like 10, 50 100 million years from now. It's a speculative argument. Of course no one really knows for sure and I'm not sure what practical value it has since I don't expect most of us will be around 50 million years from now, but if you're interested in that, that atlas does exist, and it's kind of fun to look at. Thank you for those questions.

18. Subduction: A possible mechanism for continental drift (23:12)

Alright, so we left off with the question of why was continental drift theory rejected if this essential point is one that we would nowadays say is correct, and what did it take to convince scientists? So, many people have said that the reason continental drift was rejected was because there was no mechanism to explain how the continents moved, and indeed, this is what I was

taught when I was in college. But it turns out that that claim is wrong. The short answer to that question is no. There was a lively debate in the 1920s about what the mechanism of continental drift could be, including whether the mantle was solid, liquid, plastic, or what, and several scientists, several prominent scientists proposed mechanisms, including one important American scientist. That scientist was Reginald Daly who was a Professor of Geology at Harvard University, where Professor Knoll teaches. Daly made the observation that, if you look at mountains-- and he was particularly looking at the Appalachians which were near where he lived and worked-- you can see that the cores of mountains are composed of folded sediments. So any account of how mountains form has to account for how sediments become folded and incorporated into mountain belts. And he argued that maybe that tells us something also about the mechanism of continental drift, so he developed a model that is rather similar to what today we would call subduction.

19. Daly's Model of Subduction (12:37)

So just to point out a few key points, in a moment, I'm going to show you an animation. This is a modern animation that we've created for you to try to illustrate the ideas that were being put forward in the 1920s. Now, obviously Professor Daly did not have videos or animations. I think he would have been thrilled if he could have seen his ideas brought to life like this. But the basic idea, as I've just said, is to try to explain how do sediments get folded, how do they get incorporated into mountain belts, and is that in some way related to the question of continental drift. So we begin with a crust sitting over the mantle and Daly calls our attention in particular to continental margins where sediments are accumulating in areas that geologists call geosynclines, and drawing on the idea of isostasy, he says, as the sediments accumulate, the crust beneath it is depressed and moves down into the mantle. So, in a sense, this is the same idea of the isostasy, right? We're pressing it now but instead of loading with ice, now we're loading it with sediment. So as we load the crust and it begins to sink, it begins to melt. The melting and stress create fracturing, and eventually a piece of that crust could actually sink down into the Earth and be ruptured and fractured and sink down into the Earth where it generates further melting of that slab. So this is his idea of how pieces of the crust can move back into the Earth. Now, I'm going to run the video a second time but this time I want to call your attention to what's happening at the surface, how the sediments get folded, and how this could be a mechanism of continental drift. So again, we're looking at the crust. We have rivers bringing sediment towards the continental margins. The sediments are accumulating but now watch what happens to the sediments as they accumulate. The crust is fragmenting, it's rupturing, but now as the crust sinks, we begin to see, as the slab slides, it actually drags the overlying mountains with it, and as those mountains begin to slide downward, following the slab, they compress the sediments, so we end up with a body of folded sediments on the continental margin, and meanwhile, the whole crust has moved, in this case towards the east or the right, and so that could in fact explain how large slabs of crust, continental crust, can actually move across the surface of the Earth.

20. Another model for continental drift based on convection (26:58)

So that was one model. That was published in 1926. It was widely discussed by American scientists. Meanwhile in Europe, other scientists were also approaching the question, and one of

them was a scientist named Arthur Holmes. Holmes was a British geologist who had done a lot of work related to the discovery of radioactivity and in particular Holmes had made the observation that radioactive elements are quite common in several rock-forming minerals like feldspars and micas, and these minerals are distributed throughout the Earth, so therefore radioactive elements are distributed throughout the Earth, and they generate heat. And so one of the questions he asked was, well, what happens to that heat as well as other sources of heat within the Earth? And he argued that heat from radioactive decay or other sources could cause convection currents and those convection currents could drive continental drift, could drive the motion of the continents.

21. Animation: Holmes's Model of Convection (27:58)

So, here again, we've taken Holmes idea-- this was also published in the 1920s-- and we've made a modern animation to illustrate the basic concept. So Holmes is going to argue that convection currents in the mantle, in the plastic mantle transfer heat towards the surface, and as the convection currents rise and spread out, they can drag along pieces of the continental crust above them. So here, imagine a piece of continent sitting above the mantle, convection current heat is rising and being dissipated, and as the heat rises, the crust is fractured above the convection current, the limbs of the convection currents drag the sections of the continent both to the east and the west and now you see how this becomes a mechanism for continental drift.

22. Why was the theory of continental drift rejected? (28:43)

So if we take those two theories and put them together, we essentially have a picture that is quite similar to, not exactly identical, but quite similar to the modern concept. We have Holmes giving us convection currents as a basic driving force, and we have Daly giving us a model of subduction and deformation of sediments at the surface. And essentially if we take this picture, shrink it down and put it right there on the edge of the continent then we have an integrated theory that is very close, pretty close to the contemporary understanding of what actually happens. So if it wasn't the mechanism, if people actually already understood that convection currents could explain continental drift, then why was continental drift rejected? Well, it's sometimes said that there was a consensus in the 1920s against continental drift, but that's not quite right. In reality, if you look closely at the debate at that time what you see is that the scientific community was divided. Here in the United States it was mostly rejected, but in Australia and south Africa there were a number of people who accepted the theory or believed it was probably true, and in Europe most scientists were reserving judgment. So how do we account for this difference? We like to think of science as being universal and objective. We don't really expect scientists in America to have very different views of matters than scientists in Europe, and yet we see at this time that they did. Well, if we look at the scientist's own letters and field and lab notebooks and writings from this period, which is what I do as a historian, what we see is that the European scientists had a very different approach to science and what they thought scientific method should look like. In general they tended to advocate a deductive approach to science. In a moment I'll say more about what I mean by that. And they viewed the scientists as an authority figure-- that a famous or important scientist was an authority on the issues that he spoke about. Americans, in contrast, had a different vision of how science should operate. They preferred to see scientists operate inductively and they believed that rather than

being based on the authority of an expert individual, that science should be really more democratic, rather like the United States itself. And so they made a connection between the political aspirations of a democratic society and a kind of democratic model of doing science.

23. Inductive versus deductive approaches to science (31:12)

So what exactly do I mean by deductive and inductive? Well, the deductive model of science is one you've probably been taught in school. Sometimes it's taught as THE scientific method. Sometimes it's called the hypothetical deductive method. Philosophers like to give things fancy names-- they called it the deductive nomological model. Nomological means having to do with laws, so laws of nature. So in the deductive model we take a theory, a hypothesis or a law and we deduce its implications, we deduce its consequences. Then we go out into the world or the laboratory and we design an experiment or set of observations intended to see whether or not those consequences appear to be happening in the world. If those consequences, those deductive consequences, appear to be correct then we say that the theory is supported or confirmed. If on the other hand those consequences don't seem to hold up, then the theory must be rejected, or at least modified. In contrast, the inductive model of science is more bottom-up. In the inductive model scientists go out into the world, they make observations, they may do experiments, they collect data, and then they gather it all up and try to summarize it into some kind of general theory that explains what they have observed.

24. Rejection of continental drift: Politics and science (32:28)

What we see in the continental drift debate is that scientists' political philosophy affected their scientific philosophy. That American scientists preferring and being proud of American democratic traditions wanted to see a science that reflected that democratic aspiration. And so they advocated and used the inductive method seeing it as more democratic and appropriately anti-authoritarian. This played a major role then in the criticisms of continental drift theory at that time. That could be viewed as somewhat upsetting because we'd like to think that science isn't affected by politics. But the good news is that the story doesn't stop there. That despite the rejection of continental drift theory by most American scientists, work still continued both here and abroad.

25. Hess's work on gravity anomalies supports continental drift (33:20)

And one of the people who continued to work on the problem was a young scientist named Harry Hess. And in the 1930s Harry Hess and his colleagues began to work in the Caribbean where they measured the gravity field in the Bahamas, and they suggested that their data might support the idea of continental drift. What they found was that there was a very significant negative gravity anomaly. That is to say, if you measured gravity in the eastern Caribbean, in this area over here to the east the gravity field there was much less than in the rest of the Caribbean. And so they postulated or hypothesized that you could explain that if there was a bulge in the Earth under that negative gravity field. So again, again getting back to the idea of isostasy, hypothesizing a bulge or a depression, a depression at the surface that would be reflected by a bulge underneath, and that that could be explained if, for example, there was continental drift-- let's move this out of the way for the moment—imagine if the Caribbean

plate is actually moving from west to east and as it moves, the crust adjacent to it gets deformed, and on this table it's moving upward because there's nothing to stop it from moving upward, but it could also deform downward. Well, I can't do this very well on this table, but imagine it's basically, it's something...something like that. Okay? So that's the basic idea and they argue that it could explain why you get a negative gravity anomaly but if you notice this picture here, it's caused by this piece of the continental crust moving in that direction. So this was published in 1933 and about a year or two later Harry Hess connected the idea. So he developed the idea in the Caribbean, working in the Caribbean, but he connected the idea to the rest of the world as well. He didn't think that the Caribbean was just something weird. He saw this as something that could explain geological patterns globally. And particularly he connected it to work that had been done by Dutch colleagues in Indonesia, where a similar gravity anomaly was seen adjacent to an area of very, very active volcanism. And so they began to argue that island arcs, volcanism, deep trenches in the ocean, earthquakes, and gravity anomalies could all be a reflection of moving continents.

26. Data from geomagnetism and seismology also supported continental drift (35:43)

So that makes it seem like around 1933, 1936 scientists were pretty close to where we are today. But then life intervened. World War II broke out and Hess and many other scientists became involved in war work and the question of continental drift really got dropped for the better part of 15 or 20 years. After the war, however, two new areas of research emerged, supported by the U.S. military, originally for reasons that had nothing to do with continental drift or plate tectonics. One area of research was geomagnetism. The U.S. Navy became very interested in the Earth's magnetic field because of the use of magnetism to detect submarines, particularly Soviet submarines during the Cold War. The other area was seismology. The U.S. government also became extremely interested in seismology because it turned out that seismologists were able to figure out the difference between an earthquake and a nuclear weapons test. These two areas of investigation led to two very important discoveries. One of those discoveries was the discovery of magnetic stripes on the sea floor. Now maybe some of you have learned about this in your high school earth science class, but in the late 1950s scientists measuring magnetism, mostly in the Pacific Ocean, mostly on behalf of the U.S. Navy, well, entirely on behalf of the U.S. Navy, discovered that the magnetic field of the ocean looks like this. It's striped. Now, by striped we don't mean that it's actually black and white; it's magnetically striped. When rocks form, if an igneous rock crystallizes, the minerals in that rock become aligned with the prevailing magnetic field at the time. So what they saw was that these were stripes of rock, some of which were aligned with the current magnetic field, but some of which were the reverse as if the magnetic field was the opposite of what it actually is. Well, just about the same time, some scientists in the United Kingdom explained why that could be. They discovered that the Earth's magnetic field periodically reverses itself; the North Pole becomes the South Pole and the South Pole becomes the North Pole. And this happens actually quite frequently-- at least frequently by geological standards-- every 100,000 to a million years. So if you think about Arthur Holmes's model of a splitting ocean floor and combine that with geomagnetic reversals, you can explain how magnetic stripes form. That is, new crustal material is being formed at the mid-ocean ridge above a convection cell, and now...and those rocks form, and they are crystallized in conformity with the prevailing magnetic field, but then there's a magnetic reversal and then the ocean moves a little bit again. The next set of rocks that

are formed at the mid-ocean ridge are now aligned with the reverse magnetic field, and now you repeat that over and over and over again over the course of 50, 80 or a hundred million years, you end up with magnetic stripes on the sea floor. This, people realized, supported Holmes's model from the 1930's and 20's of sea floor spreading driven by convection currents. Meanwhile seismologists were studying earthquakes and seismic activities related to nuclear weapons testing, and one of the things they discovered is if you study deep earthquakes, the very deepest earthquakes that originate from deep within the Earth, you find that they only occur at a very small number of regions around the Earth. They only occur in rather specific bands, which include the Indonesian archipelago, which Holmes had talked about-- a very strong band of deep focus earthquakes around Indonesia, but these other bands as well. These deep earthquakes could be explained if there was subduction similar to what Daly had proposed in his model.

27. Plate tectonics and continental drift accepted (39:36)

So at this point Harry Hess, who was still alive, and a number of other scientists connected the dots, and they realized that if you put all these pieces together-- the earthquakes, the volcanoes, the sea floor spreading-- you could come up with a theory which today we call plate tectonics. Now the great historian and philosopher of science, Thomas Kuhn, once said that you know that scientists have had a scientific revolution when they rewrite their textbooks, and that happened in 1973. So in 1973 the first textbook was written that explained geology and Earth history in terms of plate tectonics. It was a totally different way of writing a textbook than had been before, and this was the textbook that I used when I went to college in 1976, back in the Pleistocene.

28. The nature of scientific consensus (40:24)

So what do we learn from this story? Why is it important to study the history of science? One of my students once said "Why do we have to study a bunch of old ideas that aren't even true anyway?" Well, the reason is because we learn a lot about scientific knowledge when we study its history, and one of the things that we've learned is that scientific consensus takes time. Plate tectonics was not developed in a "eureka" moment. It took 40 years to gather enough evidence to convince scientific community. So time matters, because it takes time to do work. And our conclusions may change and our views may evolve as we learn more about the natural world. But if scientists have been working on something for a long time and if they have reached a consensus and if they do agree, then that's a pretty good sign that the conclusions are likely to be robust for some period to come. Moreover what's really important are the data, particularly in earth science, but I would argue in other fields as well. What leads scientists to consensus is the amount and the consistency of the data. When the data don't agree, or one set of data seem to be pointing one way and one set of data another way, then scientists will continue to do more research and argue about it, but when all of the data add up, then that's when we begin to see scientific consensus emerging. That said, it's important to recognize that no consensus is ever 100%. There are always some people who disagree and that's fine, but the question we need to ask if we're judging those claims is, what is the evidence to support it.

29. Science is not about “proof” (42:00)

And finally, I would argue that science is not about proof. Plate tectonics was never proved in any logical sense. Indeed, it wasn't until many years later that scientists actually figured out how to measure the motions of the continents directly. But what plate tectonics did have was a great deal of data, and the data all fit together in a highly convincing way. Still, there are some things the theory can't account for, like earthquakes in Virginia. But the important point that I hope you'll go home with, and we'll talk about more tomorrow when we talk about climate change and global warming, is that a demand for proof is a demand that cannot be met.

30. Q&A: Why do magnetic reversals occur? (42:42)

So let's stop there and take questions.

[STUDENT:] Why does the magnetic reversal occur in the Earth?

[DR. ORESKES:] Ah, that's a great question. No one really knows. It's one of the outstanding mysteries. So we know that the magnetic field originates in the Earth's core, which is partially liquid-- this gets back to the question about the interior of the Earth-- and so we know that motions in the liquid core generate a magnetic field, but exactly how and why that field reverses is not known. What we do know is that it doesn't just switch, it doesn't just flip like a switch, but the magnetic field actually dies out and then it rebuilds itself in the opposite direction. So there's a brief period during the magnetic reversal where there's actually no magnetic field at all and some people think that has consequences for the history of life on Earth but that's Andy Knoll's department.

31. Q&A: Has there been a time when the continents did not move? (43:34)

Did you have a question?

[STUDENT:] Yes. Is there a time when the processes described and theories of subduction and convection, like, not actively occurring?

[DR. ORESKES:] You mean in Earth history?

[STUDENT:] Uh-hmm.

[DR. ORESKES:] Well, that's a really good question. Again, I might have to defer that one to Andy. Certainly in the very early history of the Earth, when the Earth was first forming and very, very hot...you have to correct me if I'm right about this now...this is a long time since I've studied...I don't really work in the Archaean but when the Earth was first forming, it hadn't differentiated. Now we say we have a crust, a mantle, and core, right, but the very early history we didn't have that and that's why the Earth is...we believe the Earth is 4.5 billion years old, but as Andy was telling you earlier, the oldest rocks are only about 3.8 to 3.9 billion years. And that's because the whole earlier history of the Earth was wiped out during the Earth's differentiation. So that early history, older than 3.8 billion years, we don't believe that plate

tectonics was happening at that time. So plate tectonics really described the history of the Earth after its differentiation, consolidation and some degree of cooling.

32. Q&A: Can we predict the next magnetic reversal? (44:45)

Yeah, in the back.

[STUDENT:] Do we know when the next magnetic reversal is due to occur or when the last one was?

[DR. ORESKES:] No, I don't know...I actually don't know either of those. I think the last one was like 40,000 years ago. Do you remember? Do you know? A hundred and ten? Okay. It's in the scale of tens of thousands of years. I don't know. See? This...But no, no one knows when the next one will occur and no one could really predict it, because as I said, we don't really know what causes the magnetic field reversals, and since we don't really know what causes them we can't really predict when the next one would occur. If it did occur while we were here, though, that would be a bad thing, because during the period when the magnetic field declines, we get more cosmic radiation bombardment, because the magnetic field protects us from cosmic ray bombardment. So if we were here during a period of zero or very low magnetic field that would be a bad thing but it's not likely to happen any time soon.

33. Q&A: What are gravity anomalies? (45:44)

Yeah?

[STUDENT:] Earlier you talked about gravity anomalies. What exactly are they?

[DR. ORESKES:] Good point. Actually I was talking about that and I thought wait, if I had more time I should explain that. Right. So the Earth has a gravitational field, but if you measure gravity at any given place, it's not the same. And there are a lot of different things that can affect the gravity that we measure at any one place, and an important...one important element is what the rocks are beneath our feet. So if the rocks are high-density rocks, the gravitational field will be greater than if they are low-density rocks. The reason why Hess believed that there was...he could explain the negative gravity anomaly through that bulge-- remember the picture that shows the crust bulging downwards so the crust, so imagine this is the crust, not the mantle, right? I don't have a flexible crust here. The crust of the Earth is less dense than the mantle, so if the crust is thickened, then you have more low-density rocks beneath your feet. And so those low-density rocks create a negative gravity anomaly. If you had the opposite, if... I don't want to ruin this, but if I stretched this and thinned it out, just imagine some piece of it that's very thin, then there would be less low-density rock and so you would have a positive gravity anomaly. Gravity anomalies are also used in mineral exploration, which I used to do. Lots of mineral deposits have higher-density rocks because they have things like gold and silver and copper that are high-density materials in them. And so gravity anomalies are used in mineral exploration to find mineral deposits.

34. Q&A: What does “negative gravity” mean? (47:13)

Yeah, right here.

[STUDENT:] What do you mean by negative gravity?

[DR. ORESKES:] Negative just meaning lower than normal. So there's the normal gravitational field, the average gravitation field, the negative anomaly would be that the gravity you measure in that spot is less than normal. Positive anomaly would be that the gravity you measure is higher than normal.

35. Q&A: Does magnetic pole reversal occur gradually? (47:33)

Yeah?

[STUDENT:] When you talk about the magnetic poles reversing, is it a gradual reverse or does it happen spontaneously?

[DR. ORESKES:] Well, it happens spontaneously, right? We don't know what's causing it, but it's not, but it's...but it's not instantaneous. So there's a gradual decline in the field, the field declines to nothing and then it rebuilds with opposite polarity.

36. Q&A: What caused the Virginia earthquake in 2011? (47:56)

Yeah, in the back.

[STUDENT:] Are there theories to why the earthquake happened in Virginia like a year ago?

[DR. ORESKES:] Yeah, we had a long discussion about this yesterday. So one of the things that's very interesting about any scientific theory is that, we consider a scientific theory good if it does a lot of work, if it explains a lot of things, if it makes sense about a lot of things, we like it, we accept it, we teach it to our students, we write textbooks about it. But the reality is that no scientific theory is perfect, and there are always things in our theories that we can't quite make sense of. And Thomas Kuhn called them anomalies, some people will say those are the research frontiers, those are the areas where we learn by doing further investigations. Sometimes scientists pay a lot of attention to the anomalies because they think we can learn by studying them. Sometimes scientists brush them under the rug because we don't know how to make sense of them and we can't figure out a good way to study them. So the earthquake in Virginia is an anomaly. Plate tectonic theory holds that all of the major seismic events on Earth take place at plate boundaries. So if you live in Virginia you don't expect to experience earthquakes because you're not near a plate boundary. The nearest plate boundary to here is the mid-Atlantic ridge that runs through Iceland, so that's, what, 1,200 miles away. Where I live in California, we get earthquakes all the time and we expect them, because we know that we're living near the San Andreas Fault, and we know that that's the western margin of the North American plate. But the reality is that even though the vast majority of earthquakes occur on plate boundaries,

there are some that don't. And there are some regions of the Earth that actually have had earthquakes fairly regularly even though they're not on plate boundaries, and one example is the mid-continent of the United States. In the 19th century there was a very, very famous earthquake called the New Madrid earthquake, that was sufficiently large that, for a very brief period of time, water in the Mississippi River went upstream. And people died. Houses fell down and people were killed. That area has had a lot of tectonic activity throughout geological history and so some people think it's a failed plate boundary, that it's a place where a mid-ocean ridge began to start to form, and the continent began to break apart, but then for whatever reason it stopped, and so there's this fracture zone, this rupture that runs through the continent and we get earthquakes there, so it may be related to plate tectonic theory, even though it's not currently a plate boundary, but Virginia is not a plate boundary and it never was as far as we know. Well, it may have been at some point. But so there are things that don't fit in the theory. There are details and of course, those details are places that invite investigation and it could well be that in the future, by studying earthquakes that don't occur on plate boundaries, we will get a better understanding of some of the details and complexities of the Earth. Yeah?

37. Q&A: Is inductive or deductive science more accepted? (50:49)

[STUDENT:] Today do we support inductive, deductive...

[DR. ORESKES:] Ah, great question. One of the reasons why I found this investigation and story so interesting is because in the United States...I mean this is a complicated question so this is a generalization and some people would take issue. Lots of scientists have different opinions about this question, and scientists will give you their opinions about what they think constitutes correct scientific method, often with great enthusiasm and vigor. But in general, in the United States there's been a reversal. So just as we've had magnetic field reversals, we've also had philosophy of science reversals. So I would say that it's fair to say that most American scientists today tend to prefer deductive science. They tend to think that science should follow the hypothetical deductive method, and if you write a grant proposal you should have a hypothesis, and then you should explain how your experiments are going to test that hypothesis. And indeed, there are a number of granting agencies that actually require scientists to do that. And when I was in graduate school I had professors who told us that we should not do inductive science. So that was partly why I got so interested in the story, because I thought, it's not just that our scientific knowledge has changed, it's also that our beliefs about scientific knowledge have changed as well and our beliefs about how we get knowledge have changed and I thought that that was in some ways even more interesting than the change in the knowledge itself. So I'm interested in both in how the knowledge has changed but also in how our beliefs about knowledge have changed over time as well.

38: Q&A: Is the process of inductive science still used? (52:23)

Yeah?

[STUDENT:] You described in detail the process of deductive reasoning, gave a chart and a step-by-step but...how does the process of inductive reasoning work step-by-step and is it still being applied in some areas?

[DR. ORESKES:] Yes. The answer to the second part is definitely yes. I mean there are definitely still scientists who do inductive science. I would argue a lot of planetary science is inductive because there's so much we don't know about other planets that, when we send an instrument to Mars to collect data that a good chunk of that is essentially inductive, and certainly there's a lot of data collection being done today by oceanographers. Where I teach at the University of California, San Diego, we have big, big programs and instruments in the ocean to collect large-scale data on a lot of issues. Some of it is hypothesis-driven but a lot of it isn't. So, it's not the case that inductive science has been eliminated, and there are certainly people who will still make the argument for why basic data gathering and basic observational work is essential, even in the absence of a specific hypothesis that you're testing. And I'm sorry, I forgot what the first half of the question was.

39. Q&A: How does inductive science work? (53:29)

[STUDENT:] So, you kind of described the process of deductive reasoning with hypotheses and how does the process...

[DR. ORESKES:] How does it work? This is a very good question because of course this was the question that the critics of inductive science raised. So there's a very, very long argument in the history and philosophy of science. It goes back to Isaac Newton and Francis Bacon and the foundations of what we could call modern science. The early advocates of scientific research, people like Newton and Galileo and Copernicus and Francis Bacon were all inductivists. In fact, Newton thought that a hypothesis was a form of prejudice, a form of bias and he very famously said, when he was asked about gravity and he was asked, well, how do you explain gravity, he said, "I don't make hypotheses," right? And he just washed his hands of it. It's hard for us to believe this now and, I mean, I hope the Howard Hughes people are listening to this, because you know, if a lot of scientists just say "I just want to collect data," a lot of people today would say "Well, you can't do that, you have to have a hypothesis, you have to tell us what hypothesis you're testing." But, that wasn't how Isaac Newton thought about it. So... But then the question was raised, exactly the question you raised, okay so if you've gone out into the world and you collect data, you know I'm going to start collecting data, right? So here's my data and I'm collecting it and now I'm getting this heavier and heavier and heavier weight of data, right? And I'm carrying around all this data, and now I'm going to make sense of it, right? And I have this load of data, right? So how do I suddenly, magically transform all this data into a theory? And so people started talking about the inductive leap, that it seemed sort of illogical. There wasn't any step-by-step explanation that you could give for how you got from the data to the theory. And so people began to criticize the inductive method for being not really logical, that there was no logical account. It was sort of like "...and then a miracle occurs," right? Then there's this sort of magic trick you do to transfer the data into a hypothesis or a theory that explains it. And so that's one of the reasons that some people began to say "No, deductive science is better." Because if you have a hypothesis and it makes you make predictions and then you test those predictions, well, that's logical. Then we know what you're doing, and we can evaluate it and we can judge it. So the advocates of deductive science argued it was better logically. The advocates of inductive science said, well, they said it's what Newton did and he did pretty well. There was some good precedent for doing inductive science. Darwin was

largely inductive. I mean, if you've ever read *The Origin of Species*, you know there's a lot of data in that. Huge amounts of empirical evidence and Darwin took a really long time to write that book, in part because he was taking this very inductive approach. So it's a longstanding argument in the history of science and the lesson I take from it is, let a thousand flowers bloom. There's been good inductive science done in the history of science, there's been good deductive science done. There's been bad inductive science and then there's been bad deductive science and to me the real question is again, it gets back to the data; what is the evidence? Is it persuasive? And whether you got it through induction or deduction, in my opinion, it doesn't really matter. So, thanks so much.