Climate Change Science
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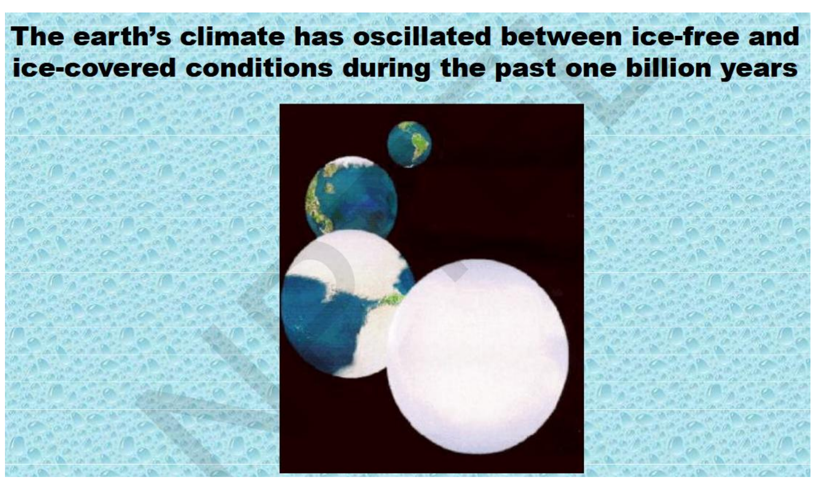
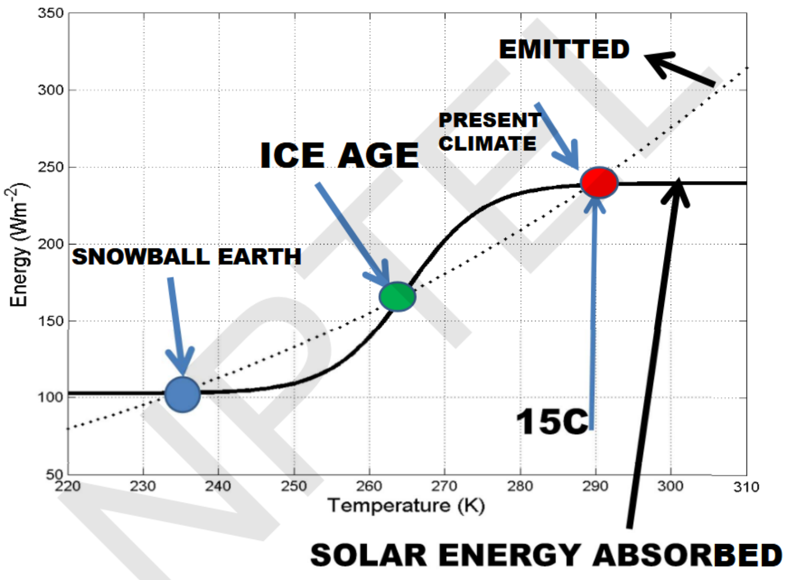
Lecture – 39
Snowball Earth

In today's lecture, we are going to discuss a very unusual event that occurred about 600 million years ago. This is called the Snowball Earth. That is the time at which the entire Earth was covered with ice. Now, this was not realized till recently. If you recall, we had mentioned in the very first lecture that Earth's climate has oscillated between ice-free conditions and ice-covered conditions during the past billion years. But the actual evidence that this has happened was obtained only recently.



Now, you must remember that the fact that the Earth's climate had oscillated can be obtained from a very simple energy balance model. If you recall, we discussed this very early in this course: that if you balance the energy coming in—that is, the energy absorbed from the Sun by the Earth-atmosphere system—and the energy radiated to space, in steady state, the two are in equilibrium: the emission and the absorption. The black line is absorption, and the dotted line is emission (in the figure given below).



We see that there are three possible solutions. That is because the absorption curve is complicated. It is shaped like an S-curve. That is because if the Earth's global mean temperature is very low, then the entire Earth is covered with ice. Well, if it is almost ice-free like today, it will be around 15ºC or 288ºK. And if it was like the last ice age, 20,000 years ago, it will be somewhat cooler and partly ice-covered. So, the amount of ice covering the surface of the Earth determines the Earth's albedo or reflectivity.

So, because of the unusual variation of the absorption of radiation, this black line is S-shaped, while the emission is a somewhat simple curve, and they intersect at three points for the present incoming solar radiation.

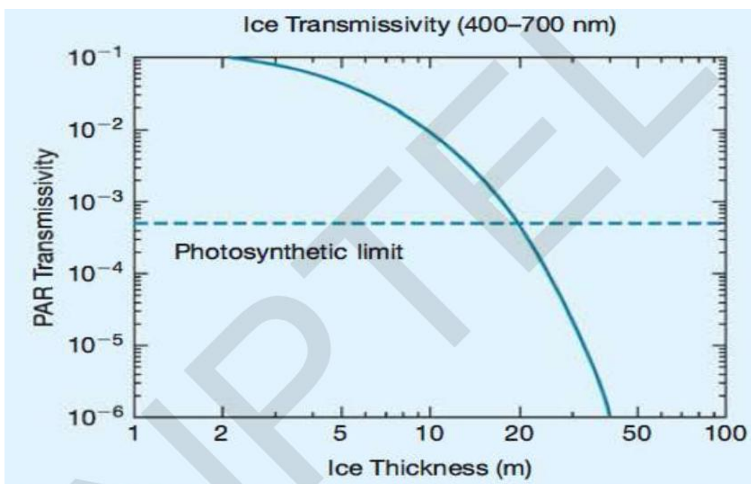
So, we had already discussed a lot about these two—even the present climate and its variation and what happened in the last ice age. We do not discuss this possibility much because, till recently, we were not sure whether this actually occurred in the past history of the Earth.

The person who first derived this equation in 1969, Mikhail Budyko, assumed that if Earth was covered with ice, there would have been no life on Earth, and such a solution is not possible in the real world. But he was proved wrong.

So, most people thought if you have an ice-covered Earth, no photosynthesis is possible. So, life as you know it, which depends on photosynthesis, would not be there after this event.

In 1969, Mikhail Budyko assumed that if all the earth was covered with ice there would have been no life on earth and hence such a solution was not possible

But the discovery that indeed there is evidence—proxy evidence—showing that Earth was indeed covered with ice completely changed the whole picture. Now, why are people worried? Because as the thickness of ice that is covering the Earth goes on increasing, the amount of photosynthetically available radiation (PAR) goes on decreasing, and if it goes below a certain limit, photosynthesis is not possible.

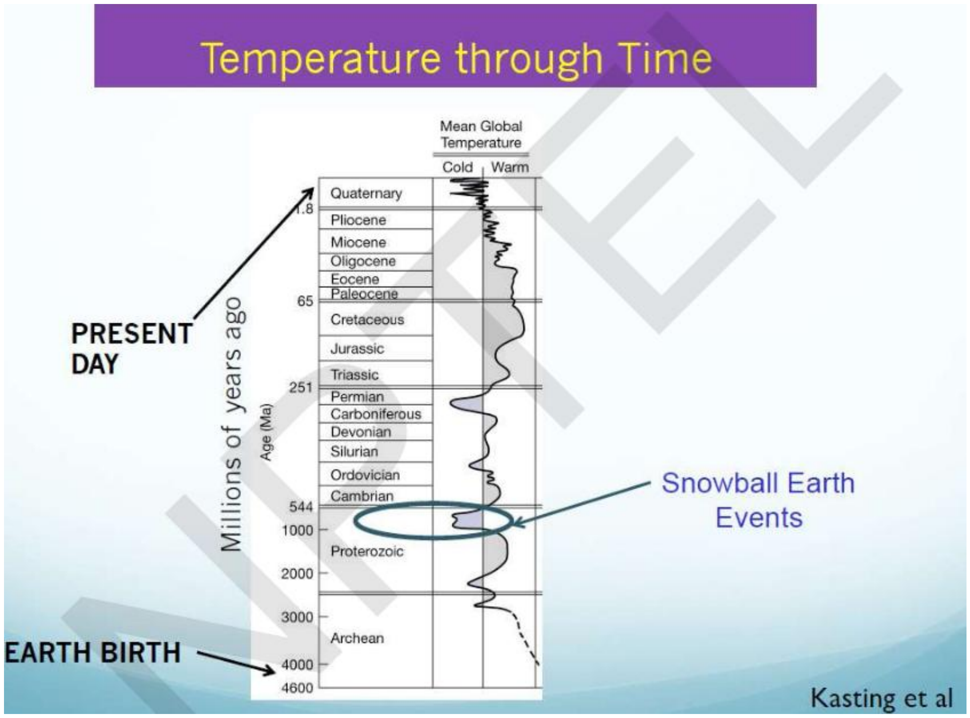


BOX FIGURE 12-2 Visible light transmissivity (400–700 nm) versus depth for clear ice. (*Source:* C. P. McKay, *Geophysical Research Letters* 27, 2000, pp. 2153–2156.)

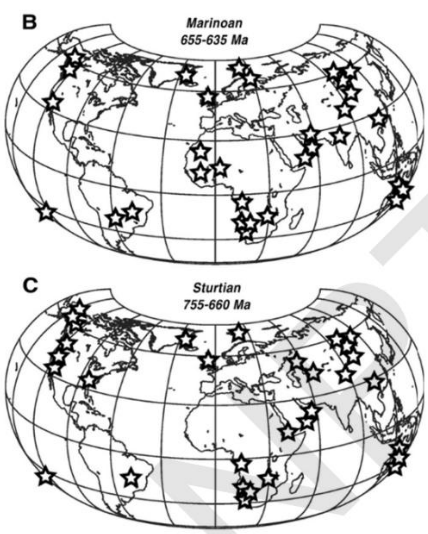
So, people felt that if ice of the thickness of 20 meters or above ever existed all around the Earth, then life could not have survived. So, that was the basis of the assumption that Snowball Earth could not have occurred.

But proxy data on global mean temperature shows that there was a period around 600–500 million years ago when the temperature of the Earth was sufficiently low that Snowball Earth could have occurred.

The figure below is from the work of Kasting et al.



When people went looking for evidence, they saw two periods: the Marinoan, between 635 and 650 million years ago, and the Sturtian, 660 to 750 million years ago, when rocks which were unearthed in these parts of the Earth were found to have evidence of glaciers.



Places were rocks show evidence of glaciation when they were in the tropics more than 600 million years ago

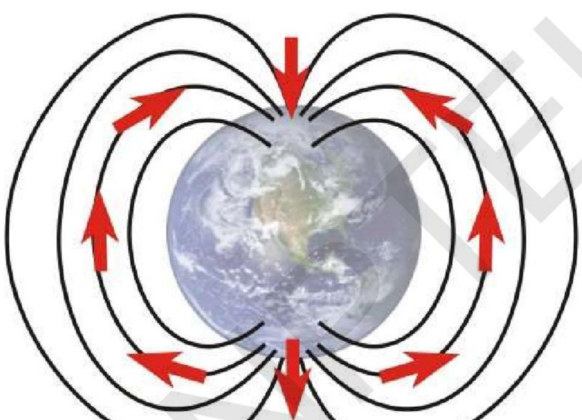
Not only that, these rocks—which are now at very high altitude, like Canada and parts of Europe and Australia—were not at this place; they were near the equator. So, how do you know that? That is based on paleomagnetism.

EARTH'S LANDMASSES were most likely clustered near the equator during the global glaciations that took place around 600 million years ago. Although the continents have since shifted position, relics of the debris left behind when the ice melted are exposed at dozens of points on the present land surface, including what is now Namibia (*red dot*).

These extreme glaciations occurred just before a rapid diversification of multicellular life, culminating in the so-called Cambrian explosion between 575 and 525 million years ago. Ironically, the long periods of isolation and extreme environments on a snowball earth would most likely have spurred this evolutionary burst.

In 1964, W. Brian Harland of the University of Cambridge pointed out that 600 million year old glacial deposits are found in every continent

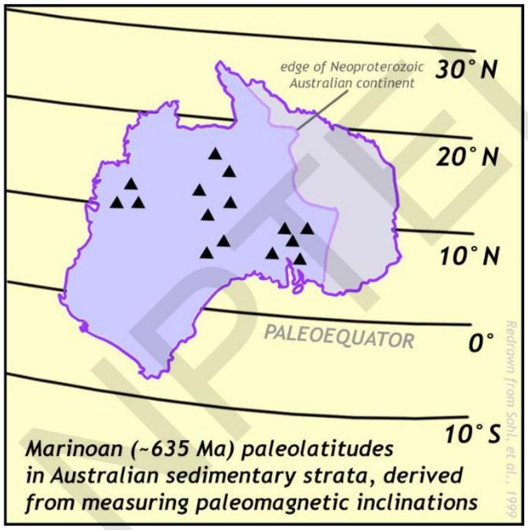
When rocks form on Earth—that is, they solidify from molten lava—they essentially freeze the orientation of the particles. The magnetic orientation with reference to the place where they became solid rocks. So, these rocks were around the equator 600 million years ago. They are now much farther away, but because we can find the paleomagnetic evidence, we argue that these rocks, when they were formed, were actually near the equator.



When a rock solidifies it retains the magnetic orientation at the time of its solidification Hence, we can infer the original latitude at which the rock was formed

Paleomagnetism depends on the fact that there are magnetic lines of force on Earth because molten lava is made of iron and it is circulating. If the rock is formed at the North Pole, then the orientation of the magnetism will be vertical. Either North Pole or South Pole. If it is formed around the equator, it will be in horizontal orientation.

This amazing technique will tell us where the rock was when it was solidified. Based on this evidence, people are saying that the rocks which are looked at today at various latitudes—which show evidence of glaciation—were actually in the tropics 600 million years ago.



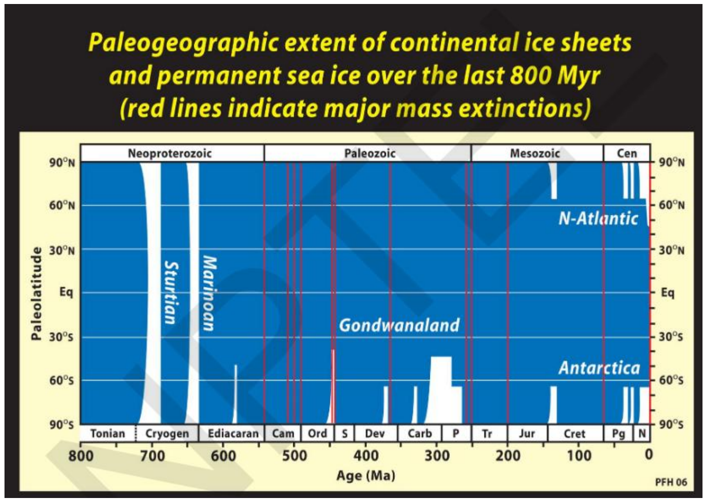
Here is an example from Australia where a lot of evidence came from. Australia now, as you know, is at 20° South, but 600 million years ago, during the Marinoan period, these rocks were close to the equator at 10° North. So, these rocks show evidence of glaciation.

That means rocks close to the equator had ice sheets on top of them, and those ice sheets, when they moved, created evidence of glaciation. So, this is the evidence which was gathered over the last 60–70 years, which enabled us to believe that there was a Snowball Earth.

Geological data has shown that two Snowball Earths occurred in rapid succession and were very unequal in duration. The first one lasted 58 million years and the second one only lasted 5 million to 15 million years. So we don't know why there is this great disparity in how long the glaciations lasted. And why was it that there was just this short interval between the two? There's only about 10 million years when there was no ice at all and then suddenly the planet went back into Snowball Earth. So why two in rapid succession?

Glaciological data has shown that two Snowball Earths occurred in rapid succession and were of unequal duration. The first one lasted for 58 million years. The second one lasted for only 15 million years.

First of all, we do not know why the duration was so different and why this global glaciation occurred during this period. There was a period of 10 million years when there was no ice at all, and then suddenly the planet went into Snowball Earth. So, this is a puzzle which has been mostly resolved in the past 30 years.

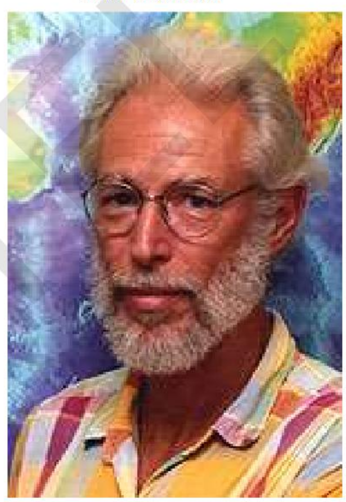


This is now the present picture. In the last 800 million years, we have evidence only for two periods—the Sturtian and the Marinoan—when ice is formed all the way from South Pole to North Pole; all the way. So, that is the Snowball Earth. But remember, this is evidence from the past. One has not been able to look at rocks from all parts of the Earth. So, we cannot be 100% sure that ice covered every part of the Earth. We can say with some confidence that ice covered most of the Earth—90 to 95 percent. 100 percent we cannot be sure of, because for that we need more evidence.

So, remember that when you come to discussion. And this also shows periods when there were mass extinctions, which we will not discuss in our course, and there are also periods when the ice came up to around 45° South. So, partly ice-covered Earth. That is not Snowball; that is a typical glacial period. For example, Antarctica and so on had glaciers occasionally, and we have them now. But in between, there was no evidence of ice.

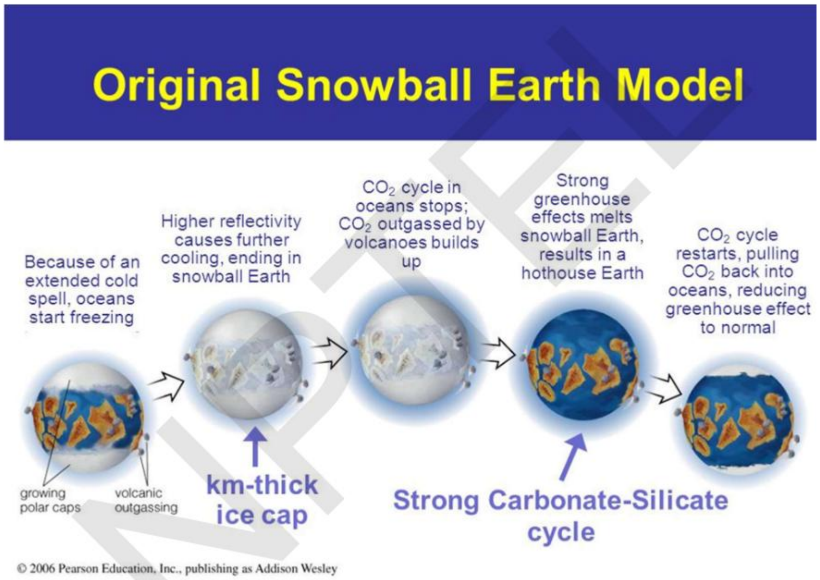
Joseph L. Kirschvink

Paul Hoffman



Now, the people who really discovered the fact that Earth was once completely ice-covered were the Caltech scientist Joseph Kirschvink, who was a biogeochemist, and Paul Hoffman, who is a geologist who went to the field and looked for evidence. So, it was Kirschvink who argued that

Earth may have been covered with ice once upon a time, and Paul Hoffman went around the world looking for evidence that this really happened. When this was first proposed, no one believed it because it looked too far-fetched based on our present-day Earth.

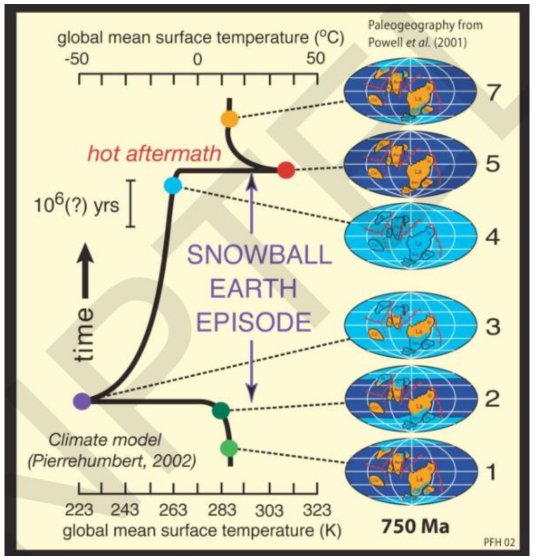


This was the hypothesis they proposed: that when most of the continents were around the equator, that is when the chances of Earth's temperature being low were highest, because the albedo of the Earth would be higher. That is what they said caused the ice to cover the entire Earth. Once ice covers the entire Earth, the carbon dioxide cycle—by which carbon dioxide is converted to calcium carbonate and it comes back through the volcanoes—that cycle is stopped because the Earth is completely ice-covered. There is no photosynthesis, so there is no possibility of a carbon cycle.

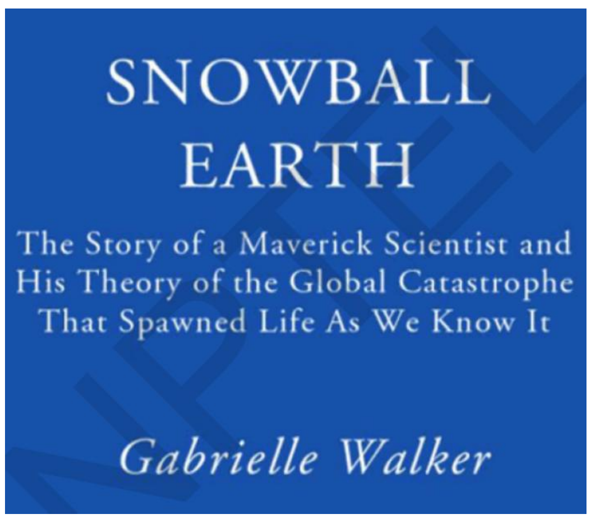
So, what happens is: when the Earth is completely ice-covered, then volcanoes continue to erupt because they are not dependent on temperature or other factors.

They depend on plate tectonics or the movement of continents. So, as the volcano goes on erupting carbon dioxide through the ice layer, the CO_2 will go on building up, and there will come a point when the CO_2 is so high, the greenhouse effect is so powerful, that it will start melting all the ice very quickly. So, this is the model they made: that the Earth gradually gets into the Snowball state, remains there for some time, and then the carbon dioxide builds up because the carbon cycle has stopped—and all of a sudden, all the ice melts in a very short period, and the Earth becomes again free of the Snowball state and will have ice only in the polar regions.

Now, what you want to remember is that this is a very rare event. During most of the other periods, it is the carbon cycle of the Earth in which carbon dioxide is converted to calcium carbonate and it comes back as carbon dioxide through the volcano that maintains the carbon dioxide amount at a reasonable level so that Earth is largely ice-free. So, you must remember that Snowball is a very special occasion. It does not occur often, and Earth being mostly ice-free—not completely—is what has happened through the history of the Earth.



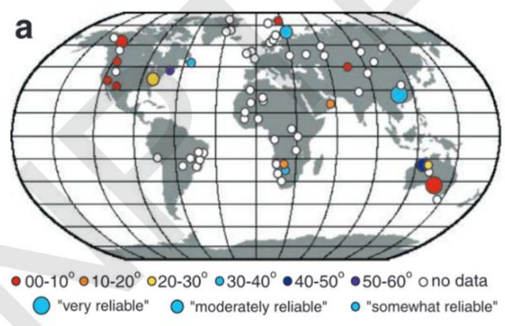
This is a pictorial indication of how we started from a polar-covered ice, slowly the ice grows, reaches the equator, becomes a Snowball, and then it comes out due to the greenhouse effect of carbon dioxide and becomes again ice-free, and the ice again builds up. So, this is a cycle that was proposed by Kirschvink and Hoffman. If you want to read about this in a simple way, I strongly recommend this book called *Snowball Earth* by Gabrielle Walker.



It is a very nicely written book, non-technical, and shows the story of this maverick scientist, which is Hoffman, and how he proposed this Snowball Earth, and how it was challenged, and how he managed ultimately to convince most—but not all—scientists that Earth was once completely covered with snow. It is a very interesting story. You must read it to understand how science progresses in the real world. When a new hypothesis is proposed, a lot of people oppose it, and then the person who proposed has to go around finding evidence to show that he is right. As the evidence builds up, the hypothesis is accepted.

You recall that Milankovitch proposed a theory of ice ages, which was not accepted. Only after he died, evidence emerged from the ice core in the polar regions that indeed, Earth went through many ice ages during the last million years. So, this is how science progresses. It is good for everyone to understand how science works. So, science works by proposing a new hypothesis. It is challenged by everyone. Then you go around looking for new evidence to support the hypothesis, and until sufficient evidence builds up, the hypothesis is not accepted. That is how science operates.

Deposition of glacial or glacial marine strata close to the paleo-equator during the Marinoan, Sturtian indicated by a growing body of reliable paleomagnetic data from different regions.



Now, the Snowball hypothesis was accepted when a large amount of evidence was gathered by many scientists from various parts of the world—evidence from rocks, showing that these rocks show evidence of glaciation, and that these rocks, which are now in Canada and in South Africa and Central Asia, were at the equatorial region a long time ago. So, you have to find rocks all over the world which show evidence of glaciation and, using paleomagnetic evidence, demonstrate that those rocks were at or around the equator when they were formed. This is the thing.

But also remember, this data is not perfect. You can see below the evidence of where the rock was in three categories: a big circle is very reliable, a moderate circle is moderately reliable, and a small circle is not so reliable. Remember that paleomagnetic evidence is not perfect. There are errors, like we saw errors in the ice age theory when we were not sure exactly when that deposit was formed.

Similarly, in the paleomagnetic evidence also, there are errors, and so not all evidence is perfect. Some evidence is very good; some is not so good. You have to very carefully combine them. But I want you to realize that there are 50 to 100 samples of rocks from all over the world which indicate that these rocks were affected by glaciers and they were around the equator. Especially you can see these red dots (in the figure shown above), which are the ones that are close to the equator.

So, based on this, what is the evidence they had? The evidence was what is called striations. That is, when glaciers move, they carry with them a lot of broken rocks and rubbish, and they actually scrape the rock at the bottom of the glacier. These are called striations. You can see them. If any of you have gone to the Himalayas and looked around the rocks, you will see evidence of striations.

Ancient glaciers left behind two kinds of signatures: (1) striations, (2) and dropstones.

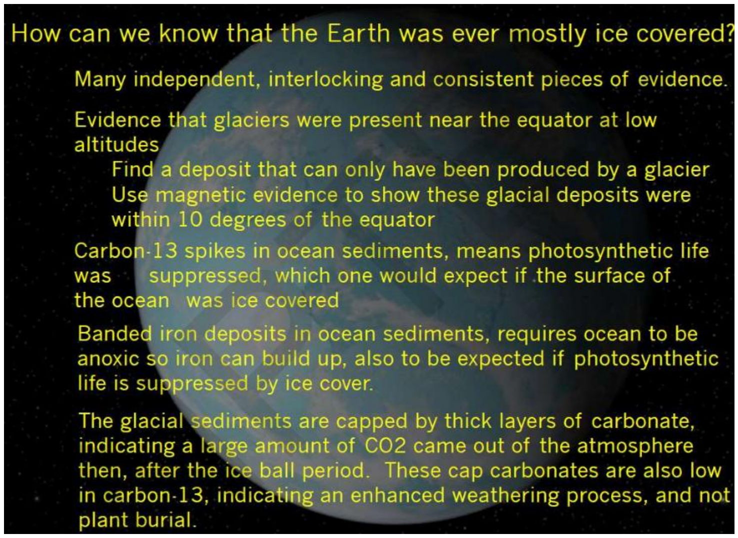
These signatures are found in in many places: for the Sturtian, there are 39 localities documented, on six continents. For the Marinoan glaciation, there are 48 places where glaciogenic signatures have been found.

The second is, as you look at these rocks, suddenly you will find rocks which are very different in character in the middle of a bunch of rocks which are of more recent origin. These are called dropstones. That is, stones which are dropped by glaciers into some other location where they did not belong. So, these are the evidences that geologists use to identify glaciation. So, there are 48 places where signatures are obtained.

Figure. Striations

This is the evidence of the striations—these scratches on the rock. So, next time you go to the mountains, Himalayas, look around. Many people go around to these places, but they do not really see interesting evidence just around them on the rocks. There are two evidences. One, of course, is these striations—these scrapings. The second is that it also polishes the rock, because when glaciers are moving slowly, they do scrape the rock, but when there are very fine particles of dust or something, they will actually polish the rock. The rock looks very polished as well as scraped. So, in between, you will see polish and then you will see the scraping.

So, we have now a lot of evidence, independent. The glaciers that were present near the equator at low altitudes. In these sediments, we also see the isotope of carbon-13 showed a very low value, which is an indicator that photosynthesis was not there at that time. So, you have two evidences: one, there was glaciation in the tropics near the equator; and secondly, based on the carbon isotope evidence, that the photosynthesis had reduced or almost stopped, which you expect if it's an ice-covered Earth.



And lastly, there are banded iron deposits in the ocean sediments. Now, what are these? Now, you must remember that the Earth contains a lot of iron. But when there is a lot of oxygen on Earth, and if this iron is exposed to oxygen, either in the atmosphere or even in the ocean—because if atmosphere contains a lot of oxygen, the oxygen is also dissolved in the ocean—so, if there is enough oxygen in the ocean, then that iron will get oxidized to hematite, which is very red in color. So, if occasionally the Earth is completely covered with snow and ice, then this oxidation cannot occur. So, when oxygen stops, you get a different kind of iron oxide. It has a different color. So, the color keeps changing in time. Occasionally, we have hematite which is very red in color and some other iron oxide which is somewhat black in color. You will see evidence of that in the next few pages.

So, what you must remember is that three independent evidences showed us that Earth was probably completely ice-covered. One is glaciers near the equator at the ground level—not on top of the mountains. Secondly, the carbon isotope evidence showing low photosynthesis or no photosynthesis. Lastly, the banded iron formation showing that iron oxide was not forming at that time.

So, in anaerobic condition, without oxygen, the stable chemical form of iron is Fe2+, that dissolves in water. But, when it reacts with oxygen, it becomes Fe3+, which is precipitated out as hematite. So, banded iron formation formed when oxygen first started building up 2 billion years ago, but not since then because there is only one kind of oxygen, hematite.

In anaerobic conditions, the stable chemical form for iron is as Fe^{2+} ion that dissolves in water

When Fe^{2+} reacts with oxygen, it becomes Fe^{3+} which is insoluble in water

Banded iron formations formed when oxygen first started building up in the atmosphere about 2 billion years ago, but not since then, except for the end of the snowball, 600 million years ago. The complete ice cover isolated the ocean from the atmosphere, allowing it to go more completely anoxic than without ice cover

From "The Carbon cycle" by David Archer

But 600 million years ago, suddenly these oxides start forming. So, we saw alternate layers of high oxide and low oxide. The above extract is from a book called *The Carbon Cycle* by David Archer. It is a very nice book which I recommend.

So, this banded iron formation in deep water is never found in very old rocks because there was no oxygen at that time.

Banded Iron Formation (BIF) - Deep water deposits in which layers of iron-rich minerals alternate with iron-poor layers.
Red beds (continental siliciclastic deposits) are never found in rocks older than 2.3 billion years ago, but are common during Phanerozoic (relatively recent) time. Red beds are red because of the highly oxidized mineral hematite (Fe2O3), that probably forms secondarily by oxidation of other Fe minerals that have accumulated in the sediment.

So, these hematites, which form when there is oxygen (Fe_2O_3), occur due to oxidation of iron after it is deposited.

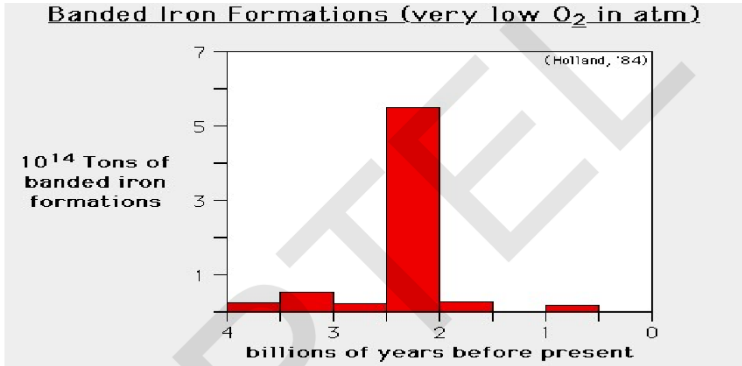
So, modern seawater contains less than one part per billion iron because iron is mostly oxidized. Joseph Kirschvink, whom we mentioned, argued that the presence of banded iron formation indicates there was a time when Earth's atmosphere had less oxygen or the ocean was covered with ice. Of course, Earth had less oxygen if you go beyond two billion years. After two billion years, oxygen started accumulating in the Earth due to photosynthesis.

Modern sea water contains less than 1 PPB of iron because iron in oxidized state is insoluble.

Joseph Kirschvink argued that the presence of Banded iron formation(BIF) indicates that there was a time when earth's atmosphere had less oxygen or ocean was covered with ice.

During the last billion years, oxygen was there. If the oxygen was there, then you should get banded iron formation. You should get only one kind of iron. Since he saw banded iron formation, he argued that Earth was covered with ice, but nobody accepted that hypothesis.

Now, the evidence of banded iron formation is seen only during certain periods in the Earth. So, it was formed—you can see the amount of iron in the last period when oxygen started forming—but in the last billion years in which you have more data, the only time it formed is in this period where we believe there was Snowball Earth (please refer to the image shown below).

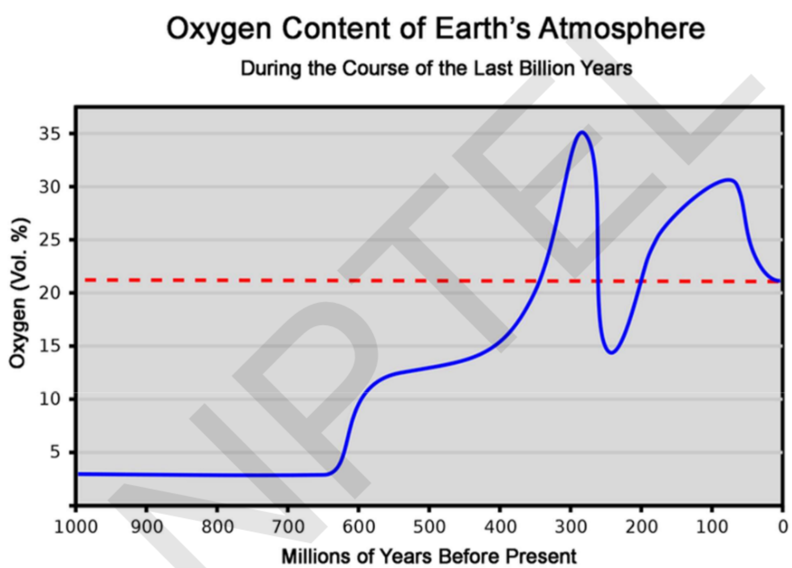


Very Large Fe Deposits

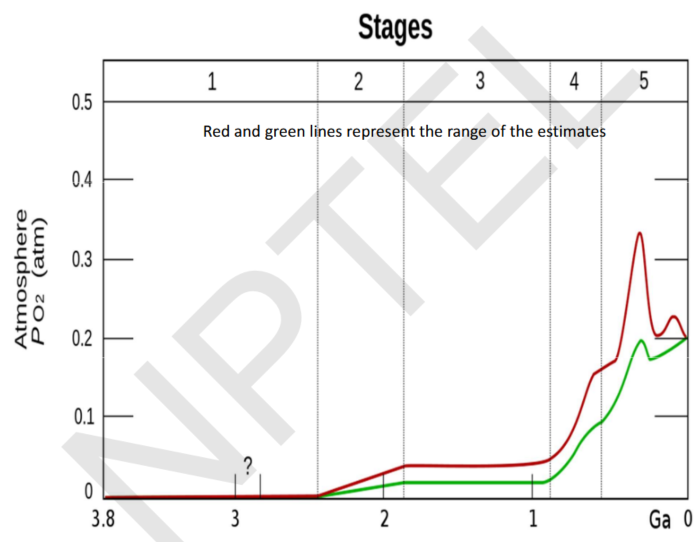
Continent	Area	Age (10^6 yrs)
Africa	Transvaal, S.A.	2100–2600
Australia	Hamersley Range	2400–2700
Eurasia	Krivoi Rog, Ukraine	1900–2600
North America	Labrador Trough, Canada	1900–2500
South America	Minas Gerais, Brazil	2000–2700

HJS/LP

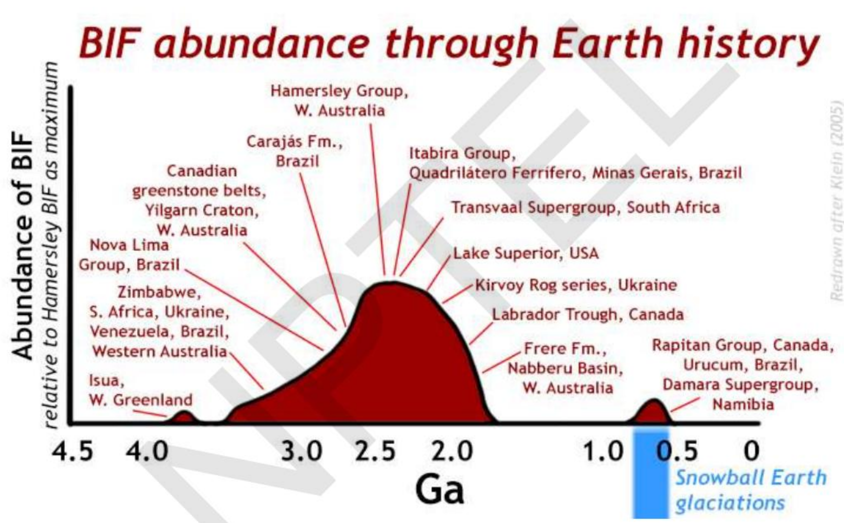
Now, the oxygen content of the Earth has varied through time. You look at the last billion years—there was hardly any oxygen on Earth. Then, after photosynthesis and various other factors, it started increasing. It went through a high and then it started declining and again it oscillated. But in the recent years, it is around, as all of you know, 21 percent.



In the past, it fluctuated a lot depending on photosynthesis and other factors. So, our interest is in the last 600 million years, where oxygen has gone up to 35% and gone as low as 15%, but most of the time is around 21%. But remember, this is not perfect. It depends on a model because to infer oxygen level in the past is not easy. You have to do it indirectly.



So, there are two or three models, and you can see there are two different models (in the figure shown above) which do not quite agree, but they all agree that there was no oxygen more than two billion years ago. It built up slowly and then rapidly. And we are concerned about the last billion years, where plenty of oxygen was there. So, we expect all the iron to be hematite, but it was not so during this Snowball episode.



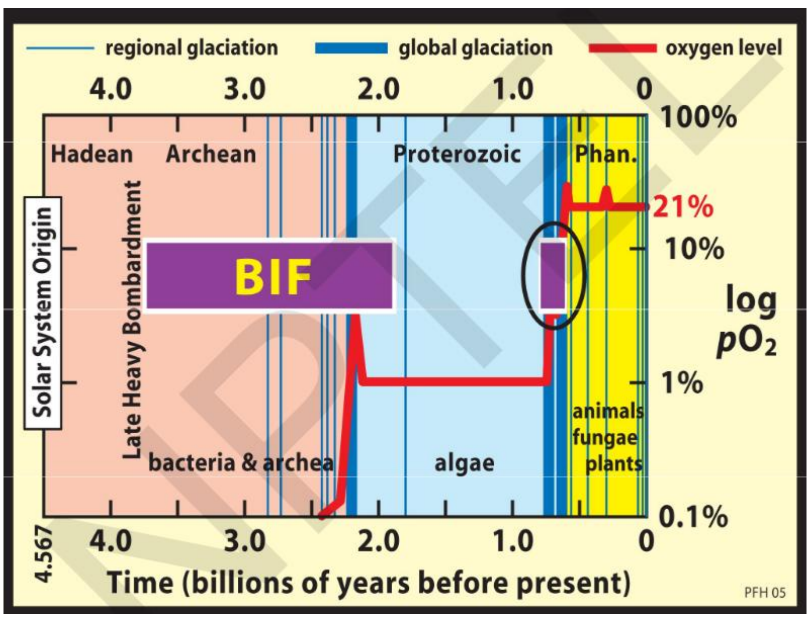
Here is an example of banded iron formation through history. When there was no oxygen, there was plenty of banded iron formed. Then, once oxygen came, we had only one kind of iron—that is, hematite. Then again, it showed a little bump in this period where Snowball occurred, and it went back to hematite later.

Please read it to understand how this banded iron formation occurs and under what conditions.

Banded Iron Formations(BIF)

Formation of BIFs requires that large amounts of soluble iron must first exist in the ocean, which can happen only if major portions of the ocean are anoxic. The reservoir also must be low in sulfate; if sulfate is present in considerable quantities, sulfate-reducing bacteria can use it as an oxidizing agent, leading ultimately to the deposition of pyrite before the iron can be deposited as oxides in BIFs. The BIFs are deposited where iron-rich anoxic water comes into contact with oxygen. Neoproterozoic BIFs do not form in the aftermath of the major glaciations, as might be expected from a scenario in which the ocean reoxygenates upon deglaciation. Rather, they are interbedded with or below diamictites and sometimes exhibit glacial features such as dropstones. The way to fit this into the Snowball picture is to assume that the deep ocean is anoxic—and also low in sulfate because of the cessation of land weathering—but that limited coastal oases remain oxygenated; it is in these oases that the BIFs were presumably deposited.

Shown below is a picture of the banded iron formation—not there in the first 2 billion years of the Earth.



Once oxygen came, the oxide started forming, and then it declined, and then it came again. So, we are focusing on this period where we have banded iron and we want to know if it is on account of Snowball Earth.

Here is a picture of the banded iron.

You can see the color changing quite rapidly—bright red of hematite, then some other oxide which does not have that color, then back to red, and so on. So, these were the first evidences for Joseph Kirschvink to say that something happened. You see layers of banded iron. In between, you see that there is no banded iron and these rocks are very different from rocks in other layers.

These are calcium carbonates which contain this iron oxide. So, this is called dropstone. These are rocks of a different kind which were deposited on top of one rock and then more deposition occurred above. So, this is in Canada, which is where Hoffman first looked at this and was puzzled. So, this was the first interesting evidence of a lot of banded iron, no banded iron, but evidence of glaciation, and then banded iron.

So, the argument is that when Earth does not contain much ice sheet, the ocean contains lots of oxygen. Fe^{3+} is preferred and you get one kind of iron oxide. When Earth is completely covered with ice sheet, you get Fe^{2+} because of reduced oxygen in the ocean, and you get a different kind of iron oxide.

When you see alternate layers of these iron oxide layers, you must assume that Earth was covered with ice sheet and then it was uncovered, so it alternated.

The figure shown below is from Hoffman's website.

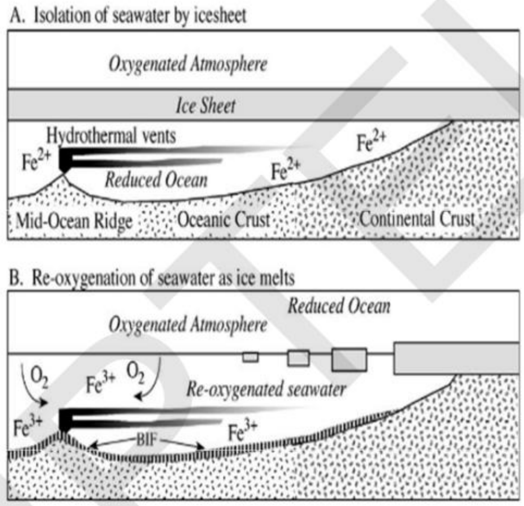


Fig. 6. Model for formation of Neoproterozoic banded iron formations (BIF). (A) Snowball Earth: anoxic ocean. Ice covering ocean surface isolates seawater from mixing with atmosphere, cutting off the source of oxygen. Oxidation of organic matter consumes oxygen dissolved in seawater, with the result that seawater becomes anoxic and reducing. Iron introduced as Fe^{2+} at mid-ocean ridge hydrothermal vents remains in solution, causing a buildup of Fe^{2+} in seawater. (B) Deglaciation: ocean ventilation. Melting of ice allows mixing of atmosphere and seawater, re-oxygenating seawater. Increased oxygen concentrations in seawater oxidizes Fe^{2+} dissolved in seawater to Fe^{3+}. This forms insoluble iron-oxides and is deposited as BIF on the seafloor. Modified from Fig. 8 in http://www-eps.harvard.edu/people/faculty/hoffman/snowball_paper.html.

Let us summarize what we have learned today.

Hard snowball is when earth is completely covered with ice
Soft snowball or slush-ball when some open water is near the equator

Geological evidence for a hard snowball

- Glacial deposits (diamictites, dropstones) at low latitudes
- Cap carbonates
- Reappearance of Banded Iron Formations (global ocean anoxia marker)
- Isotopic evidence of very high CO_2 after deglaciation

The assumption that the Earth was completely covered in ice is called "hard Snowball." There are people who believe it may not have occurred because the evidence is not perfect. There are some who believe in "soft Snowball" or "Slushball," where ice covered most of the Earth except very close to the equator. There was an area where there was no snow, so that life could survive. Now, this is the thing that many geologists and biologists believe in, because they cannot believe that if the Earth was completely covered with snow, then life would be gone. So, they wanted some region—very small region—in which life would survive for some time until the Snowball ended.

So, we do not worry about the hard or soft. We go by glacial deposits at low latitudes, of which there are plenty. Then, on top of that, there are calcium carbonate layers—huge layers—when the Snowball ended and Earth had a very strong greenhouse effect. Then again, it reappeared: the banded iron formation. Isotopic evidence from carbon-13 of very high CO_2 after deglaciation. All these are evidence. But of course, whether it is hard or soft Snowball is not so easy to convince. We will continue this issue in the next lecture.

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