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The 2024 Kyoto Prize Commemorative Lecture

Paul F. Hoffman

# A Ramble Through Geologic Time

I thought long before I went to university that I wanted to do something in geology. I collected fossils and I collected minerals, and I'd read about philosophy and a little bit about the philosophy of science. And so I wanted to do something in geology, but I didn't really know what geologists did, and I didn't learn about it in my first year of university either. All I saw was a geologist standing in front of a lecture theater.

But I was fortunate. At the end of my first year at university, I got a job as an apprentice working for a real geologist, who was making geological maps of an area in the boreal forest and lakes of northwestern Ontario. We were in the field for four-and-a-half months, a party of four people, the party chief, who was making the maps and three students.


Fig. 1

We didn't see anyone else except the pilot of a bush plane, who came in once a week and dropped off some food, although we were usually out of camp when he came (Fig. 1).

Four-and-a-half months, we were in the northern Ontario bush making a geological map, which meant going out every day and walking through the forest, and whenever you see a rock that you were sure was part of the bedrock and not something that glaciers had moved, seeing what it was and identifying it and seeing how it was oriented and trying to put it into your developing picture of the structure and history of the area.

Or other days, you'd paddle a canoe along the lakeshores because there's a lot of excellent exposure along the lakeshores, and so a sort of outcrop, which is where a piece of bedrock is exposed, outcrop by outcrop, you'd build up this view of what's going on. And sometimes nature helps you out.

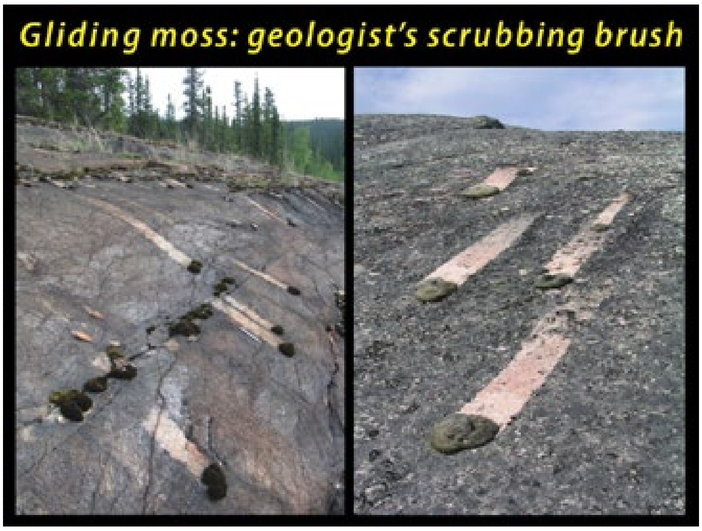

Fig. 2

A lot of times, the rocks are actually, you can't see them because they're covered by lichen. But fortunately, there are clumps of moss, which very, very slowly, increment by increment, millimeter by millimeter, slide down the slope, and they go so slowly that the lichen where they are sitting dies because it's in the dark, and so it leaves behind it a streak where the rock is beautifully exposed, and you can see exactly what it is because there's no lichen (Fig. 2). So nature actually prepares the rock in advance for the geologists to come and investigate.

Fig. 3

But more seriously, many people think that geological mapping must be pretty routine work, I mean, you're just putting colors on a piece of paper representing different rocks. But actually, it's real science in real time because every time you go to a rock outcrop like Fig. 3 and then figure out what it is and how it fits into your picture of the regional structure and its history, and once you've done that, then you look out there and you see all these other rocks that you could go to, but you don't have time to go to them all. And so you have to decide which ones you're going to go to. Of course, how you decide is that you make a prediction of what each of those rocks should be according to your understanding of the structure and the history.

Therefore, the one you need to go to is the one that would be most devastating for your understanding if it isn't what you predict it would be. And I would like to think that I have never gone to an outcrop without an expectation. So, geological mapping is not routine: it is observation, synthesis, hypothesis, and test, in real time, on the time it takes you to walk from one rock to another. When you come back in the evening, you're physically tired, but mentally you're just completely exhausted.

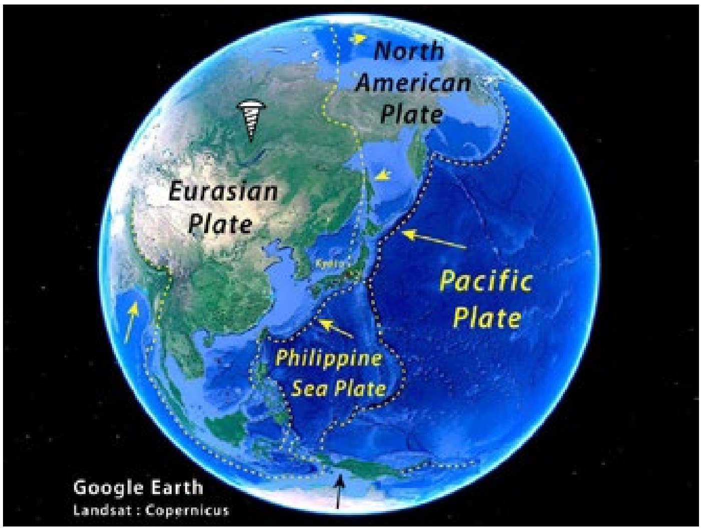

Fig. 4

As it happens, Kyoto stands at the junction of four tectonic plates (Fig. 4). The Eurasian, North American, Pacific and Philippine Sea plates all come together very close to here. This idea of plate tectonics, that there are large sectors of the Earth's surface that are in motion relative to each other, revolutionized Earth sciences in the 1960s. In fact, precisely during the period at which I was at university, and as I jokingly said yesterday, if only we had known. And my work basically was to demonstrate that plate tectonics has been going on for billions of years.

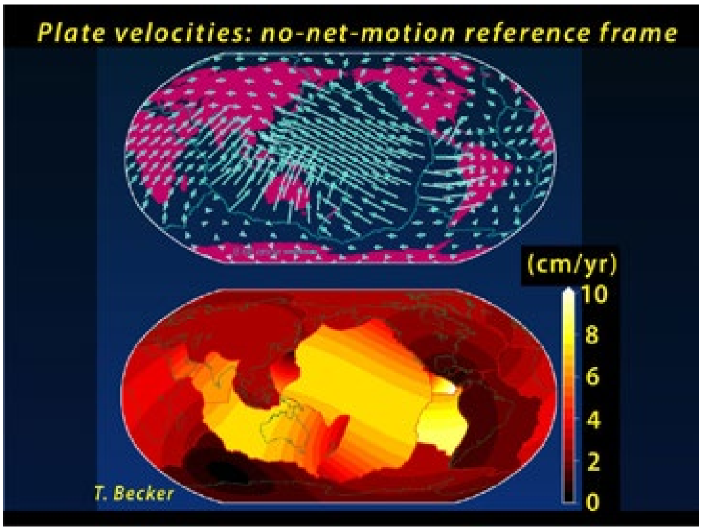

Fig. 5

Here are two depictions of the motions of the plates, so to get you oriented, that's Africa and Eurasia, Australia, Antarctica, South America, North America, and then there's West Africa again (Fig. 5). The arrows indicate the direction of the plate motion, and the length of the arrow is proportional to the velocity. The same map is shown on the lower panel, except that it is colored according to velocity. So, the very bright colors are the plates that are moving rapidly, and the darker colors are the plates that are just hanging around. They're not doing much at all.

And what you see is that there's only a small number of the plates that are moving rapidly, the India-Australia Plate, the Pacific Plate, the Nazca Plate and the Cocos Plate, and those are the plates that have trenches along a large fraction of their margin. And the motion of the plates is towards those trenches. Those trenches are places where the plate bends down and is actively sinking; it's plunging back into the mantle from which it came.

Only the oceanic plates can do that because they're negatively buoyant; they want to sink. The continents are like life jackets. They resist subduction, so they hang around at the surface.

I mentioned yesterday that one of the things I discovered from looking at plate tectonics from a perspective of billions of years is that the continents have undergone this stately dance where they all come together for a while, and then they break up and disperse and then they come back together, and again, now they're in a different location and a different configuration.

And this is of course a depiction of what is happening today. When these cold slabs of oceanic skin or lithosphere sink down into the mantle, because they're cold, they cool the ambient mantle, and as the ambient mantle cools from a long history of sinking into a trench, what happens is that the ambient mantle itself starts to sink because it's been chilled and thermally contracts. Of course that means it has to upwell somewhere else.

And so you get this rolling action of things coming towards this sinking area, which in the world today is in the northeastern part of Eurasia. And that convection, along with the act of sinking in the slabs, tends to draw all the continents towards that sinking area, just like leaves over a gutter.

So, what this means is that the Pacific Ocean is the only ocean today that is closing. All the other oceans are opening. So in effect, all the continents are moving towards each other, and they're going to aggregate right here, East Asia.

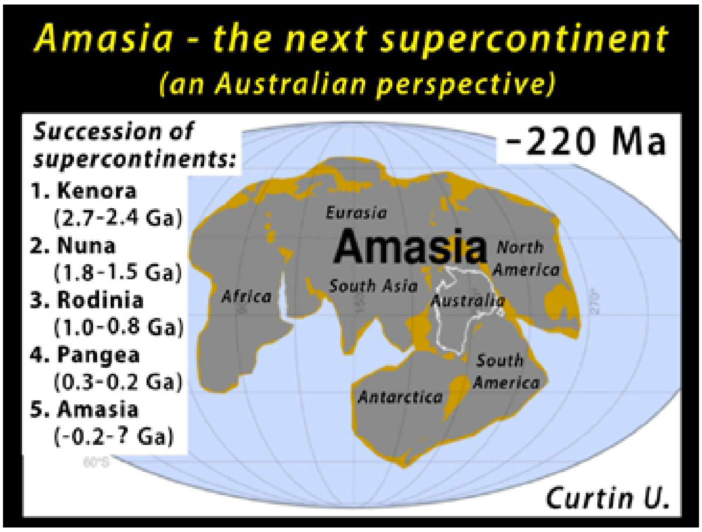


Fig. 6

Zheng-Xiang Li, Yebo Liu, Chuan Huang (2022)
https://www.curtin.edu.au/news/media-release/pacific-ocean-set-to-make-way-for-worlds-next-supercontinent/

So the next supercontinent, which I've called Amasia, will look something like Fig. 6. Australia will actually arrive before the Americas; it will have some protection. We have a little over 200 million years with which to prepare.

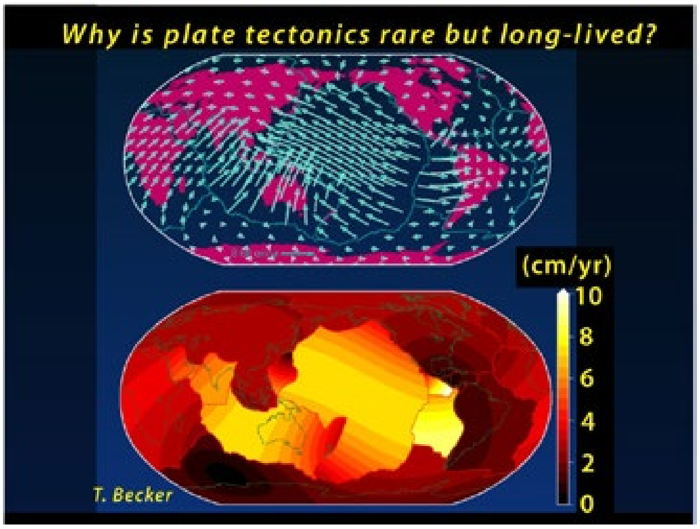

Fig. 7

Plate tectonics is very old on Earth, at least billions of years. Maybe it goes right back to the beginning. But Earth is the only body in the solar system that has plate tectonics. It's possible that Venus had plate tectonics in the past, but it certainly doesn't have it today.

So why is this?

The reason is that plate tectonics is very hard to start but easy to maintain once you get it going. And the reason it's hard to start is because you have to tear that shell. That hard, tough, cold shell, you have to tear it to get the sinking process started.

I think that plate tectonics likely started very early in Earth's history when the Earth was still very hot, the skin was thin, and it was being pelted by asteroids. I think that's likely when the tearing and the sinking of the oceanic plates began, but once it gets started, then the plate motions themselves require areas where plates are diverging, it's mid-ocean ridges, places where they are converging, where you have a lot of volcanic arcs, those plate boundaries are maintained weak and thin, and so subduction can begin there. So it's a self-sustaining process. It's easy to keep it going once you get it started.

So my prediction is, we don't have that many bodies in the solar system, so it's not that great a test, but we have a much larger, a vast number of exoplanets, and we don't know yet how to tell whether an exoplanet has plate tectonics or not, but I'm hopeful that in the not-too-distant future we'll figure out how to do that. And my prediction would be that plate tectonics will turn out to be rare but long-lived where it occurs.

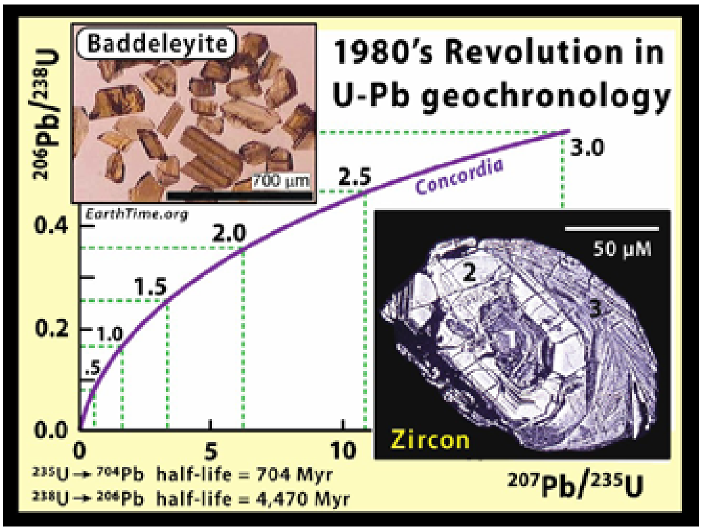


Fig. 8

I was very fortunate as a field geologist interested in tectonics that the early part of my career coincided with a revolution in geochronology, that's dating rocks by radioactive decay. I won't go into details, but there was a quantum leap in our ability to precisely and accurately date igneous rocks, rocks that crystallized from a magma using mainly this mineral, zircon (Fig. 8).

The importance of that is that if you're making hypotheses or models about historical events, cause and effect relationships are easily tested with dating because the cause must precede the effect. And in fact, anything that involves historical, working out things in a sequence, is most easily falsified by accurate dating. Dating also governs the rates at which things happen, which is another potential way of falsifying an idea. So this revolution in geochronology really converted a lot of what I was doing from competitive draftsmanship into real science, which means falsifying hypotheses.

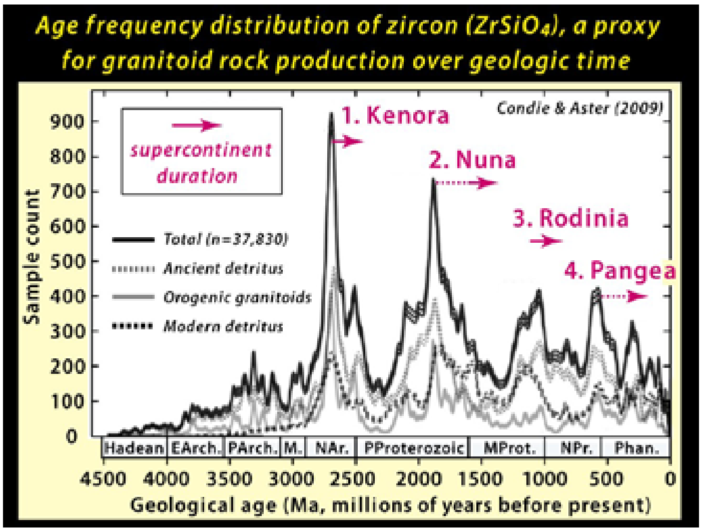


Fig. 9

Condie, K. C., and R. C. Aster (2009),
Zircon age episodicity and growth of continental crust,
*Eos Trans. AGU*, **90**(41), 364, https://doi.org/10.1029/2009EO410003.

And as it happens, if you take all the tens of thousands of igneous rocks that have been dated, both directly and from grains of sand in modern rivers and ancient rivers, and you plot them all on a histogram from four-and-a-half billion years, the beginning of the Earth, to the present, and do their frequency according to the age of that zircon crystal, which you can date each of those grains, you have these four peaks (Fig. 9). Zircon is mostly a minor constituent of granitic rocks, and granitic rocks form, most of all, when continents collide and the crust thickens and then thermal relaxation causes melting and you get large granitic bodies.

These peaks correspond to the four supercontinents that have occurred in the last 3 billion years, and Amasia is projected to be the next one.

Fig. 10

As I was nearing 50 years old, I was looking for something to do after plate tectonics, and I met this guy Joe Kirschvink, who was an old friend of mine, a paleomagnetist from Caltech (Fig. 10). He told me about this idea that he named snowball Earth, and really, the key thing was it was a self-reversing snowball Earth. He didn't actually develop the theory. That had already been developed, but he was the first one who thought it had an application to geology that this event might have actually happened. It was developed in climate science as a theoretical possibility but was assumed to have never occurred.

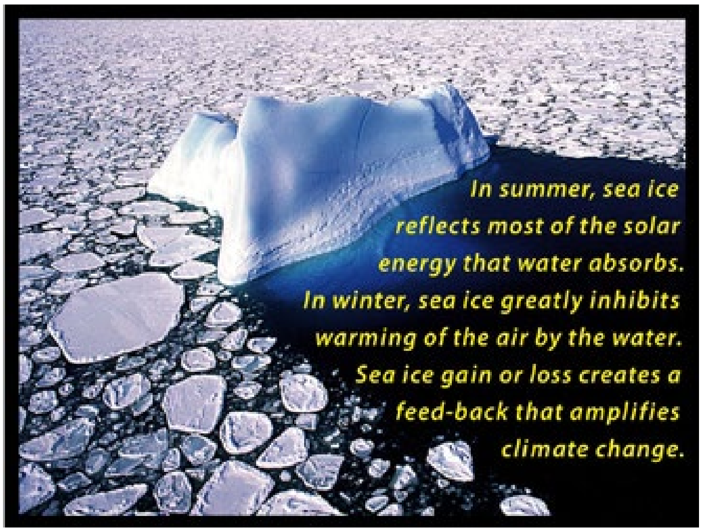

Fig. 11

The key thing is that sea ice, which can either grow or shrink, creates a positive feedback that amplifies any climate change (Fig. 11). In other words, if there's a cooling, there is a sea ice response, which is more sea ice. It amplifies the cooling, makes it colder, in addition to the original cold. And the same in reverse: if it's warming, you get less ice, so there's an additional warming.

The reason for this is that in the summertime in the polar regions, a lot of sun coming down, most of the solar energy that would be absorbed by water is reflected by the ice and lost. If it falls on the water, it's absorbed, and it warms the water, then the water warms the air. If it hits ice, it's reflected and gone, lost.

In winter, there's even a larger climate effect because if you have sea ice, it prevents the air from being warmed by the water because in the wintertime the air is much colder than the water and you would have a real limitation on how cold the air could be if the water was exposed, but if it's covered by ice, the air is a little bit warmed by the water by diffusion through the ice but much, much less than it would be if no ice were present.

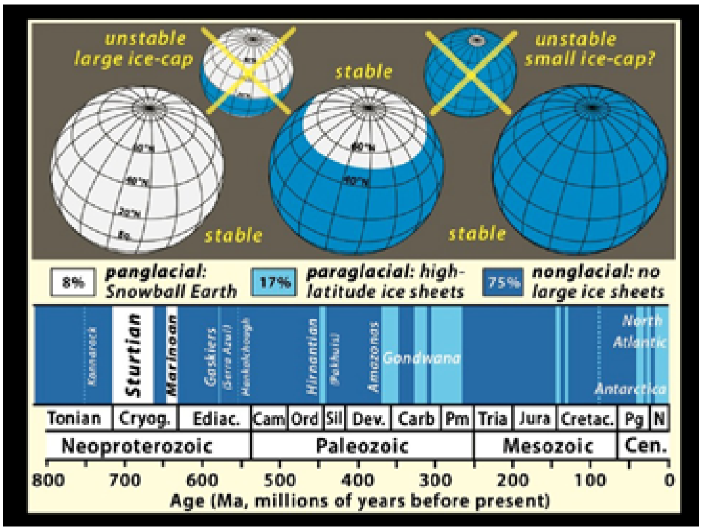

Fig. 12

So it's a very important feedback, and what climate models showed, already in the late 1960s, is that there's a tipping point in the size of the summer polar icecap. At the tipping point, the feedback becomes self-sustaining and the growth of the ice becomes unstoppable. The ice caps grow uncontrollably until they meet at the equator. Then the surface temperatures fall far below the freezing point everywhere, and the ice thickens, flows under its own weight, and heals any opening that might develop. As a result, about 99.9 percent of the ocean would be plunged into perpetual darkness. Primary food production would cease.

The same might happen, although this is much less certain, at the warming end. A very small polar cap is unstable. So the idea is that we can be in the climate we're in, which is this one (the Earth image in the middle of Fig. 12), we can be in this one (the Earth image on the right side of Fig. 12), which we were in 50 million years ago, when the late period, the dinosaurs, or we can be here (the Earth image on the left side of Fig. 12), but you don't go smoothly from here (the Earth image in the middle of Fig. 12) to here (the Earth image on the right side of Fig. 12); you go there abruptly and violently.

Climate scientists first thought there would be no escape from a global glaciation (the Earth image on the left side of Fig. 12). There would be no way of reversing that because of the high reflectivity of the ice cover, therefore it could never have happened because we are here. Therefore climate scientists assumed there was no reason to talk to a geologist. As it happened, geologists had for 90 years been sitting on data that showed that global glaciations probably did occur, but they had no idea how such a thing could occur. They had no idea there was already a theory to explain it.

It was a sad thing that the theory was there and the observations were there, but they were in different worlds because of lack of communication between climatology, which was at that time, and still to a degree, a branch of physics, and geology. My passion is to bring these fields together.

In fact, these three states, you can map that out on the climate history of the last 800 million years. You can see that about 75% (dark blue, Fig. 12) of the last 800 million years has been the state shown as the right globe (Fig. 12). And about 17% (light blue, Fig. 12) has been the state shown as the middle globe (Fig. 12), the one we're in today, and these are the two snowball events (white, Fig. 12) which have been the state shown as the left globe (Fig. 12).

Here's the base of the Cambrian (time point at the left end of the era shown as "Cam", Fig. 12). The first animals, large animals, are about here (Ediacaran, shown as "Ediac." in Fig. 12), and then these are the two snowball Earth events that occurred in rapid succession (white vertical bars in Fig. 12). The first one lasted 55 million years, the second one anywhere from 4 to 15 million years.

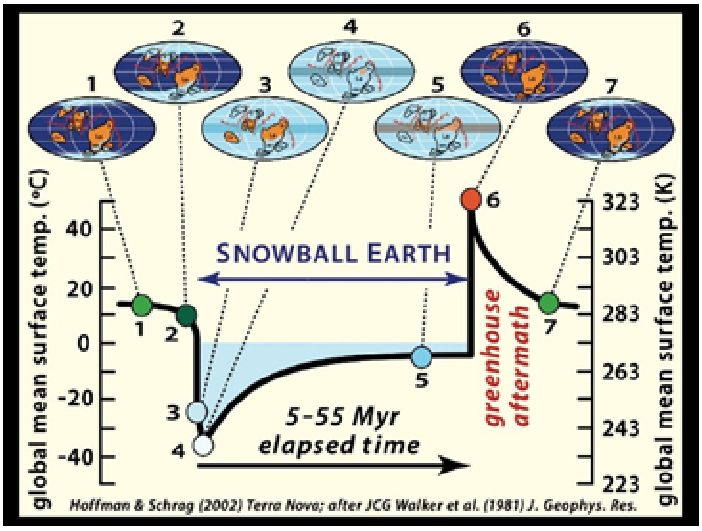

Fig. 13

The beauty of the snowball Earth ideas is that it's self-reversing, and that was first appreciated by a small group of planetary scientists at Ann Arbor, Michigan. They realized that plate tectonics would continue. Plate tectonics wouldn't care if the ocean had a kilometer of ice on it. Carbon dioxide would continue to be emitted by volcanoes as a result of the geochemical cycling of carbon driven by plate tectonics. However, the emitted carbon dioxide could not be scrubbed from the atmosphere because it's only soluble in liquid rain. It's not soluble in snow. And so, the carbon dioxide that would be coming out of volcanoes would just accumulate. And slowly, the carbon dioxide would build up, build up, build up.

If you came along and you got to that tipping point and you plunged into the snowball Earth, initially the tropical continents wouldn't be glaciated, but eventually they'd become glaciated too, that would be the very coldest period. And then, because of the accumulation of carbon dioxide over millions of years, the temperatures would rise (Fig. 13). They would rise rapidly at first and then much more slowly later on, because the temperature-CO2 relationship is logarithmic. You have to double the carbon dioxide for every increment of warming, and when you have a lot of carbon dioxide, it takes a long time to double it.

Eventually, either due to a combination of more and more greenhouse warming and the darker and darker equatorial surface because of the accumulation of dust on the surface, you reach the point where you first expose dark seawater at the equator. Then you would have the same ice-albedo feedback working in reverse. Dark water absorbs more solar energy, which increases the melting rate and makes more water, which absorbs more energy. Very rapidly, all of the ice disappears, and you're left in a torrid aftermath in which you have a combined effects of intense

$CO_2$ greenhouse but a dark energy-absorbing surface (Fig. 13).

What is beautiful about this is that it makes predictions that can be tested with new geological data. That is what drew me to the hypothesis. I thought it really deserved to be tested. If global glaciations had in fact occurred, the ramifications for the evolution of life would be profound. The predictions were that the duration of a snowball should be very long length, millions to tens of millions of years, its onset and the termination should be very abrupt and globally synchronous, and the long snowball should be followed by the hottest climates and the highest $CO_2$ the Earth has ever experienced. Now, each of those predictions has been verified multiple times.

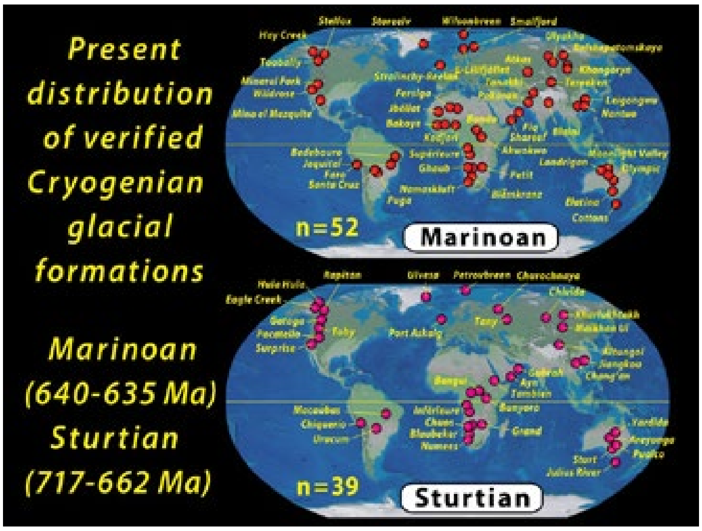

Fig. 14

Fig. 14 is a distribution of the Cryogenic glacial deposits. It’s the longer older one (bottom) and the shorter younger one (top). As you can see, they’re really widespread on virtually all the continents, except Antarctica where you can’t see very much. And it’s been known actually for a long time. I mean, not as many deposits, but the idea that they’re on, but geologists are: “Oh well, it’s continental drift. You know, you put different continents and polar regions at different times, don’t worry. It’s just like glaciation today.”

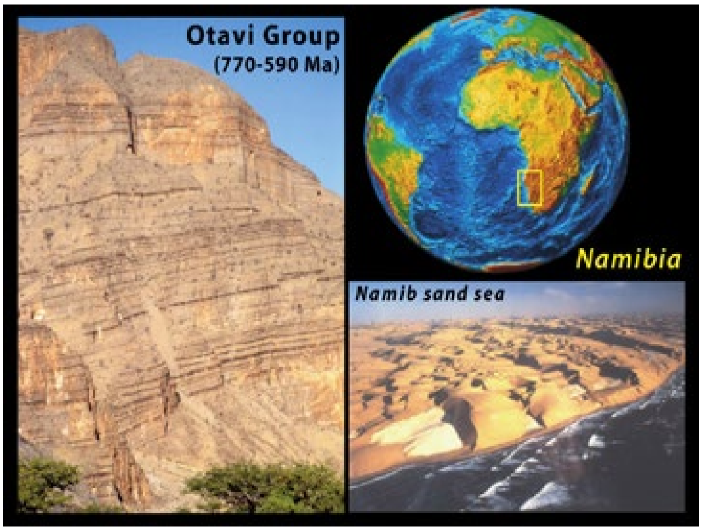

Fig. 15

But I wasn’t so sure, and one of the reasons was that many of these glacial deposits are associated with carbonate rocks, and here in northern Namibia is one of the regions that I decided to study in detail (Fig. 15). I've spent 30 years doing fieldwork there, in the northern part of Namibia on the arid west coast of Southern Africa. There is a beautiful thick carbonate succession there, which has both of those glacial deposits, certainly glacial. There's no question about it.

The importance of this is that, regardless of global climate, carbonate always forms preferentially in the warmest areas of the surface ocean. It's just basic carbonate saturation chemistry. That's why coral reefs are in the tropics. So if you have glacial deposits at sea level in the warmest part of the surface ocean, where, in addition there are no mountains from which glaciers could descend from frigid heights, that means colder areas must have been frozen as well.

So, long before we had the dating or any of these other tests, I thought this is not a normal climate. This is something radically different.

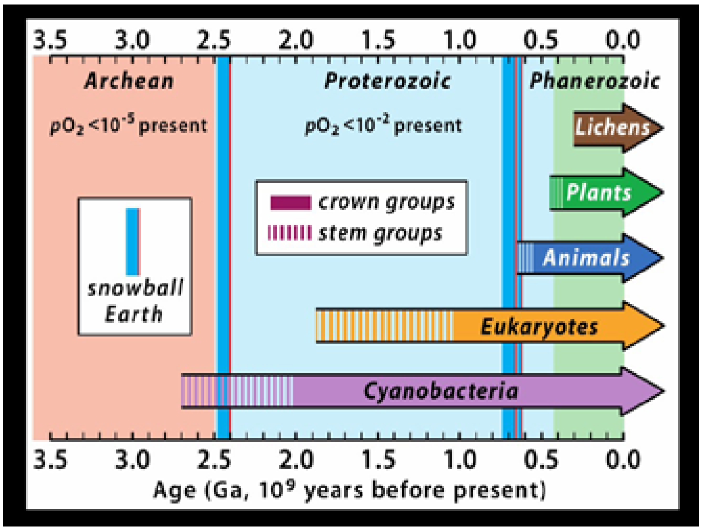


Fig. 16

Okay, what about the biological response?

Life was well evolved. Fig. 16 is a timescale again, three-and-a-half billion to the present, and these are the Cryogenian snowball Earth that I've studied (the right vertical bars in Fig. 16). This is the one that Joe Kirschvink has mostly studied (the left vertical bar in Fig. 16). It's associated with the initial oxygenation of the atmosphere. And these snowball Earth occurred after life was, quote "advanced." We had bacteria, including cyanobacteria. You had many different eukaryotes, eukaryotic algae, including multicellular algae. We had protists and heterotrophs, we had fungi. They had most of the constituents. We didn't yet have animals, although molecular clocks project the last common ancestor of animals to be in the Cryogenian.

We have actually organic chemical indicators of the first animals between those two snowball Earth events. And then land plants come later, although there are indications that a lot of the genetic toolkit for dealing with the difficulties of living on land actually may have been developed during the snowball Earth times.

So the question is, how did these organisms here survive if the oceans were completely dark and the surface was frozen everywhere?

Fig. 17

Here's what I think happened. It's interesting because it's the same thing that's happening today, except in reverse.

Deer flies, which bite your scalp, and so all field geologists know where the deer fly line is, have moved at least 500 kilometers northward in my career as a field geologist in response to global warming. I think snowball Earth, it's just the same thing in the opposite direction. So long before the snowball Earth times, there were mountains that projected above the snowline, like Mt. Fuji. And this one here is right on the equator, this is Mt. Chimborazo (Fig. 17). It was made famous by Aimé Bonpland and Alexander von Humboldt, who studied the vegetation zonation with altitude here.

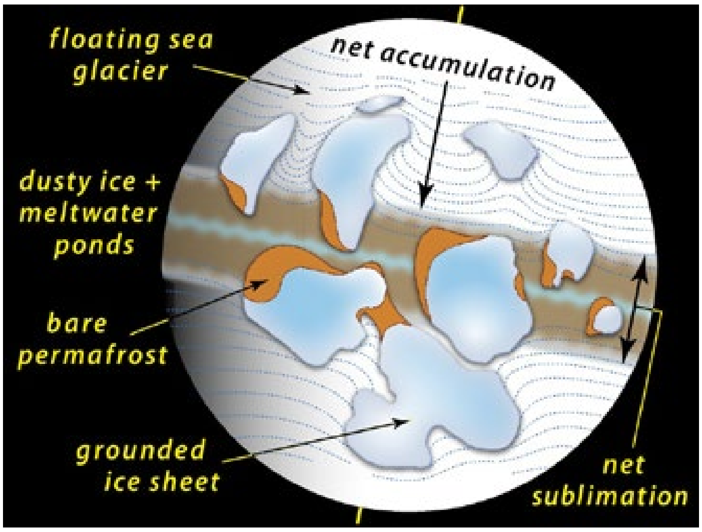

Fig. 18

So long before snowball Earth, glacial and peri-glacial habitats were colonized by microbial organisms. When snowball Earth occurred, they just moved with the ice sheet margins to the equator because that's the zone of net sublimation on snowball Earth (Fig. 18). And so they said, "Wow, this is great. Our habitat area is vastly enlarged and the cruelty of winter is greatly reduced," because you hardly recognize winter at the equator.

Those organisms that were pre-adapted, they flourished, and when the snowball came to an end and the oceans rose because the ice sheets melted, warmed rapidly and were full of nutrients, being biologically vacant. The surviving cold-adapted organisms had a choice, either to go back to the mountaintops or to restock the oceans.

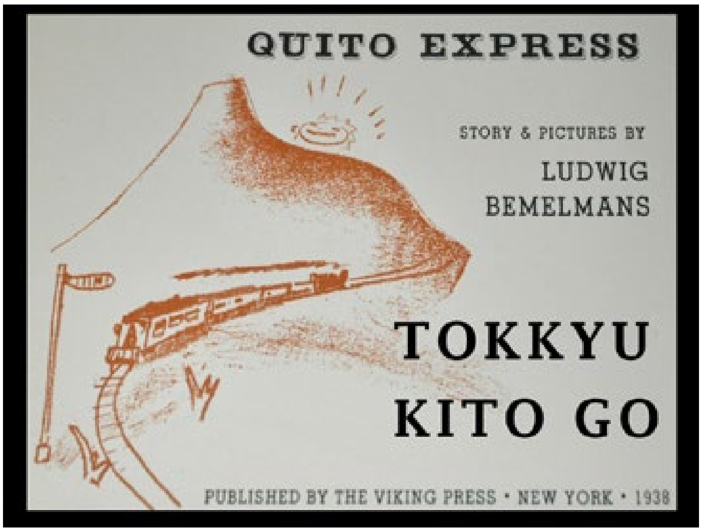

Fig. 19

I call this the Quito Express hypothesis. This is about the train that goes back and forth from Quito (Fig. 19). It passes Chimborazo Mountain down to the coastal city of Guayaquil on the Pacific just about on the equator.

Fig. 20

Now there are two ways of testing this idea, and the first is, do these polar alpine microbial ecosystems have enough diversity to account for all the radiations of life that came after? Here's where I'm greatly indebted to Japanese scientists who have been very prominent in the field of both Antarctic and Arctic microbial ecology, for a very long time, and these are very actually quite diverse ecosystems (Fig. 20).

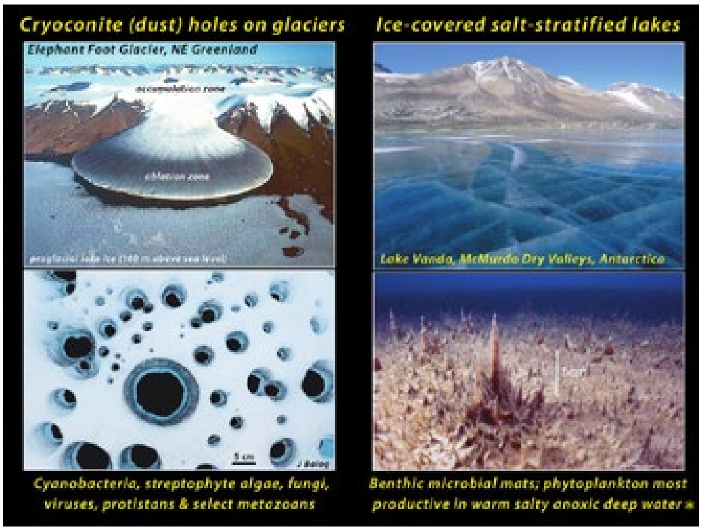

Fig. 21

*Timescales of Growth Response of Microbial Mats to Environmental Change in an Ice-covered Antarctic Lake. Hawes I, Sumner DY, Andersen DT, Jungblut AD, Mackey TJ. *Biology* **2**(1), 151–176. 25 Jan 2013. MDPI.

So here are two. This is called cryoconite (Fig. 21 left). All glaciers have an accumulation zone and ablation zone. The ablation zone is dark because it's got these holes called cryoconite holes. They are about half a meter deep in summer. They've got meltwater in winter, they freeze up. And the meltwater is there even though the air temperature is below freezing because there's a dark clump of dust at the bottom that absorbs solar energy and allows the melting.

The dark color is mostly from heavily pigmented cyanobacteria because the cyanobacteria is about 10% of organic matter. The hole hosts other organisms as well, protists and algae and fungi and even micro-invertebrates. And so that's a freshwater environment, in very bright light.

This is another one (Fig. 21 right). These are these ice-covered lakes in the dry valleys of Antarctica, and they are salt stratified because of intense sublimation. The dense bottom waters are salty and because they are isolated from the surface, they absorb solar energy and act as a heat trap. They are quite warm, anoxic, and nutrient-rich. Most of the primary productivity is there because of warmth and nutrients, despite very dim light. The environment is almost exactly the opposite of surface cryoconite holes and ponds, which are oxygenated, brightly lit and drinkable fresh water, but cold and nutrient-starved.

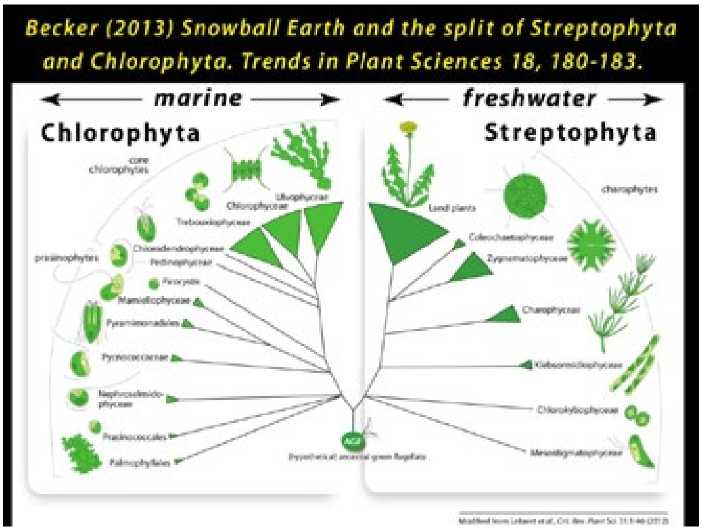


Fig. 22 Phylogeny and Molecular Evolution of the Green Algae.
Leliaert F, Smith DR, Moreau H, Herron MD, Verbruggen H, Delwiche CF, De Clerck O.
*Critical Reviews in Plant Sciences* 31(1), 1–46. 14 Feb 2012.
Taylor& Francis. Reproduced by permission of the Taylor & Francis

That actually explains why there are two classes of all green plants (Fig. 22). There are the chlorophytes, which are mostly marine, and the streptophytes, which are almost exclusively fresh water.

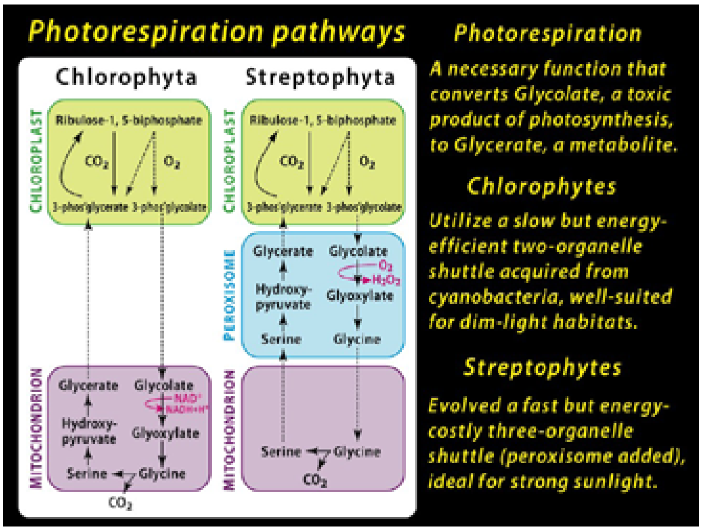


Fig. 23

And they have different photorespiration mechanisms (Fig. 23). Photorespiration is a way phototrophs get rid of toxic byproducts of photosynthesis. It's an essential function for phototrophs. Chlorophytes, the ones that would be living in the dim light in those salt-stratified lakes, retain an old-fashioned mechanism that they inherited from cyanobacteria. It's very slow, but it's very energy-efficient. So it's ideally suited for this dim light habitat under an ice cover in a lake. Streptophytes, on the other hand, have a newly evolved, three organelle-mechanism that is very fast, but it uses a lot of energy. But of course if you're at the surface of that bright sunlight, you have a surplus of energy.

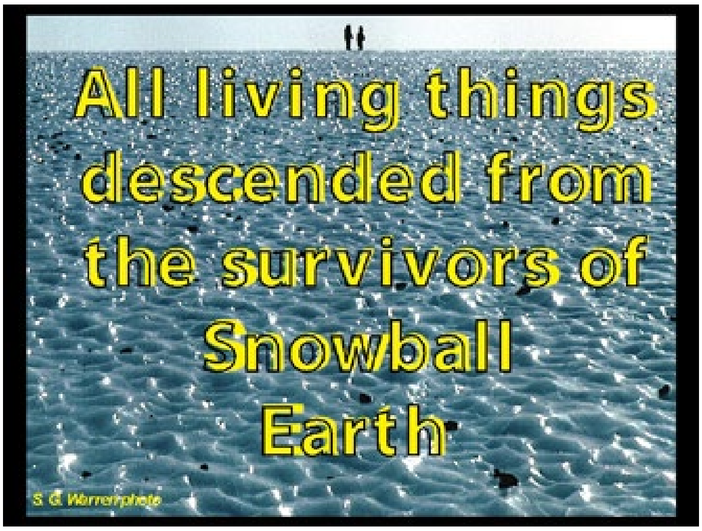

Fig. 24

Okay. So here's the bottom line.

All living things descended from the survivors of snowball Earth (Fig. 24). It's only a small subset of what had evolved up until that time. That means that earlier fossil record is additionally precious because we don't have those lineages anymore. They became extinct. But who we are is derived from the survivors. And that tells us quite a bit. If that's true, that tells us a lot about, and should be testable in the genomes of living organisms, because the genomes encode ancestry that can be mapped out on phylogenetic trees.

But we have to convince biologists that this is worth doing because it's deeply rooted in biology that life originated in the tropics, and cold environments are highly derived, and of course, but if you look at the history of life from the additional snowball perspective, the life we have could have had quite a different ancestry. I'm not saying life originated in cold water, but it lived in cold environments for a long time that allowed for its preferential survival.

I've had so much fun unearthing these unlikely stories from Earth's own past and sharing those stories with others. That's just been a wonderful thing to have devoted my life to.

Thank you very much for listening to my stories.

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You can watch the interview video after the commemorative lecture on the Kyoto Prize YouTube channel.
(https://youtu.be/uau89JLXiyw?si=_GgMLQgTTjV7AQ1i)