1. Beginning of Lecture 1 (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 first lecture is titled: The Deep History of a Living Planet. And now, a brief video to introduce our lecturer, Dr. Andrew Knoll.

2. Profile of Dr. Andrew H. Knoll (1:12)

[DR. KNOLL:] In the broadest sense, I'm interested in how the world that surrounds us today came to be. And we've known for a long time from the fossil record that the species that we see around us, in forests, in the sea, are not the same species that inhabited those environments in the past. And what makes it exciting for me is that over the past decade or so, we've learned to read Earth's environmental history using predominantly the chemistry of ancient rocks in a very new way. And that allows us to see how life and environment have interacted with each other through time. We know that we're living at a time of geologically-rapid environmental change. And therefore, knowing how the biota has responded to environmental change in the past may give us a better sense of what could be in store for us over the next hundred years or so. I think it's become clear that we cannot understand the diversity of life around us unless we put evolutionary history into the context of Earth's dynamic environmental history. Equally, we can't understand how life is going to respond to changing environments in the future unless we can understand how biological and physical processes interact. Much of modern science really now works at the intersection of traditional disciplines, and certainly there's a broad range of interactions where biologists need to understand how the Earth works, and geologists need to understand how life works.

3. Earth’s history is recorded in rocks (3:07)

[DR. KNOLL:] It's a real pleasure to be with you all today. In the time we have together I'm going to talk about three topics but all of them derive from a single, fundamental, and to my way of thinking, remarkable fact about the Earth. And that is that we live on a planet that records its own history. From that we learn that there is a history of life that confirms the predictions of evolutionary theory. We learn that the environment has changed repeatedly and markedly through time. We live on a dynamic planet and importantly as we think about our future, we come to understand how life has responded to environmental change in the past; something that may help us as we try to understand what will happen in our fairly immediate future. So, what is the nature of that record? Well, this is my library. This is the Grand Canyon. You've all seen pictures of it; some of you may have visited it. It is a remarkably beautiful
place, but what makes it especially beautiful for an earth scientist is that the layers that we see, one on top of another, are sedimentary rocks; that is, accumulations of sand or mud or calcium carbonate bedded as limestone, that have formed one layer atop the other, over on the order of 250 million years. And each one of those beds records aspects of the biology, the organisms that were present at the time and place that rock was deposited in the form of fossils and chemical records of life. Also the physical and chemical characteristics of those rocks record aspects of the environment when those rocks were deposited. So, with a little bit of training, one can learn to read that history and understand how life and environment have changed through time.

4. North America 20,000 years ago (5:16)

Now let's just take a little bit of time to think about how we actually read this record and we'll start at a time which, in geological sense, isn't that long ago, that's about 20,000 years ago, and the picture you see here is a painting that shows, in a sense, what you might have seen in suburban Washington, D.C. 20,000 years ago. If you look at it, it's very cold, in fact you wouldn't have to go very far north from here to find the southern extreme, a vast ice sheet up to 2 kilometers thick. We look at the vegetation: there's a few trees and shrubs in the valleys but mostly the landscape is covered with grass and low herbs. And the animal life is certainly something that you wouldn't expect to find in Washington today. There are these huge elephant-like mammoths; you can see a rhinoceros; there are lions; and a number of other large mammals that are no longer on this planet. So I've made three statements really about Washington, D.C. 20,000 years ago. One is a statement about life, one is a statement about environment, and the third is a statement about time. So you might well ask, how do we actually come to have confidence in those statements? Well, let's take the mammoth as an example and the mammoth itself, no longer with us, but from its bones we know that the extinct mammoth was very closely related to elephants we can study today. So you see a lower jaw in the pictures of a mammoth and here's a mammoth tooth that you can have a look at. The roots on the bottom, and then this grinding surface, much like modern elephants, that allows them to grind woody plants and things like this, and also, if you look over on the table there's actually a larger souvenir of one of these mammoths, it's the femur bone. You can see the head at the top which is what articulated into the hip and by actually studying those bones we can understand a great deal about mammoths and how they made their living.

5. How do fossils form? (7:31)

Now a word about how those remains came to be incorporated in the fossil record. Obviously all fossils start out with a living organism and the living organism, like all living organisms, dies, and after the mammoth died, decay would have set in. Scavenging mammals would have pulled apart its flesh; bacteria, fungi would make short work of most of the soft tissues. However, because the bones are not so easily broken down, they stand a chance of actually accumulating in the geologic record. So that's really the first feature of an organism that gives it a relatively high probability of entering the fossil record; that is having hard parts--bones, shells, wood, things like that. But that's not enough. What has to happen then is that sediments must cover these remains and incorporate it into a sedimentary rock. And then of
course, through later erosion those remains will be exposed again at the surface and can be studied by scientists.

6. How do we know there was an ice age? (8:43)

Now I also made a statement about climate, suggesting that 20,000 years ago we were near the height of an ice age. What allows us to make that kind of statement? And I call your attention just to this picture of the arctic island of Spitsbergen. It's about halfway between the northern tip of Norway and the North Pole, and I show you this because this is a place where there are active glaciers today, and if you look at the bottom of the picture you'll see this train of boulders. In fact it's a train of materials that contains, cheek by jowl, everything from dust-size grains to rocks the size of a refrigerator. Those will get carried by the ice down to the terminus of the glacier and they will then accumulate as a remarkably unsorted group of rocks. That's what we see today where ice is an important feature of the landscape. If we look at rocks 20,000 years ago from the northeastern or north central United States or southern Canada we actually see very similar rocks. So on the left-hand panel you see a coastal shot of Rhode Island and again you can see very large, very small rocks jumbled together, bearing the hallmarks of deposition by ice. On the right you just see this large boulder sitting all by itself in a park in New Jersey. We can actually tell on the basis of the chemical and physical features of that rock where its source was and the source is hundreds of kilometers to the north. It was carried to that spot in New Jersey by ice.

7. Methods for dating the fossil record (10:24)

But how do we know when this happened? If we know there was a time in the past when there were mammoths and glacial ice, how can we put a date on it? And in order to understand that we have to think about the concept of radioactivity. As most of you know, elements come in different forms or isotopes, some of which are quite stable but some of which actually break down into daughter products on timescales that we can actually measure in the laboratory. You've all heard of carbon-14 and that illustrates this process in a way that's actually relevant to dating the events of 20,000 years ago. So carbon comes in three isotopic flavors. 99% of all carbon has 6 protons and 6 neutrons or carbon-12, so-called. About 1% has an extra neutron, carbon-13. But a couple of parts per trillion have 2 extra neutrons— they're carbon-14 and carbon-14 is unstable and will decay to nitrogen. Where does that carbon-14 come from? It's actually formed in the atmosphere by cosmic rays bombarding nitrogen and that produces carbon-14. That carbon-14 becomes part of carbon dioxide that gets incorporated into plants by photosynthesis and then into animals that eat those plants. The bones of the animals, wood from the trees can accumulate in the geologic record and once they accumulate, the carbon-14 begins its slow disappearing act. It will decay to nitrogen, and from laboratory analyses we know rather precisely the rate at which that carbon-14 decays. We know that in 5,730 years, half of the carbon-14 that was originally present in the sample will be gone. Another 5,730 years later, half of what was remaining will be gone and so on. So if we have some idea of the amount of carbon-14 when the object formed and can measure the amount of carbon-14 that's left in the object we can actually put a pretty good date on it.

8. Reconstructing life from 100 million years ago (12:43)
So, in principle then, we can use fossils to give us a sense of life's history. We can use the physical and chemical characteristics of rocks to develop a sense of environmental history and we use radioactivity to actually put dates on these events. And by that same logic train and series of observations we can make, with some confidence, the statement that 100 million years ago, had you been around Washington, you might have seen something like this. Now we have a very different dominant animal on the land-- the dinosaurs-- and again, while we know there are no dinosaurs here today, we actually have their skeletons, which tell us a great deal. This, for example is the tooth of Tyrannosaurus rex, one of the great predators of the Cretaceous period. We can tell it's actually a predator because of the nature of the teeth. Predators tend to have sharp molars like this-- canines rather-- herbaceous dinosaurs that are eating plants tend to have teeth more for grinding, like we saw with the mammoth. Also, we know a lot about the plants, so now we have a woodland and a fairly lush vegetation. And both from the evidence of those plants and from evidence of the chemistry of small microorganisms that live in the ocean, something that my colleague Dan Schrag will talk about in his lecture, we understand that 100 million years ago that the Earth was a great deal warmer than it is today. And of course, we then have volcanic rocks containing minerals that include uranium and it's the breakdown of uranium that gives us these dates of 100 million years.

9. The Cretaceous mass extinction (14:38)

Now we might pause to ask, why is it that we no longer see dinosaurs? And as some of you may know that story is actually a fairly interesting one. It isn't as though dinosaurs sort of slowly peter out through time outcompeted by mammals. In fact, mammals and dinosaurs existed together for something like 150 million years, and for pretty much all of that time, mammals were just little rat-like things that kept out of the way of the dinosaurs. About 65 million years ago the dinosaurs disappear in what appears to be a geologic instant. And when scientists went and looked at the chemistry of the rocks at that moment of extinction, both for dinosaurs and many other creatures, they found evidence that led to the interpretation of that extinction in terms of this: about an 11-kilometer-across meteor hit the Earth causing ecological catastrophe. We actually even know where it hit because if you go down to the Yucatan Peninsula in Mexico beneath younger sediments is evidence of the crater. So this is interesting. What it tells us is that in addition to the processes of natural selection that allow populations to change through time and shape evolution, there are physical perturbations to the Earth's system that operate on short time scales that can actually remove a lot of the diversity that had evolved over millions of years.

10. What was life like 500 million years ago? (16:18)

Well, let's go way back. A hundred million years is a long time. I appreciate that, but let's go back 500 million years. What do we see in terms of life then? We don't see dinosaurs, we don't see mammals, in fact, we don't see any bony animals on the land, but the seas are swimming with organisms, of which the most common and diverse are these organisms that we see in this panel, the trilobites. And again, we have a nice example of a 500 million-year-old trilobite right here. If you look at this, its structure, at least in general, should be familiar to you. It has a segmented body. If you could flip it over you would see it has jointed legs and that actually tells
us very clearly that this belonged to the same group of organisms as insects, lobsters, shrimps, crabs today, that is, the great phylum of the arthropods. A large majority of all the species of animals on Earth today are arthropods. Fossils tell us that was already true in the oceans 500 million years ago. Again, we might ask, so where are the trilobites today? And there are no trilobites today. They were important parts of marine ecosystems for about 270 million years but the last trilobite died during another mass extinction. If we look at this diagram, it's an interesting one. It represents the collective work of thousands of paleontologists over many years, but it's a compilation of the number of different kinds of marine fossils that are found at different intervals of geologic time from the beginning of the Cambrian period, a little more than 540 million years ago, to today, and this measures the number of genera and if you look, clearly the diversity of life in the oceans has increased through time, but the course of diversification never did run smooth. You'll see that diversity goes up and then it drops, it goes up and then it drops, and there's a particularly big drop 252 million years ago at the end of the Permian period. This is the largest known mass extinction-- something like 90% of all the species in the ocean disappeared during this extinction. Unlike the extinction that did in the dinosaurs 65 million years ago, the upper arrow, this extinction seemed to have nothing to do with extraterrestrial input. It just shows that our own planet is capable of producing conditions that are inimical to many forms of life. What happened? Massive volcanism seems to be the answer. If you go to Siberia, you will find something on the order of 2 million cubic kilometers of lava that were extruded over an area maybe half the size of the continental United States very rapidly. That put a lot of carbon dioxide into the atmosphere. We had global warming. It made the pH of the oceans go down, something called ocean acidification. It drove oxygen out of sub-surface water masses in the oceans. If you read the newspapers you know that we are living in an accelerated path entering into a time of global warming, ocean acidification, and oxygen removal from the oceans. So in some ways, this event 252 million years ago is an extreme example that might tell us something about what to expect over the time scale of our grandchildren's lifetime.

11. Earth's history is much older than animal history (20:18)

Let's then ask, how far back can we take this geologic record of animals and the answer is about 580 million years. You see in the left and right panels on the screen the kinds of animals. They're very different from what we see today. They're sort of quilt-like structures that obtain their food by absorbing molecules. Remarkably, we have embryos preserved from that age, as well as that sort of spiky thing in the bottom. We have little cyst-like structures that serve to protect these embryos when conditions for growth were not very good. Some of you will have had sea monkeys sometimes at home, where you take this little powder, put it into water and a couple of hours later you have little shrimp-like organisms swimming around. The powder in the sea monkey jar is actually these little cysts that protect the embryos, then the embryos germinate. So we can trace animals back that far, but in terms of total Earth history there's still a way to go. The oldest geological evidence we have for animals takes us back not quite 580 million years but we live on a planet that is more than 4.5 billion years old. And so what we're going to do in the next session is talk about how far back we can trace a record of life. How long has our planet been a biological planet? What was the nature of environmental history before the origin of animals?
12. Q&A: How does diversity rebound after mass extinction? (21:58)

But before we do that let me just stop and take some questions. Yes, in the red sweater.

[STUDENT:] During crustacean period 90% of the sea animals died. How was it that there are so many now if over 90% of them died?

[DR. KNOLL:] Oh, well, two things happened and it's a question of timescale. We have this extinction event, it removes a lot of diversity, and then we can actually look in the fossil record over the, say, 10 million years following that and what we see is that diversity rebuilds; that is, speciation events occur, and through time, biology is quite capable of reproducing-- not reproducing but restoring the diversity that was there before the extinction. It's not the same organisms. That is, most of the organisms that were ecologically dominant before the mass extinction are pretty much gone, and then new organisms become dominant in their wake. Just like mammals really radiated after the extinction of the dinosaurs to fill in all the ecological niches we see them occupy today. So the good news is that following a major extinction, life can re-diversify. The bad news, at least for us and our grandchildren, is that the timescale of that reconstitution of diversity is tens of millions of years.

13. Q&A: How do historic warm climates relate to global warming? (23:33)

Another question? Yes.

[STUDENT:] You said earlier that the Earth was warmer when the dinosaurs were around. Were you referring to its climate or the Earth itself and can you put that in context of what people refer to as global warming?

[DR. KNOLL:] Good question. I'm really referring to the climate. It turns out you can ask a simple question and that is, if you go outside and look at a square meter of the ground you might ask, how much of the temperature you record on that is going to come from heat escaping from the interior of the Earth, and how much is coming down from the sun as modulated by atmospheric composition. And it turns out that the sun wins a million to one. What really controls the temperature on the Earth's surface is this combination of sunlight and the greenhouse properties of the atmosphere, So yes, I'm talking about a warm climate. We do know that the Earth's interior has been cooling through time, just because some of the heat generated in the Earth's interior is coming from radioactive decay and that's something that will peter out through time. To put it in the context of global warming, we know that the Earth has been warmer than it is today for much of its history. So the problem, at least as far as either life, or economies for that matter, are concerned, is not simply that warmer is better or worse. The problem is one of rate. When things change slowly, organisms can adapt. When things change rapidly, it's very difficult for organisms to adapt. So all of the life we see around us is well-adapted to conditions that we see today. All of our farms and economic systems are adapted to the distribution of climates that we see today. If those change over a million years, everyone can accommodate. If they change over 50 years, it's much more difficult.

14. Q&A: How do you know how much 14C was in an animal? (25:48)
One more question? Yes, ma'am.

[STUDENT:] I understand how you know that carbon decays but how do you know how much was in the animal originally?

[DR. KNOLL:] That's a great question. The question is, I said at least in carbon-14 you have to have some sense of the production of C-14 and how much would have been in at the time the organism was living, and in order to learn that we need to go and look at the amount of carbon-14 in rocks of... in materials of known age. You can think, how will I know the age of something that lived 1,000 years ago? One good way to do it is to look at trees. If you've ever cut down a tree or looked at a tree cut down in the Washington area you'll see it has tree rings. And they actually vary from year to year in a way that allows us to identify different years. And there's a record of tree rings that goes back well over 10,000 years at this point. So we can calibrate it using that. We can also look at corals in coral reefs. And again, corals lay down new bands of growth that show an annual pattern and we can actually look at that through time. So that's really the way you can calibrate and the reason you have to do that is that the rates of C-14 production vary through time. That wasn't known when this technique was first discovered but we now know they vary and we can accommodate it in just that way. Okay?

15. The tree of life suggests that the deep history of life is mostly microbial (27:28)

Okay. Let's get at this question now. What is the deep history of life like? And the first question we have to ask is what should we expect to see? Our expectations for what we should actually look for in these older rocks on Earth are very much conditioned by phylogeny, or sometimes called the tree of life. This is a phylogeny of all life. It presents a hypothesis of the genealogical relationships of all organisms. Basically, all efforts to make this kind of tree of life show that the tree has three major branches. On right are eukaryotes. That is, organisms with cells with a membrane-bounded nucleus like your own. On the left are bacteria, the bacteria of our normal experience. And then, discovered only in 1977, is actually a third major branch of the tree called the Archaea. The Archaea are small, simple microorganisms, but many features of their cell chemistry and genetics suggest that they're actually closely related to eukaryotes. The reason for showing this is that all of that animal evolution that we outlined over the last 580 million years really represents the distal tips of distal branches of one limb. The same thing would be true of plants. So in concept if we want to think about a deeper history of life, the tree of life suggests that that deep history is microbial. Now, that raises an interesting operational question. It's one thing to say that the deep history of life is bacterial but it's another thing to know whether tiny little bacteria can actually leave a discernible fossil record in very old rocks.

16. Microfossils provide a record of microbial history (29:33)

So in order to address that question we're going to take just a mini-field-trip to Spitsbergen, the same island that I showed to show these boulder trains being transported by ice. In fact, here's the same picture I showed before, but now let's look at the mountains between the valley glaciers. These are sedimentary rocks laid down between 750 and 800 million years ago. To give you some sense of the spatial scale here, each of those swatches of gray and white is about
300 meters, 1,000 feet thick. And if we look at the limestones that make up those bands they show evidence of formation under conditions that today we might see in a place like the Bahama Islands. So the answer to why come here? Rocks that predate the oldest animals are well-exposed, so it's a good place to ask about early life. The record is also very well-preserved, and, interestingly when these rocks formed, they were in the tropics.

17. Animation: Arctic Island Was a Tropical Island 500 Million Years Ago (31:04)

This is just a little video to give you some sense of the physical dynamism of the Earth. Obviously if something was deposited in the tropics that is today found at 80 degrees north latitude, something had to change. The reason things change is plate tectonics. Naomi Oreskes will talk about that in detail in her talks, but this is just a little video to show you the odyssey of Spitsbergen through time. We're going to run time backwards. Okay, there's Spitsbergen today and let's see what happens. There is the ice age. You can see the Atlantic is closing up. Spitsbergen is slowly meandering south toward the equator, and by the time of the first amphibians it's in an equatorial clime. Now when those trilobites existed, there it is, and 750 million years ago, it was here. We can make that video largely because of the magnetic properties of rocks which allow us basically to know where pieces of real estate were in the past.

18. A closer look at Spitsbergen Island (31:51)

Okay. Let's take a look at one of those limestones here in the left-hand panel and what you'll see is there is a layering, which geologists will know that kind of swaley, uneven layering is very much the kind of accumulation of carbonate muds that we would find on the right in the Bahama Islands today, particularly where those muds are actually interacting with microbial communities. There's also a little bowing up at the top of the left-hand panel. That kind of structure again is one that is from a buckling of the rocks, which happens in the upper part of the tidal zone. If you look microscopically at those rocks you would see features of cement precipitation that are associated with tidal limestones in tropical environments. The physical characteristics of this rock tell us that it was deposited in something that to a first approximation resembles the coastline of the Bahamas today. But I call your attention to those black pancake structures on the left panel. Those are concretions of silica that's very fine-grained quartz or SiO2. Those actually grew within the sediments soon after they were laid down. That silica basically acts like a plastic almost, to incorporate and preserve textures on a very fine scale within the rocks. If I take a piece of that chert, cut a paper-thin slice, and put it under the microscope, here's what we see. Those are microfossils, only a few microns in diameter, of bacteria. In fact, they are very likely cyanobacteria which are, as we'll see, a particularly important group of bacteria. So that tells us that in principle, we can look more deeply into the history of our planet to unearth a record of life.

19. Microfossils show similarities to modern-day cyanobacteria (33:57)

This is just to give you a sense of how one might interpret one population. This handsome fossil here was originally a single cell. The cell itself is decomposed to that sort of amorphous goo that you see in the center, but you'll see that in life, that cell secreted a series of polysaccharide
envelopes around it. They were elongated in the downward direction so that actually acted as a stalk that anchored that cell to the ground. We can look at a population of these and reconstruct a simple lifecycle. The cells grew, as they got larger they made these stalks, they reached a size, a particular size and then cleaved many times without intervening growth to make reproductive propagules that completed the lifecycle. Armed with that and another important feature, we know that those fossils lived in an environment very similar to coastal Bahamian environments today. We can actually go down to the Bahamas, and in those sediments that are most similar to the physical and chemical features of those rocks that we saw in Spitsbergen, we find these little black crusts forming and those little black crusts are made of single-celled cyanobacteria that makes these envelopes that make stalks. Here, separated by 750 million years we have living in fossil populations very similar in form, very similar in lifecycle, very similar in environmental preference and that allows us to interpret those fossils as cyanobacteria.

20. The importance of cyanobacteria (35:47)

Now, I happen to be one of the few people, probably in this room and well beyond it, who think that cyanobacteria are the most important organisms that ever evolved on this planet. They're certainly important for paleontologists because those organic sheaths or envelopes that cells secrete, are in essence the hard parts of microorganisms. They are not easily broken down by bacteria. They can accumulate as a fossil record. The cyanobacteria have a particularly good fossil record as we go back into the deeper parts of Earth history. But there's a biological reason why we should be interested in cyanobacteria and that is that they are the only group of organisms ever to evolve a form of photosynthesis that uses water as a source of electrons. Why is that important? It's because the byproduct of that reaction is O2, oxygen gas, and it's safe to say that the reason we have oxygen in our environment today that allows all of us to breathe is because of the photosynthetic activity of cyanobacteria and their descendants, the chloroplasts of algae and land plants. So they're enormously important to the history of life and environments.

21. Stromatolites in the fossil record and today (37:11)

It turns out microorganisms leave a very different and more conspicuous record of their former presence. If you look at that cliff on the left-hand side about half way up you see these little lozenges of buff-colored materials. Those are actually microbial reefs, and on the right you see one of those close-up. It's made up of these columns of laminated structures; the laminate bow upward. Those are called stromatolites and they are a geologic record of microbial communities interacting with the physical environment. We know that stromatolites in the past made reefs as large as the reefs made by corals today, so they're important structures, and there are places we can still go today, such as here in Shark Bay in Western Australia, where we can see cyanobacterial communities accreting these modern stromatolites. The panel on the right simply shows one of these domal structures cut in half so you can see those domed laminations that are the hallmark of stromatolites.

22. Lipids as molecular fossils (38:22)
There are still other ways that microbial life leaves a signature in sedimentary rocks. Most sedimentary rocks including the ones from Spitsbergen have at least a little bit of organic matter that survived decay and was incorporated into those rocks. They tend not to contain things like DNA and proteins. Those are too easily broken down by bacteria in search of food. But things like lipids preserve pretty well. So one thing to think about is that when you die, the last bit of you to be present for future generations to ponder might well be the cholesterol in your blood vessels. So think of that next time you have a hamburger. What's nice about this is that different organisms make different kinds of lipids so there's a large number of eukaryotic and bacterial groups that are not represented by body fossils but have left this chemical signature.

23. **Stable carbon isotope ratios show evidence for life** (39:21)

And then finally, bacteria are small but they are so numerous that they can actually influence the chemical composition of sea water. What this cartoon is meant to illustrate is that in the process of photosynthesis, cyanobacteria or any other photosynthetic organism will have a menu, if you will, of CO2, some of which contains the heavier isotope of carbon, heavier stable isotope, carbon-13, some of which contains carbon-12, and for reasons that simply have to do with the differing mass of those CO2 molecules, the C-12-bearing CO2 will be preferentially incorporated into organic matter during photosynthesis. What that means is that if we can measure the ratio of C-13 to C-12 in the organic matter, and then measure the same ratio in limestones associated with that organic matter, they will differ in that ratio. They'll actually differ by around 25 parts per thousand. We can measure that with a mass spectrometer and we do that for the Spitsbergen rocks, we have strong confidence that there was a biological carbon cycle driven by photosynthesis on the basis of that chemistry. Turns out we can do exactly the same thing with sulfur and show that there was a biological sulfur cycle at the time of those Spitsbergen rocks.

24. **Life evolved at least 3.5 billion years ago** (40:49)

So, there are a number of different signatures of life, of microbial life, that we can take back through time and the question now becomes how far back can you go? This picture that we see here is of a rock about 3-1/2 billion years old in Western Australia. It originated as a limestone and I hope you can actually see when you look hard is those domed, and in this case cone-like laminations-- those are stromatolites. That's evidence of microbial live 3-1/2 billion years ago. If you look at the carbon isotopes of this rock they again suggest there's a biologically-driven carbon cycle. If you look at sulfur's isotopes they suggest that there was a biologically driven sulfur cycle. And that's about the end of the road. So what that tells us, that in the oldest rocks we can look at profitably as paleontologists, life is already a feature of our planetary surface.

25. **Life existed before Earth had atmospheric oxygen** (41:53)

There's something else we can say about that life, and that is it basically operated without oxygen. And if you want to know how we can say that, these cliffs in this picture are some very good evidence. This is iron formation, and again I have an example here. Iron formation is a rock that's commonly banded, and the bands contain iron minerals. The red here is an iron
oxide, hematite, and much of the iron that has ever been mined for industrial purposes formed on the early Earth as these deposits. Now, the interesting thing about iron formation is that it cannot form in the oceans today, not even in principle. And the reason is that when you put iron in a solution that contains oxygen it immediately precipitates as an oxide. The evidence of these sedimentary rocks is that that iron was actually transported through deep oceans, perhaps for long distances without ever coming in contact with oxygen. Ferrous iron or reduced iron can travel in solution very well. So here's just a little cartoon that in a world before oxygen, it turns out that a number of living photosynthetic bacteria can actually use ferrous iron as a source of electrons for photosynthesis, so they can actually generate iron oxides without the need for O2. Those would immediately precipitate, fall to the sea floor. It's also the case that early cyanobacteria might have generated oxygen through photosynthesis and that could oxidize ferrous iron which would also fall to the sea floor. There's reason to believe on the earliest Earth, and that example of iron formation that I just showed you is about 3.2 billion years old, that probably the left-hand side is what was going on. By around 2.5 billion years ago, that cliff that I showed you, perhaps the right-hand side was important as well. But in any event we would have this iron rain down on the sea floor, preserved today as iron formation, providing evidence that, prior to 2.4 billion years ago, which is when this iron formation largely disappears, there was little or no oxygen in the atmosphere and oceans. Around 2.4 billion years ago, we start to see at least low levels of oxygen accumulating in the atmosphere and surface ocean, and one of the projects that you have and can do, and some of you have done is to make a Winogradsky column. I won't talk about this in detail, except to say that if you actually remove the part of the column at the top, where you have cyanobacteria and oxygen using a respiring bacteria, the bottom part of the column really presents ecosystems as they might have existed on the early Earth.

26. Animal diversity and size increased with higher oxygen levels (44:56)

Moving to a conclusion then for this, after 2.4 billion years ago, once oxygen starts to permeate surface environments, we start to get evidence of a new form of life, and that's eukaryotic cells, seen here in a variety of different types of fossils. Those diversify through time, and that diversification eventually includes the ancestors of animals, and that actually then ties us to the record of the first module. Molecular clock estimates, that is, just biological estimates, suggests that animals may have originated about 750 to 800 million years ago but we don't have a record of that for 200 million years. How do we reconcile that? Well, one possibility, I think the likely possibility, is that early animals were constrained by environment to be very tiny things unlikely to accumulate in the fossil record. What could constrain them to be small? The answer is oxygen, and indeed there's evidence that, right about the time when we first start seeing large animals, we see geochemical evidence that oxygen is sharply increasing in environments and indeed, once we have evidence of oxygen increase, then we see the tremendous diversification of animals that we see today.

27. Summary of the biological history of Earth (46:25)

So just to bring this one to a close and then we'll stop a little bit for questions again, if we look over this whole pageant of biological history that Earth has recorded for us, for the first billion years or so, it's a world of anaerobic bacteria and Archaea with no oxygen. Then for the next
nearly 2 billion years, there's a little bit of oxygen in the surface oceans and atmosphere, but nothing you could breathe. And to that world we add microscopic eukaryotes, and then only in the last 600 million years or so, do we have a world of what you and I would regard, a world with breathable air, and that's the world into which the complex large animals and plants of our daily experience evolved.

**28: Q&A: What is the evidence placing Archaea close to eukaryotes?** (47:17)

So with that, more questions. Oh, yes. Sorry, I couldn't see you over the camera.

[STUDENT:] You mentioned that the genetic makeup of archaeobacteria actually makes it closer to the family of eukaryotes. Can you just elaborate on that?

[DR. KNOLL:] Sure. Some of the microorganisms that are on the Archaeal branch today were known years ago but they were just thought to be weird bacteria. When people starting using genetic sequence, as a sequence of bases in DNA, to gauge the similarity and closeness of evolutionary relationship of organisms, it was found that the Archaea were actually very different from bacteria even though they were both small and simple. And so in their molecular makeup of genes and proteins, many of those genes and proteins are more similar to eukaryotes than they are to bacteria, and just the way-- you've probably studied transcription and translation in biology class, if you look at the details, the molecular details of transcription and translation, eukaryotes and Archaea are very similar, bacteria are somewhat different. And so there's really a whole catalog of differences that suggest that at least there's a large genetic heritage in eukaryotic cells of Archaea. Having said that, there's also a genetic heritage that comes from bacteria and a number of people think, I think perhaps wisely, that the eukaryote actually begins as a symbiosis or a merger between a bacterium and an archaean. Another question?

**29. Q&A: What causes iron to accumulate in large bands?** (49:03)

Yes sir.

[STUDENT:] If there was a band of iron deposits in the rocks that means a lot of it must have accumulated at once. What would have caused a lot of iron to be...

[DR. KNOLL:] That's a good question and there are several possibilities. We think that the source of the iron is the deep ocean and that's then upwelling. You can have seasonal upwelling, as we do in places today. It could actually just be episodic, that you have blooms of surface organisms that are affecting the photosynthesis and the activities of the surface. But there's also a trick. It turns out when you look at, at least, the centimeter-style banding that you would see in this rock up here, some of that banding actually originates after the sediment hits the sea floor. Because what actually comes down to the sea floor is not only the iron but it absorbs silica on it and then it gets into the sea floor. Bacteria actually use that iron for respiration, it frees up the silica, and you end up making these bands.

**30. Q&A: Can you explain the magnetic evidence for continental drift?** (50:17)
Yes sir, in the...

[STUDENT:] You talked briefly about how the Earth, the geological formations moved, and you talked about their magnetic properties and that's how you can figure it out. Can you explain that a little?

[DR. KNOLL:] Sure. It turns out, and this is a good example, that when these minerals actually form in the sediment, they will actually form in a way that their crystals are aligned with Earth's magnetic field. As you may know, the Earth has a magnetic field. It's not quite aligned with the spin axis of the Earth but it's close. And so when sedimentary rocks are deposited, or when volcanic rocks are deposited, and they have iron bearing minerals that crystallize in the lava, the orientation of those reflects the magnetic field. And so as long as that signature is retained, then even though the rock may move over here, its magnetic memory will actually tell where it was when it was formed. That's a very simple explanation but it's, as Naomi will talk about, it's been a remarkably powerful thing in helping us to learn about plate tectonics. One more question—

31: Q&A: How did O2 level increase lead to greater animal diversity? (51:38)

[STUDENT:] You mentioned that oxygen increase leads to diversification of animals. Can you explain why or how?

[DR. KNOLL:] Okay. If we had a boat here, we could go to places in, let's say, Long Island Sound or in parts of the Chesapeake, where there's a gradient, where you go from essentially high oxygen down to no oxygen. If you look along that gradient today, you'll see that, until you get down to maybe 30% of today's oxygen level you don't see...or of full oxygen levels, you don't see much change. But below that you start losing fish. You go a little bit deeper, you start losing arthropod predators. You go a little bit deeper, you start losing things that make shells, and so when you get down into environments today that have very little oxygen the only animals that can survive there are tiny, tiny animals. These are animals that might be 100 microns long and 10 microns wide. And we know why that is. It's simply that, without oxygen, there are forms of life, particularly predators and large animals, that simply can't exist for physiological reasons. So if we take that into Earth history we then find empirically, just by observation, that in the long 3 billion years when geochemistry tells us there isn't much oxygen, we don't see any large animals. Once geochemistry tells us that oxygen has increased, to levels that should in theory support large animals, we actually see them. In that sense oxygen is just, in a sense, a barrier. A low oxygen is a barrier, you remove the barrier, and then all of the other processes that would give rise to diversity of animals can operate.

32. Our fascination with other planets in the solar system (53:32)

Well, let's go for the last module then. And what we're going to do is actually go out of this world, literally. I've just spent the last hour arguing that we can reconstruct the biological and environmental history of our own planet because we have this record of sedimentary rocks deposited through time. In theory we might be able to do that for any planet, perhaps most
planets preserve a record of their history, and as pretty much all of you know, over the last
decade it has been our privilege as scientists, and my personal privilege, to actually apply that
logic to Mars. So let's see what we learned. Let's start at the beginning. I think many of you
know that people have been interested in planets through antiquity. Shepherds out on hillsides
thousands of years ago noticed that most of the stars in the heavens migrated across the night
sky in a very orderly fashion but that there were some things, which they called wanderers or
planets, that didn't follow the same path. It was with the Copernican revolution, pushed ahead
by Galileo in particular, that people came to appreciate that those wanderers were in fact not
stars but were objects like the Earth, and that the Earth was one of a series of planets that
revolved about our sun. In fact, from that moment, you can go to the works of John Milton, for
example, and Milton talks about these other planets and he assumed that they would have had
mountains and forests and river valleys and quite possibly organisms much like us. That was
the expectation.

33. Mapping the “canals” on Mars (55:29)

Well, scientific thinking about Mars really took root during the Victorian age of the 19th
Century. This was an age of great exploration on the Earth and for many European nations there
was this mantra of, sort of, find it, claim it, name it, and map it, when mapping was really what
constituted knowledge of these newly-found areas, and that coincided with an improvement in
telescopes, so that people began to map Mars as a way of understanding another planet. On the
left-hand side here we see one of the earliest examples of this, by a British astronomer,
Nathaniel Green, and he drew actually a very beautiful map in pastels and very appropriately
shows a lot of uncertainty as to what the features of Mars were like. That map was totally
eclipsed in the public's mind within a decade by a map made by an Italian astronomer named
Giovanni Schiaparelli. And as you can see in the middle panel, Schiaparelli didn't show much
uncertainty at all. He shows these land masses or light masses that are separated by channels,
which he called canali. And Schiaparelli's map was itself eclipsed by a quite remarkable map
made by an American amateur astronomer named Percival Lowell, and you'll see that Lowell
shows these canali as being ruler-straight. In fact he interpreted them as canals, in our sense of
the word, and interpreted the map of Mars that he drew as the record of a technologically-
advanced civilization that used great aqueducts or canals to take water from seasonal melting of
glaciers at the poles to parched civilizations at lower latitude.

34. Popular culture and its fascination with potential life on Mars (57:31)

And I think it's fair to say that Lowell set off an international sensation. You can see that here.
Here's one of my favorites. It's an advertisement for a British soap company, the first message
from Mars: "Send up some Pears' soap." There's some sheet music, a very popular piece, "A
Signal From Mars," and of course, as many of you know, there were many, many books written
about Mars, and in almost all of these, literally all of which are forgotten, the Martians were
this wise old civilization that helped the Earth. The one book from that whole period that we all
still read is the one that saw the Martians as invaders rather than our friends and that was of
course, H.G. Wells's "War of the Worlds."

35. Alfred Russell Wallace: Mars climate is too hostile to support life (58:20)
But not everyone was excited by Lowell's conclusions. In fact, a lot of astronomers were very uncomfortable with this although they elected not to challenge him in the public arena. The one person who did was a man named Alfred Russel Wallace. Now some of you may know Wallace's name, because 50 years earlier, he articulated a theory of natural selection independently of Darwin, and the first paper ever published on natural selection as a mechanism for evolution was co-authored by Darwin and Wallace. Now here he is as a septuagenarian, again coming to the fight on Mars. He wrote a book in 1908 called Is Mars Habitable?: a one-word abstract for that book would be "no." He basically said Mars was too far away from the sun, it was too cold, too dry, it couldn't possibly support life.

36. Space exploration increases mapping resolution of Mars (59:19)

The interesting thing is that neither Wallace nor Lowell had anything like the resolution of the surface of Mars to support the kind of statements they made. That really didn't come until the age of satellite exploration beginning in the 1960s. This is an image from Mariner, one of the Mariner fly-bys in 1969, and it shows a dry Mars covered with craters. It looks much more like the moon than it does like the Earth. But some of the later Mariner missions which had a little bit more resolution, and the Viking mission in 1976, also noticed that there were places on the Martian surface where there were channels that looked like the dendritic patterns that we associate with streams, and which almost certainly formed by the movement of water across the surface of the planet. So there's increasing resolution. By the 1970s we were also landing on Mars, and here's an image from the 1997 Pathfinder mission. Now that's resolution for you. That's the surface of Mars and you might look at that and say "eh, it doesn't look very biological." You're absolutely right. This is a very harsh environment. In fact, because of the temperature and pressure, very low atmospheric pressure of the Martian surface, liquid water is actually not stable on the Martian surface today. So I don't think Mars is a place to look for life today, but one can ask the question, if we could find a sedimentary rock or rock record that would record Martian history, is it possible that Mars was once somewhat different than it is today.

37. Evidence for some Martian rocks being deposited by wind (61:12)

Now, this is again a shot taken from orbit, the Mars Reconnaissance Orbiter that is still working on Mars, this image was taken in 2008, and what you see is a valley with two hills and those hills show this step-like pattern of layered rocks. Each of those would be about ten meters thick. So that suggests there is a sedimentary record to look at on Mars, but what you have to do is go there and have a look. So as many of you know, in 2003 NASA sent two rovers to Mars. There's a picture of them. They're identical twins, Spirit and Opportunity. Spirit, which gave up the ghost about two years ago, went into a crater thought to be an ancient lakebed at Gusev, and Opportunity, which I've had the privilege to work on, and which by the way is still operating today, landed on the Meridiani Plains as you see here. I'm going to talk about Opportunity, because Opportunity landed in a landscape full of sedimentary rocks. And you can see here, this is what you might see on the edge of the Grand Canyon but actually it's on the edge of a Martian crater and you're looking at sandstones deposited through time. And I'll call your attention to the fact that if you look right in the middle of the panel, most of the laminations are
going like this but you see things that are on a high angle. If any of you have ever been to Zion Park in Utah you would see a similar thing, and to a geologist when you get that kind of angled bedding on the scale of meters thick, that's a sign that these rocks were deposited by sand dunes. Now we can get some real resolution, because Opportunity had on it a little hand lens so we can go right up to those rocks and look at them close up, and what we see is the laminations again. Those laminations are made of individual layers of sand grains, of sand-sized grains one grain thick. The grains are very well sorted which means all the grains in the laminations are the same size and as you can see where the arrows are, they're actually very well rounded. And again, we know from our experience on Earth that those kinds of things form in association with sand dunes. So we have several lines of evidence that suggest sediments are forming, they are blowing around Mars. Many years ago, and I should say that we don't have really good age resolution on these, because we don't have the radiometric ages on them, but based on the density of craters, these sedimentary rocks are thought to be certainly more than 3 billion years old, perhaps 3-1/2 billion years old. They’re about as old as the oldest rocks that we looked at on Earth.

38. Evidence for water on Mars (64:18)

This is one of my favorite pictures that Opportunity took. You can see as it looks up the side of this crater wall a series of different types of sedimentary rocks that are shown in different colors. The little orange patches that you see is where Opportunity stopped and drilled surfaces to take chemical measurements and we can do with those rocks exactly what geologists would do on Earth: make a stratigraphic column. And the bottom are these rocks with the high angles. Those were formed by sand dunes. Above them are rocks that are evenly laminated, which were also associated with sand. We can see re-crystallization that reflects a water table locally going up and down. And right at the top, you'll see there those little scallop structures. Those are called ripple marks, and if we look at the ones on the left and you can see they're little centimeter-scale scallops, those are ripple marks on Mars. The ones on the right are from the Earth and we know from both observation and experiment that ripples of the size and shape of the ones on Mars only form when water is transporting the sand grains, so there's evidence of water here.

39. Geological processes on Earth inform us about past Mars environments (65:40)

Just to give you a sense of how our experience on Earth informs what we do on Mars, here is exactly the same sedimentary motif that I just showed you from Mars, but this is from a coastal dune field in Namibia in southwest Africa today. Again, you'll see the lower layers on an angle. Those are migrating sand dunes. Above those are these so-called Aeolian sheet sands where wind blows things that accumulate flat layers and then only at the top do we see layers associated with transient lake systems, a little bit of water. All of that kind of evidence allows us to develop a picture of what the Martian surface at Meridiani Planum might have looked like 3-1/2 billion years ago. This is a picture, again it's an Earth picture taken in the empty quarter of the Arabian Peninsula, and it shows just migrating sand dunes, occasional playa lakes that come and go as the water table goes up and down, and that probably isn't a bad idea to think about what this part of Mars might have looked like early in its history.
40. Chemical analysis reveals the environment on Mars (66:50)

We can also draw some chemical inferences about these rocks. Opportunity has three chemical instruments, of which one is this alpha particle x-ray spectrometer. What it does is, essentially, there's this prehensile arm that places it on a sample. It then emits alpha particles and measures the emission of x-rays from the bombarded target and uses that to develop a sense of, a quantitative sense of elemental composition of the rocks. Here I've just shown you one sample of those sandstones. The cations are on the right, the anions on the left. The cations are mostly calcium, magnesium, iron, and aluminum. That's not too surprising because the volcanic rocks that make up the surface of Mars are mostly basalt, the kind of lava forming in Hawaii today, and that's very rich in those elements, correspondingly poor in things like sodium and potassium which are more common in the crustal rocks of the Earth. But the real surprise comes in the anions. Most of these anions are sulfate, like in gypsum or today on the Earth. Not much chloride, not much phosphate. And it looks like these are salts. If these rocks are rich in salts that means there must have been chemical interactions between water and the precursor of volcanic rocks. Again, more evidence of water, and some evidence of the particular properties of that water, because one of the minerals we've been able to identify is something called jarosite. Jarosite is a mineral that if you want to find it on Earth, you go to acid mine drainages where it's very common and really only forms at low pH. So when we put together all the information on the physical and chemical characteristics of these ancient rocks on Mars we find that yes, there was liquid water. It might have been short-lived but it was there. We also find however that it wasn't a planet much like the Earth as we know it. It was arid, it was oxidizing. Most of the iron in the original volcanic rocks is reduced iron, Fe2+; most of the iron in the sandstones is Fe3+. And at least in this time and place, it was strongly acidic.

41. Highly acidic water on Earth can harbor life (69:28)

I have to say that no one has ever found any strong evidence for biological activity, past or present, on Mars. It doesn't mean it wasn't there in the past, but what we can do is use this information on environmental history at least to constrain our thinking about the possible presence of life on Mars. We can start by again looking at places on Earth that are similar to what chemistry tells us about the Martian landscape at Meridiani Planum. Rich in iron oxides and jarosite-- here is a place on Earth today that's precipitating iron oxides and jarosite. It's Rio Tinto in southern Spain. The water that comes out into this basin has a pH of 1. It actually precipitates...all the red and orange stuff here is precipitating jarosite, other iron sulfates, iron oxides, very, very similar in fact to the chemical profile of what we see on Mars. Is this a bad place for life? Nope. Full of microorganisms. All sorts of things. In fact, they actually fossilize in the precipitates as they form.

42. High water activity is critical for life (70:45)

So, in a sense, acidity is not a game-breaker for speculation on life, but since these are salts, we ought to ask about salinity, and in fact, what we're going to talk about just for a few minutes is something called water activity which is kind of a fancy chemical way of thinking about salinity. Water activity just measures the percentage of all the water molecules in a solution that are available to do the work of water. Why aren't they all available? Well, as we see on the right
there it's because ions that are in solution form short-term transient weak bonds with that water and it becomes unavailable. And so the way this works is the saltier your solution the lower your water activity. And we know a lot about how organisms do or do not tolerate low water activity because it's actually the basis of the food preservation industry. You all know that people have salted meat for thousands of years to keep it from spoiling. The reason the salt works is it lowers the water activity of the fluids in the meat so that no bacteria can live there. Pure water has a water activity of 1. Sea water has a water activity of 0.98 and pretty much almost all the life that we know on Earth operates at a water activity between 1 and 0.95. Orange juice concentrate-- this is where experiments in the food industry come in-- will actually support the growth of a small number of bacteria. A saturated halite solution-- water that's just about to drop salt as a deposit-- can actually be tolerated and lived in by a few Archaea and a few fungi, and the world record holder, at least at the present, is a fungus called Xeromyces which can grow at a water activity of 0.61. Now, I point out honey here. All of you have done an astrobiological experiment in your own homes even if you don't know it. That is you opened up a jar of honey, you took something out, you closed up the jar, you put it on the shelf and didn't notice it again for five years. The question is when you look at it again, has the honey spoiled? The answer is no. The reason it didn't spoil is that honey actually has a water activity lower than anything known to support life on this planet. If you put water in that honey it'll spoil within days. Okay?

43. Martian water activity suggests life could not be supported on Mars (73:28)

Anyway, I show you this because if we can make an estimate of the water activity of those brines that percolated through Meridiani Planum 3 billion years ago, maybe we can say something about the possibility of life. Just to show you how this works, let's just start out with a beaker of water, put some salt into it, let it dissolve, and then evaporate the water. What happens is the concentration of salt goes up, but it only goes up to a certain point because at some point it reaches saturation and precipitates halite. We can display that same chemistry on the right as a function of water activity. As we evaporate the water the solution gets saltier, the water activity goes down and at the point where water activity is 0.75 that's when you form salts. So the salt, by its precipitation, gives you a quantitative record of the water activity of the fluid. Now, you have to know the composition of the dilute fluid first. We know that for sea water, by measurement, on the left, and through modeling and experiments we can make a pretty good estimate of what dilute brines would have been under Martian conditions. And then if we go through this argument of starting with a dilute fluid, and through time just evaporating it, on the Earth, which is in the blue on the left, gypsum comes out at about 0.92, some organisms can tolerate that. Halite at 0.74, Epsom salts at 0.63, and so it goes. If we do the same exercise with Martian fluids we find that gypsum comes out in fairly dilute solution. Epsom salts, which are the dominant salts in those sandstones at Mars come out at a water activity that would kill 99% of all organisms we know of on Earth, and some of the late precipitates on Mars are actually table salt, halite, NaCl, and at that point, the water activity on Mars would be lower than anything known to support life on this planet. So when we take the Mars evidence then it suggests that these brines on Mars, yes it was water, but that water evolved in a way that would have been challenging for life as we understand it. But I'll also say that there are variations on Mars, and just this last spring we published a paper on these dandy little beds here. The brown area is just volcanic rocks. The white thing that you see going across
here is actually a vein of gypsum, calcium sulfate. And remember that gypsum precipitates from a Martian solution at relatively mild temperatures and relatively mild salinity. So that's evidence that at least at some times and in some places there were waters that were, in a sense, more comfortable, if you will, for life as we understand it.

44. Mars rover Curiosity: A new chapter of Mars exploration (76:46)

Okay. What we've learned so far from our nine years on Mars is that Mars indeed was somewhat different earlier in its history than it is today but it never really looked like the Earth. It was not a big ocean planet. There was water, transient, for the last 3 billion years probably Mars has been at least nearly as dry as it is today. Awful place for life today, merely a bad place earlier in its history. And as some of you know, there's a new chapter in Mars exploration beginning and that is, just a few months ago NASA landed the Rover Curiosity on Mars. It is more capable in terms of its instrumentation than Opportunity was, so it can make different kinds of more sophisticated measurements, and the target area is spectacular. If you like the Grand Canyon as an example of layered rocks through time on Earth, look at this in Gale Crater. Again, what you see, those layering, those sedimentary rocks, and this is a record of the sedimentary history of Mars more than a kilometer thick, presumably representing millions of years of history. So there's a lot to be discovered. I'll just end then with this beautiful picture, which shows the sun setting over Gusev crater on Mars. And what we're learning about Mars suggests that by the time life was emerging on Earth and starting to become an important planetary component on Earth, the window for life at the Martian surface was closing. That said, what this tells us in principle is that by continued exploration of our own solar system and beyond, we can actually come to understand other planets and their histories using the same sort of tools that we used to come to understand our own planet's history, and within your lifetimes we may know the answer to one of the most profound questions about life that we can even ask, and that is, is life on Earth unique? Is it even unusual? You may actually know the answer to that within your lifetimes. So thanks. I'll be glad to take some more questions.

45. Q&A: Does water freeze or boil on Mars? (79:17)

Yes sir.

[STUDENT:] When Mars has both low temperatures and low atmospheric pressure would water freeze or boil at the surface?

[DR. KNOLL:] What will happen is depending on where you are in that temperature and pressure space, the water is commonly frozen and is ice. There's plenty of ice, water ice on Mars. But under the conditions of Mars, when that ice transforms it doesn't transform to water. It undergoes something called sublimation and it goes immediately to water vapor. There is a tiny amount of water vapor in the Martian atmosphere, there's lots of ice. The only thing missing is liquid but that's the form of water that makes the difference for life. Okay?

46. Q&A: What caused the atmospheric change on Mars? (80:11)

Yeah, in the back.
**[STUDENT:]** What caused the change to the atmosphere that prevented liquid water from being available on Mars?

**[DR. KNOLL:]** That's a good question...

**[STUDENT:]** ...eventually because I mean, if their window of life closed will our window of life close?

**[DR. KNOLL:]** Interesting question. I'll answer the second part first. Don't sell your long-term bonds. I think the Earth is going to be okay for awhile. Mars is an interesting story because...your question is a very good one because what I've told you suggests that conditions would at least allow for liquid water in the past, may well have been somewhat warmer than they are today, and the theory is that early in its history Mars had a denser atmosphere than it has today, but that atmosphere was lost, and the loss of the atmosphere seems to be related, at least in part, to the freezing of the interior of Mars-- and how does that work? Once you freeze the interior of Mars so that it no longer has a liquid core, then it won't have a magnetic field and in the absence of that magnetic field, particles coming from the sun called solar wind could actually strip that atmosphere. One view is that Mars's atmosphere has slowly been stripped through time. Another process that have worked is that CO2 in the atmosphere would actually...again, just become dry ice, and so there's plenty of frozen CO2 on the Martian surface today including in the ice caps. Water vapor would come out as water ice, and there might have actually been some loss of nitrogen by reaction, just chemical reactions with surface rocks to make things like nitrate that accumulate in soils. So it's a combination of those processes but I think the biggest things in Martian history, and Dan may wish to correct me on this, are A, the loss of the magnetic field, and B, something I didn't talk about is that Mars has a very unusual tectonic history relative to what we know on Earth. There's an interval of time that corresponds pretty closely to when these rocks at Meridiani formed, when there was a lot of volcanism on Mars. That would actually bring gases, renew gases in the atmosphere, but that seems to have slowed down also billions of years ago. There are processes that would act to continue to deplete atmospheric gases, but the processes that would add gases to the atmosphere simply declined to unimportance. Further questions?

47. Q&A: How will we continue to look for life on other planets? (83:07)

Yeah.

**[STUDENT:]** My question relates to the end of your talk. You said that possibly in our lifetime we would understand if there's life on other planets. What are some of the forefront prospects that we can look at for life in the relative nearby region?

**[DR. KNOLL:]** Sure. There's three ways we can think about exploring the universe for life. In our solar system we can do what NASA has been doing on Mars. We can actually go there with remote geologists and possibly sometimes some poor real geologist may go to Mars, and so we can do all the kinds of things, but more sophisticated things, than I've explained to you, we can do by going to Mars, by going to the moons of Jupiter. But you know...other planets in
other...surrounding other suns are really too far away to do that, at least by any technology that's remotely imaginable for the next hundred years, and so for those we have to image them. As you may know, there's a mission flying now called Kepler which has found literally thousands of candidate planets around other stars. Some of them are actually Earth-like or very near to Earth-like. So again, one of the things that will happen again, certainly over the next few decades in your lifetimes will be that we will be able to look at the atmospheres of those planets. And just as there's a relationship between life and the atmosphere on Earth, we might be able to use those atmospheres as proxy signals for life. But even that will only take us out for a couple of light years. And so for the rest of the known universe, the only way we're going to find out if there's life elsewhere is if they tell us, that is something like SETI where we get signals from extraterrestrial life. So my guess is that, I expect the most exciting information about other planets that has to do with the possibility of life, really to come from this exploration of other solar systems.


You had a question.

[STUDENT:] What are the differences between land versus marine reefs. I always though reefs were only, like, coral in the ocean, so what exactly constitutes a reef?

[DR. KNOLL:] Okay. Good question. I didn't mean to imply that there are reefs on land. All the reefs are in the ocean, and a reef in general is where organisms build up the profile of the sea floor in a way that physics would not do. It just builds up these structures sometimes all the way up to the surface. And you're right: if you look at the world today, the major builders of reefs are corals. But it turns out that's only been true for the last 40 or 50 million years. If you go back to the time of the dinosaurs, there are reefs that are made by sponges, many extinct sponges. You go back deeper in time, there are reefs that are made by other groups of microorganisms, extinct relatives of corals, and if you go back to a time before there are animals, it's not that reefs disappear but now the reefs are all microbial. If we run that from the bottom to the top, organisms first started accreting structures above the sea floor very soon after life began. They were all microbial. When animals evolve, animals start participating in reefs, but reef builders tend to be very vulnerable to times of mass extinction, so there have been half a dozen times when reefs have just collapsed through time and Earth history, and the reefs that we see are simply the most recent incarnation of reef biology. Okay. Listen, thank you very much. I will be around for the next two days and I'd love to meet many of you and talk to you.
"Our Planet" is a three disc set consisting of three different collections of the History channel's most Earth-centric specials: "How the Earth was Made", "A Global Warning?" and "Life After People" (my personal favorite) to journey through the past, present, and future of Earth. "How the Earth Was Made" is a 90 minute special that explores how our understanding of the Earth's age went from being based on scripture to reading rocks. Because it ALREADY HAPPENED in THIS location and then you get to learn the history of an abandoned city somewhere. Interesting, addictive, way overly dramatic, the best part of this set for me. How long will it take your house to fall down and what would it look like?