The evolution of the Earth and life
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Lecture 59
Evidence of Early Life

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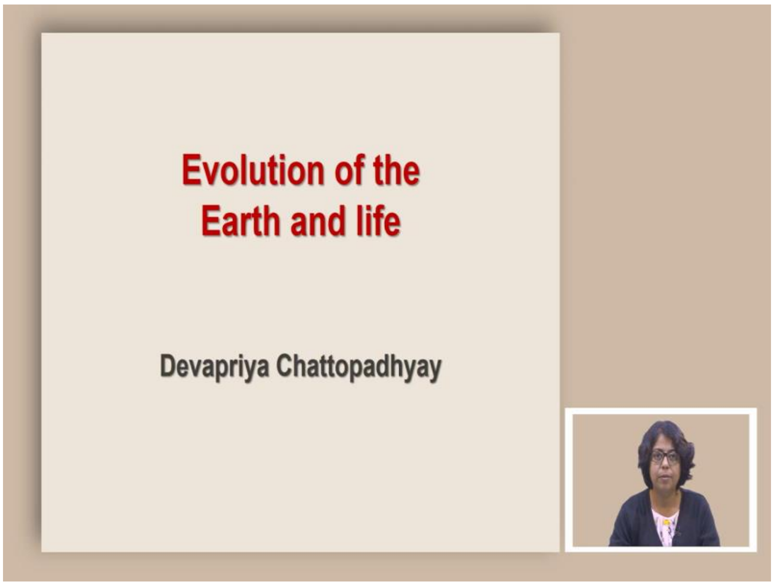

Welcome to the course Evolution of the Earth and Life. Today, we are going to talk about the early evidence of life.

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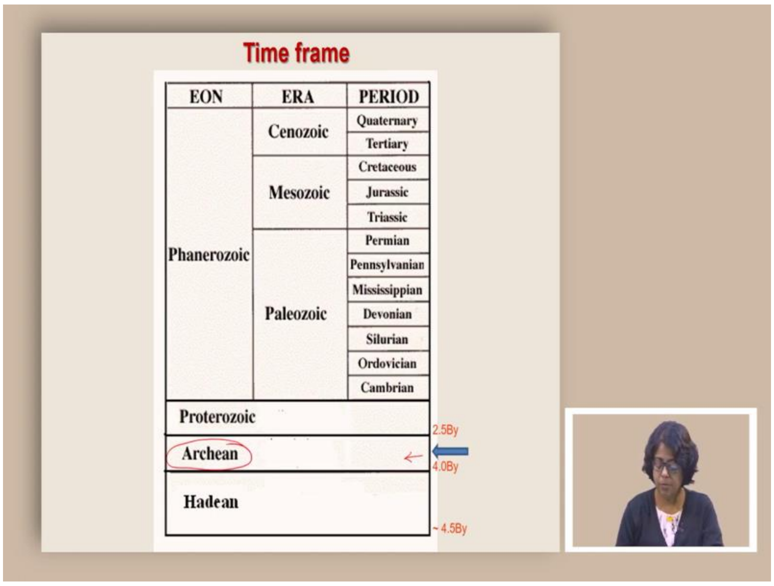

The timeframe on which we are going to focus would be somewhere between 4 billion years and 2.5 billion years. So, we are primarily going to focus on time, EON, which is called Archean.

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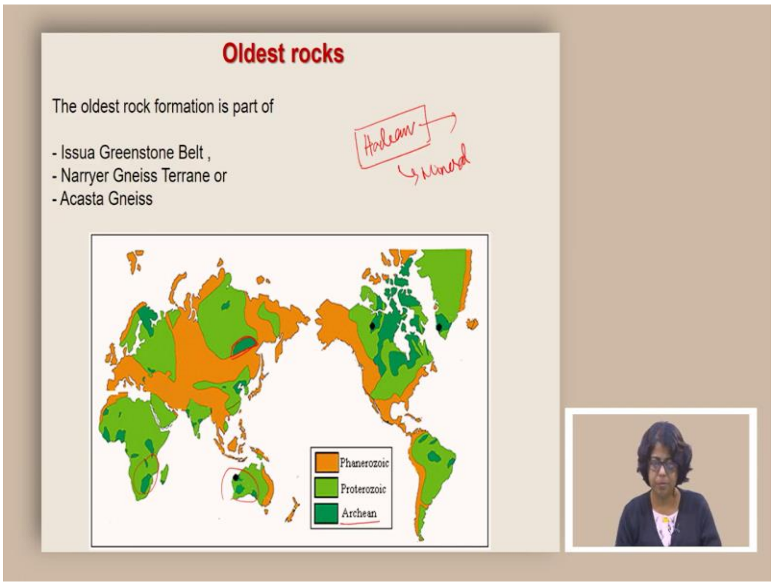

When we talk about the evidence of life, we need to talk about a bit about the oldest rocks to because if we are looking for the evidence of life, it has to come from the rocks. If we look at the rocks of the oldest time, we will find that there is the distribution of rock types. And it tells us that there are different very old rocks distributed all over the world. The Archean is the time where we are interested, but as we know that it is not the oldest time the oldest time is Hadean.

But Hadean is represented only by minerals, the original rock we do not have, and therefore Hadean is very hard to comment on in terms of the possibility of life because we do not have the record whether the life was there or not. It is insufficient evidence at this point to comment. But when we look at Archean, we have plenty of rock record, which helps us to understand the world better during this time.

And we can also search for evidence of life in this time. So, now if we look at the distribution of Archean rocks in the world, what we will find these dark paths, the dark green bands are the paths which represent Archean rocks. These are part of the stable continent, which are often preserved well, and these are the Archean cratons and sometimes we find really, really old Archean rocks.

And some of them are Issua Greenstone Belt, Narryer Gneiss terrane or Acasta Gneiss these are some of the places which are really old, in terms of its age, even within Archean. And they are distributions are either in the Greenland, or in South Africa, or in places in Australia. And these places are helping us to develop the early evidence of life.

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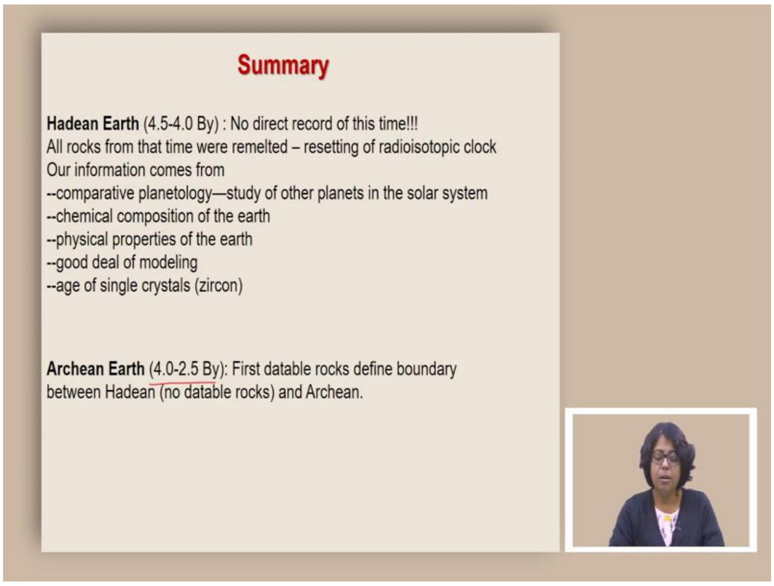

So, what do we know about Hadean? We know that it the time range between 4.6 to 4 million years, we do not have any direct record of the time. We only have these minerals. So, we only the zircon minerals, which tell us something about the temperature, the condition, the evidence of liquid water. But when it comes to life, it becomes very difficult to comment.

But when we look at the Archean rocks, we are covering a time span between 4 billion years to 2.5 billion years. These are dateable rocks. And that is what defines the boundary between Hadean that there was no rock, no dateable rock, and then we start finding the first dateable rock in Archean and that is what defines the boundary between Hadean and Archean.

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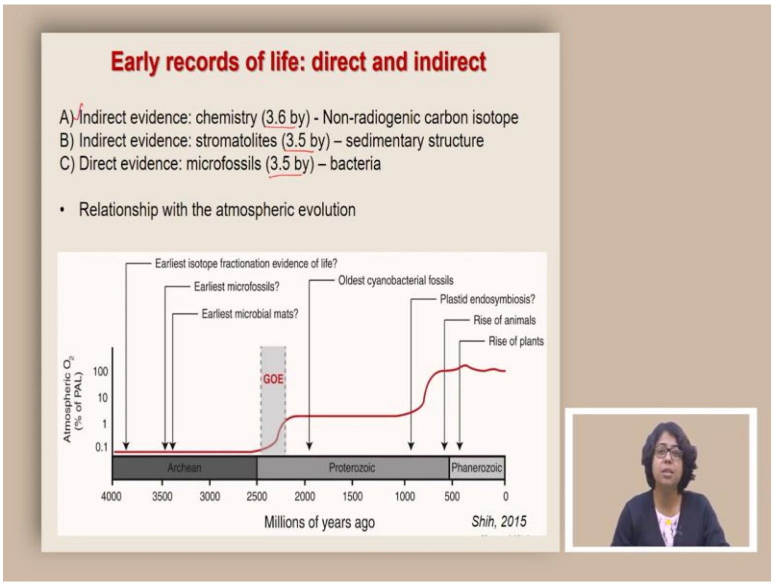

Now, we look at the types of evidences that we can expect. So, we are going to classify these evidences into three types. The first type is an indirect evidence from chemistry. And that is that dates back to 3.6 billion years, which tells us something about life. There is another type of indirect evidence, which is a trace fossil. And that gives us an age of 3.5 billion years. And finally, we get something like a direct evidence of microfossils.

And that also comes around 3.5 billion years. Now, based on these people have determined that in Archean, there was definitely life. And probably life was there as early as 3.6 billion years ago. There was another important thing that was happening in after Archean, during Proterozoic, and that is the development of oxygen. So, we are going to touch upon some of these issues while we talk about the early evidence of life.

But one thing is important to recognize that during Archean, all the evidences are telling us that the oxygen concentration was very low during Archean. And this is important to keep in mind because we are going to talk about life. And often we associate life with proliferation of oxygen, we think that life requires oxygen. And it is important because now we are looking at Archean recall, it is quite clear that the Archean did not have enough oxygen, but it had life.

In fact, from the modern-day record also we know there are types of life, which are extremophiles, they do not require oxygen always. In fact, they cannot live in oxygen rich environment. So, oxygen is not really a prerequisite for life. So, now, let us take a look at the indirect evidence the first indirect evidence.

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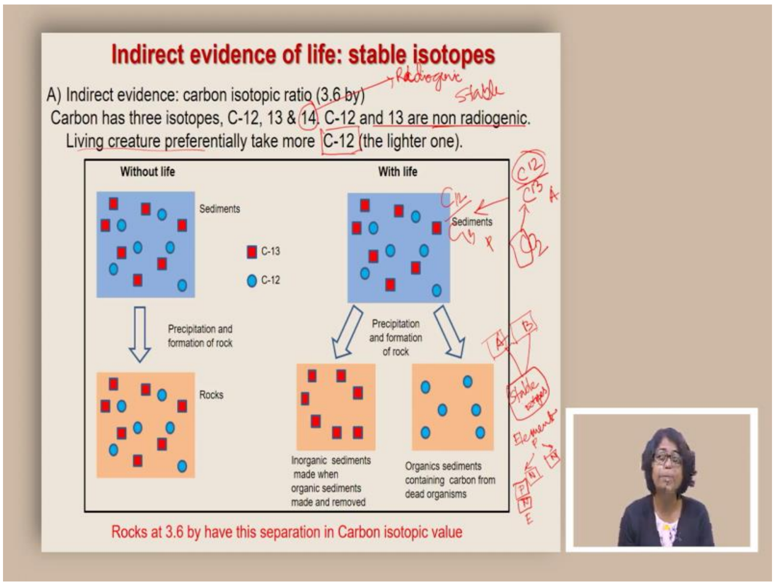

So, the first indirect evidence that we will be talking about is going to be of stable isotopes. Again, what is a isotope? As we mentioned before, that an element has proton, neutron and electrons. Now, these proton numbers are primarily determining the character of the element, the neutron is basically giving the mass and there can be of the same element, there can be types, where the neutron number differs, because the neutron number when the neutron number differs, they are going to have different mass the elements of the same element the isotopes can be of different mass and they will be varying in their movement.

So, the proton number remains the same, but the neutron number can be different and therefore, the mass number would be changing and these are the types which we call isotopes. Now, there can be different types of isotopes of the same element, some isotopes could be radiogenic that means, they decay, they are not stable, they decay and therefore, they create daughter relevance from the parent elements.

But then, there can be other types of isotopes, which are called stable isotopes. These stable isotopes are different in terms of their neutron number definitely. So, they will have two different masses, if we are talking about two isotopes of the same element, but they are stable. So, they are not going to decay naturally. And they are simply going to be there with different proportion because they differ in their mass.

If there is not phase change, they will have different probability of going to a different phase. By phase change, I mean changes in their physical state, it could be a situation where they are going from liquid to vapor, it could be a situation where they are going from vapor to liquid back again or they are crystallizing from the liquid. So, any such change is going to change the ratio of different isotopes of the same element if they are stable, primarily because of their past difference.

If you have the same energy to vibrate, the ones which are lighter, is going to vibrate more. And therefore, in these kinds of phase transitions, they behave differently than the heavier ones. Often the lighter ones are preferred to go to the next phase, instead of the heavier one, because of the energy constraint and their vibration. Carbon has three isotopes, C 12, C 13, C 14, C 12 and C 13 are non-radiogenic, they are the ones which we call stable.

On the other hand, C 14 is the one, which is the radiogenic isotope, and we use it for a different purpose. We use it to date rock. But these stable isotopes are very important to recognize some of the biological mechanisms. And many of the biological pathways are determined using these isotopic ratios. So, now we look at the living creatures, the living creatures have different tendency of taking different isotopes.

The living creatures, especially if we think about the plants, they have a preference for the C 12. So, if we look at the plant material, we are going to see that the C 12 is more compared to other materials, which is outside. So, let us take an example. Let us say we are measuring the C 12 and C 13 ratio of the atmosphere and it has some specific ratio. And the plants are taking atmospheric material into their body when they are basically absorbing carbon dioxide from the atmosphere.

So, when they are taking carbon dioxide, in carbon dioxide, there is also a carbon and this carbon will have some C 12 and C 13 ratio, which represents the atmospheric C 12 C 13 ratio, but when the plants take it, the preferentially take C 12 compared to C 13. So, this atmospheric C 12 C 13 ratio is going to be different from the C 12 C 13 ratio of the plants.

And this difference tells us that the biology is involved in this kind of phase transition, because they are preferentially taking it. And therefore, if you are in a world where you have to recognize which is atmospheric and which is plant derived, you can look at these ratios. And the ratio difference tells you something about which is coming from the atmosphere and which is coming from the plant. Now, let us take a look at more complex issues.

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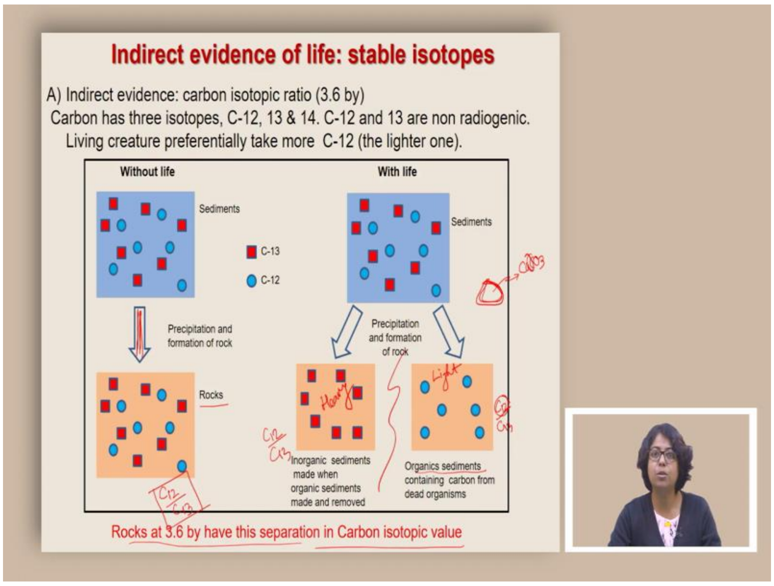

Without life the sediments will have some C 12 C 13 ratio. But then, when it is converting to rock, some of them might be removed, some of them might not be removed, but there will not be any preferential removal. And therefore, these sediments when they convert to rocks, they are going to maintain the same C 12 C 13 ratio. So, there will not be any difference between C 12 and C 13 ratio between the sediments and the rocks.

Now, there are different kinds of sediments, let us say we start with the same C 12 C 13 ratio. And then there are some rocks which are being created by involvement of biology. What happens if biology is involved to create these rock they are preferentially going to take the C 12 and therefore, the rocks that they are going to create they will have a more preference to C 12 and C 13.

And therefore, this one will be dominating compared to the C 12 C 13 that was produced in a place where it was not involving biology. So, let us try to understand it again. We are starting with sediments of water, which also has a C 12 C 13 ratio. And some of the rocks are being created by organisms such as let us imagine the shells the clams and snails, they are shells are made up of calcium carbonate.

Now, these calcium carbonate has these carbon and because these carbon they are actually taking it by the biologic processes, these carbon will have a stronger signature of C 12 compared to C 13 in terms of the ratio. And therefore, the organic sediments that are made up of crushed shells, they will have a lighter signature lighter means the C 12 compared to C 13 ratio, then something which is not creating using these crushed shells, but because they are preferentially taking the C 12 the remaining one is going to be more heavy in C 13.

And therefore, we are simply going to call it a heavy one. And this one, we are going to call it a light one. So, this light one is going to be a signature of life. On the other hand, if you simply get a very heavy one, that also tells you something about the presence of life, not creating the sediments or rock, but they must have been around because of which you are seeing the separation between very light composition of the rock and very heavy composition of the rock in terms of C 12 C 13 ratio.

If there is a world where there is no such separation, that strongly tells you that there is no life involved in any of these process, and that is what is depicted in this particular picture. So, using carbon 12 13 ratio or stable isotopic ratio of carbon, it is possible to recognize whether the biological activities were involved during a particular time looking at the stable isotope ratios of carbon of the sediments or the rocks.

Now, when we look at the rocks at 3.6 billion years ago, we do find that these separation in carbon isotopic value, we do find quite light carbon isotopic values in many of the rocks, which directly tells us that they have been biologically developed. So, maybe the biology contributed in terms of creating some of these rocks and these rocks are all Archean rocks. So, this one is one of the most strong indirect evidence of life using stable isotopes.

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Now, we are going to talk about another indirect evidence, but this is an indirect evidence of the activity of organisms and it is called stromatolite. Stromatolites are sedimentary structures, as well as a crease fossil, which looks like this, it commonly looks like a cabbage where you see multiple layers and these layers are showing you patterns which are created by a bacterial column. So, these are some of the pictures.

So, this is actually a modern-day representation. So, this is modern day microbial mat from Bahamas where the microbial mat can form note proper development of stromatolite, but microbial mats can form. And number B is a terrain with Archean stromatolite. So, you see these mound-like structures, these are typical variation of stromatolites. And if you look at a cross section, then it will look at these cabbage like shaped these are what is called stromatolites. Now, let us try to take a look at how they form.

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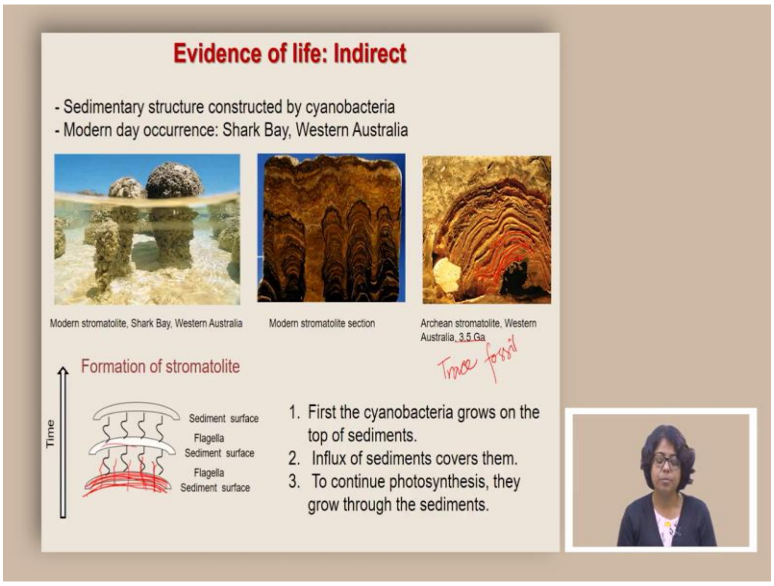

When we try to understand how stromatolites form it is much easier to do it if there were recent development of stromatolites and then observe it. So, people found out that in modern-day Shark Bay in Western Australia, they have development of stromatolites. This is a bay it is a relatively isolated place and it has very high salinity because of which all kinds of organisms that you commonly find in an open marine condition are not there.

There are not that many fishes, or snails or clams and you see these development of stromatolites. When people observed it how they form what they found is that there are microbial mat. So, these are bacterial mat that develops at the beginning at the sediment surface. And these mats they have a gluey structure and because of that the sediments stick to it. And we are primarily talking about sediments which are mostly carbonate.

So, once it sticks it also tries to harden. But this covers the bacterial mat around below. And therefore, they try to survive and the next time we see another development of mat. Some of these actually extended their flagellum and created another layer on top of it. So, it is going to create another layer, which will again keep on adding sediments because it has the sticky substance to it, which will attract the sediments and the sediments are going to settle.

By the time the sediments are settling here, the ones which have settled down, because of the action of the carbonates, it may have already hardened. And once hardened, the next layer is going to appear as a different layer. And that is why you are going to see layer upon layer structure, and not all the layers are going to be compressed to show a single layer pattern. So, this is the reason you are going to see these cabbage like shape, because every layer is telling you a different time of hardening and different time of deposition.

Now, why do not we find such stromatolites today, other than the Shark Bay, the reason is, even if there are other places where you see development of microbial mat, often organisms such as fishes, snails, they eat it, they constantly eat the sediments. And in the sediments, if there are microbial mats, they are immediately going to eat it. And therefore, these microbial mats do not survive, unless it is a completely protected restricted environment such as Shark Bay. In Archean, that was not the case.

There were no other organisms, which were heavily eating the sediments. And therefore, many of these microbial mats got protected. And they got protected, they kept on growing in these layer upon layer fashion, and created the stromatolites. So, we look at the stromatolitic record, and it dates back as old as 3.5 billion years ago. And we find these Archean records of stromatolites. Who are the responsible organisms?

The responsible organisms for making this structure were a type of cyanobacteria which do not require anything else. And they can survive in water, even in different salinity. And they can grow and attract sediments and create this fossil record of their activity. And such fossil record where it is recording their activity, and not the animal themselves is called a trace fossils. So, stromatolite would be an example of a trace fossil.

Now, you may ask that what happens to these organisms which were in between? Well, these organisms, they do not have a hard skeleton, and therefore they do not get preserved, although we may get some layers, which is simply rich in carbon. But we do not really get the complete preservation of the cyanobacteria. And that is why the stromatolites are primarily the record of their activity, their habitat, but not their body fossil.

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The direct evidence of life comes from other places. And these are in the form of microfossil. So, around 3.5 billion years ago, we started getting records of microfossils some of them look like these segmented worms and which has some grooves in it, others are all single celled microfossils. So, this is the actual fossil, the top panel and this has been compared to the modern-day cell division pattern and showed the comparison and this has been found from the Swaziland of South Africa, this is also 3.5 billion years.

Now, there has been quite a bit of controversy in terms of whether they are really bacterial remnants or whether it was produced by some inorganic process which developed these kinds of patterns such as cracks later filled up by carbon rich material. It is hard to comment on it simply because there are so few and so small that it is difficult to talk about specific examples and their validity.

But if you do a carbon isotope analysis, a stable isotope analysis, many of them also show a very light signature, which is supporting the idea of life generating these patterns. However, with combination of both direct evidence as well as indirect evidence, so include the carbon isotopic signature of all over the world of the Archean rocks, the evidence of stromatolites, it is quite clear that the first life must have been there very early in the Archean because we started getting these records all the way from 3.5 to 3.6 billion years ago.

So, clearly during Archean there was life. Now, the question is, what did it do to the earth. So, we are going to talk about a little bit about how it impacted the earth.

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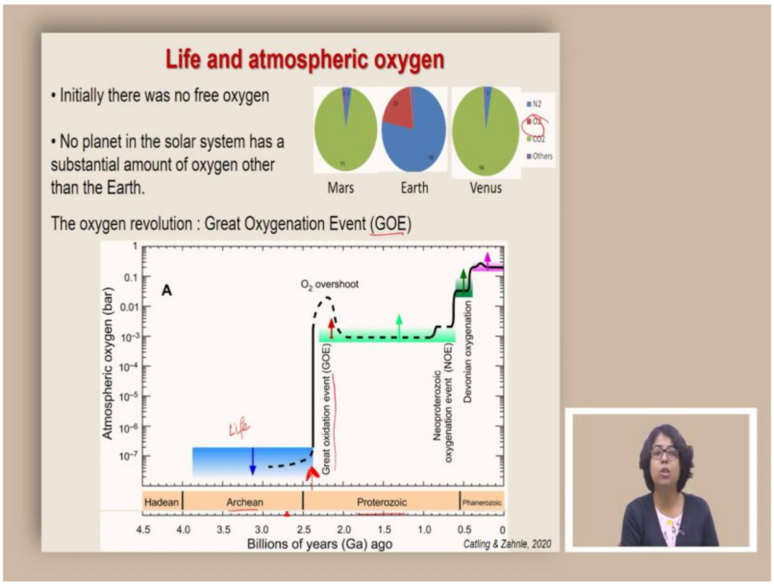

Now, we are going to talk about a bit about atmospheric composition. As I mentioned that we often think that life is an integral part of the earth and it depends on oxygen. But we also learned that in Archean there was not really free oxygen. And there are various ways of testing it, what kind of minerals we were getting from Archean is a good indicator of whether they were free oxygen, there are minerals that cannot form unless it is an oxygen poor condition.

So, one of the example is pyrite, calm composition of it is FeS2. So, this pyrite cannot form if there is too much oxygen, it will only form in reducing condition that means no free oxygen. And we find these kind of materials or these kinds of minerals in Archean not only that, there are plenty of other evidences which tells us during Archean there was not much free oxygen.

It is also not hard to believe because when we look at the planets of the Earth's neighborhood, we will find that in Mars, if we look at the composition of the atmosphere, that the composition looks quite different, and the primary difference comes from oxygen, that the Earth has oxygen, this red part is an indicator of the oxygen.

And if you look at if you search for that red part in Mars or Venus, you are not going to find any, we chose that Earth has something quite distinct about the oxygen concentration. And because we know that the planet sort of started around the same time they had similar history. So, we should expect that the initial part of the earth must have been similar to other planets too. And if we go by that, it is not very hard to understand that initial part of the Earth, initial history of the Earth must have been devoid of oxygen there must not be a lot of oxygen at the beginning.

Now, the question is when did the oxygen started to increase and we have enough evidence which tells us that the oxygen concentration started to increase somewhere around this time and this time is basically called a great oxidation event or GOE. This GOE is on evidence, which clearly shows that the oxygen level was low before and high afterwards, it was still not as high as we see today, but it was definitely significantly larger compared to the Archean times.

Now, let us try to understand what are these evidences that tells us that there was no oxygen or very little oxygen before this geo event and afterwards it increased. So, we are now talking about a time which is in Proterozoic and Archean. So, we are going to look at somewhere around 2.4 billion years ago. So, which will be in Proterozoic but more about early Proterozoic. So, we are going to look at Archean and early Proterozoic.

So, what do we know about Archean? We know that there was life in Archean, there was also liquid water, there was enough the temperature has cooled down significantly, there was rock, we only have to solve whether there was oxygen or not. And that is what we are going to look at this GEO event.

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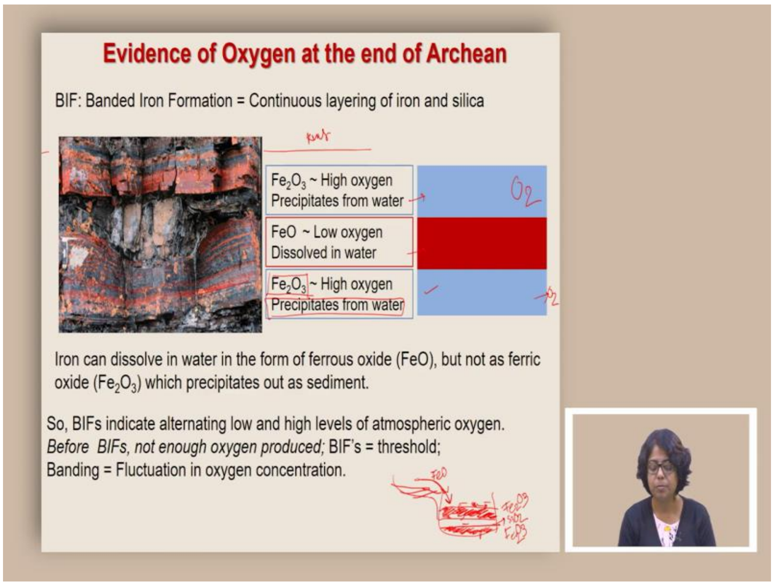

So, the evidence of oxygen at the end of Archean comes from different sources of information. One such a thing is called BIF or banded iron formation, this is a continuous layering of iron and silica. So, if you look at a banded iron information, what you are going to see there there are red bands and then there are blueish brands. And these two have very different composition.

And these bands are information sometimes are extended all the way for few kilometres. So, it is a really large accumulation of iron and silica, which are continuous. And from the laws of stratigraphy, we know that if we are talking about continuous that means all of them form together. Now, let us take a look at the composition of them.

So, what we find is that there is a variation in terms of the composition, there is one layer where the iron concentration is quite high, and it is in the form of Fe2O3, this Fe2O3 can only precipitate if oxygen level is high, then that means that it cannot when it gets oxidized, it cannot be a ferrous oxide, it will basically convert to a ferric oxide and ferric oxide cannot be dissolved in water, they will precipitate that is the rust.

So, that is why they are going to precipitate and this layer, this blue layer is carrying all these precipitation of iron ferric oxide and therefore it must be indicating a condition of rich in oxygen, high oxygen concentration. Now, we come to some other layer which is red in color. And there we see mostly silica, and it does not have the interpretation is that this is the time where we do not have enough oxygen and therefore, the iron can be in ferrous oxide form which is soluble in water.

And therefore, they can precipitate, they do not have to precipitate out of the water, they can still be in solution. But then we again have layers which are indicating high concentration of oxygen. So, there are a couple of questions. One is that why it is changing. Secondly, why do we find this massive deposit of ferric oxide, what we do not find in the early Archean, we do not find it beyond level of Proterozoic.

So, what happened during Proterozoic and this is one of the critical points where these GEO is established. So, one interpretation is that during Archean because of the low oxygen concentration, whatever continents were there, and when they were getting eroded, all of these eroded material could stay in solution for longer time. So, even if they were eroding Fe, it may be in the FeO phase.

It can be carried in water and be deposed and be in the ocean for a longer time, because it is still in a FeO phase and therefore it is not precipitating. And then if there is a change in oxygen concentration and the oxygen concentration increases, then everything that was partly dissolved in ocean water will start to precipitate. And once it starts to precipitate, it is going to create a layer which is going to be rich in this Fe2O3 because that stuff is that is going to be created during high oxygen intervals, converting this FeO to Fe2O3 and this will precipitate.

But then let us consider a situation where the oxygen level is again low. Then this phase is going to continue this is not going to precipitate. The only thing that is going to precipitate is going to be silica. So, you are going to form a layer which is rich in silica. Again, another layer where this process repeats and then we will have high concentration of Fe2O3. And this is how the layering started. Why do not we find such BIFs modern day?

Because whenever the continents are getting eroded, because of the availability of oxygen, all that FeO gets converted to Fe2O3 and immediately precipitates right there, it cannot really get transported to a basin where it can deposit for so long and with such a high volume. So, probably this BIF the contiguity of BIF indicates the heavy concentration of iron in solution that was building up during the entire Archean and eventually precipitating out of that whenever there was an increase in oxygen concentration.

But what created that oxygen concentration is a mystery. But what we know today that the primary contributor to oxygen concentration or increasing oxygen concentration is photosynthesis. So, one idea is during this time, probably there were development of photosynthesizing organisms, not completely developed plants, but probably bacterial composition who are responsible for photosynthesis, and therefore releasing oxygen.

And if you release oxygen, that is going to build up over time, after oxidizing all the available material, it is going to still build up over time that we see even today. So, these fluctuating oxygen concentration could have been response to photosynthesizing organisms, responds to seasonal fluctuation, but it is still not clear what created such distinct fluctuation.

But one thing is very clear from the observation that during early Archean, we do not find these BIFs, we started finding these BIFs, which correspond to increase of oxygen during these GEO events. And once we cross Proterozoic, there was not much available FeO to precipitate and therefore we do not see major development of BIFs afterwards.

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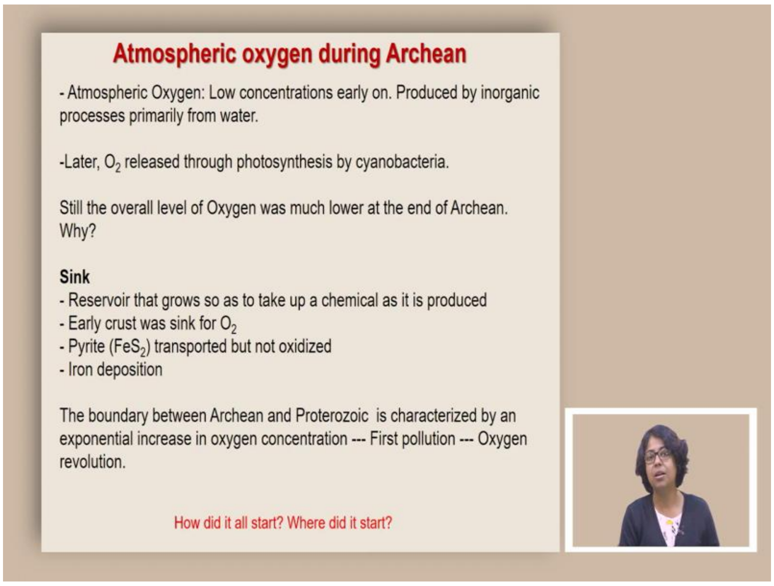

So, atmospheric oxygen during Archean must have been low. And even when it increased, there was the overall level of the oxygen must have been lower at the end of the Archean because even if the oxygen was increasing, there was enough material on the ground, which was constantly taking up this oxygen and getting oxidized to form other minerals, such as Fe2SO4. So, everything that was being in the reduced form with the addition of oxygen will get to convert into an oxidized phase and therefore sucking up the oxygen from the atmosphere.

So, the overall concentration of oxygen in the atmosphere probably was still low. And this leads to speculation that what was the effect of such oxygen increase during this time, because oxygen is a very potent gas and groups which evolved during Archean at low oxygen concentration must have been facing a situation which is similar to an environmental pollution, there was this potent gas that they were not adapted to, and probably it killed many organisms which were only adapted to a reducing condition.

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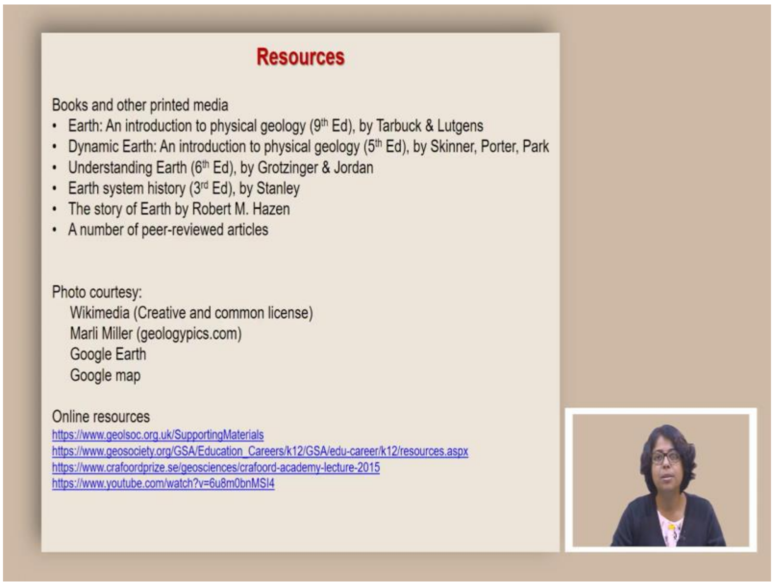

So, in summary, today, we learned about some of the evidences of life and what are the timeframe that we get these evidences from. We talked about indirect evidences in form of stable isotopes. We also talked about indirect evidence is in the form of crease fossils. We talked about some of the direct evidences in terms of microfossils.

Then we talked about a phenomena that happened end of Archean Proterozoic, which is the great oxidation event, which helps us to understand what was the oxygen condition like in the atmosphere of Archean and what was the animals like during Archean, so it was quite clear that during Archean there was life, but that life was not adapted to oxygenated environment. And then we go to Proterozoic and we started seeing a more oxygenated environment. Here are some of the resources that I used to make the slide.

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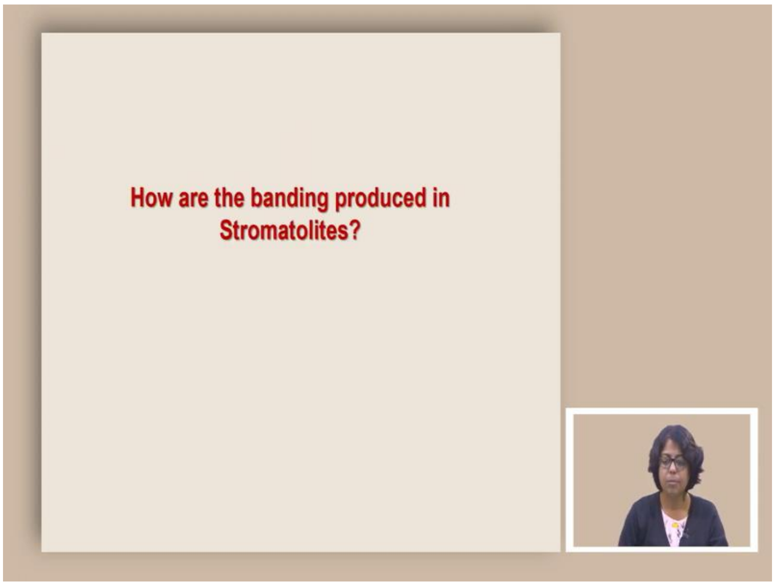

And here is a question for you to think about. Thank you.