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## **Snowball Earth**

Ice entombed our planet hundreds of millions of years ago, and complex animals evolved in the greenhouse heat wave that followed

By Paul F. Hoffman and Daniel P. Schrag

Imagine the earth hurtling through space like a cosmic snowball for 10 million years or more. Heat escaping from the molten core prevents the oceans from freezing to the bottom, but ice grows a kilometer thick in the 50 degree Celsius cold. All but a tiny fraction of the planet's primitive organisms die. Aside from grinding glaciers and groaning sea ice, the only stir comes from a smattering of volcanoes forcing their hot heads above the frigid surface. Although it seems the planet might never wake from its cryogenic slumber, the volcanoes slowly manufacture an escape from the chill: carbon dioxide.

With the chemical cycles that normally consume carbon dioxide halted by the frost, the gas accumulates to record levels. The heat-trapping capacity of carbon dioxide--a greenhouse gas--warms the planet and begins to melt the ice. The thaw takes only a few hundred years, but a new problem arises in the meantime: a brutal greenhouse effect. Any creatures that survived the icehouse must now endure a hothouse.

As improbable as it may sound, we see clear evidence that this striking climate reversal--the most extreme imaginable on this planet--happened as many as four times between 750 million and 580 million years ago. Scientists long presumed that the earth's climate was never so severe; such intense climate change has been more widely accepted for other planets such as Venus [see "Global Climate Change on Venus," by Mark A. Bullock and David H. Grinspoon; Scientific American, March 1999]. Hints of a harsh past on the earth began cropping up in the early 1960s, but we and our colleagues have found new evidence in the past eight years that has helped us weave a more explicit tale that is capturing the attention of geologists, biologists and climatologists alike.

Thick layers of ancient rock hold the only clues to the climate of the Neoproterozoic. For decades, many of those clues appeared rife with contradiction. The first paradox was the occurrence of glacial debris near sea level in the tropics. Glaciers near the equator today survive only at 5,000 meters above sea level or higher, and at the worst of the last ice age they reached no lower than 4,000 meters. Mixed in with the glacial debris are unusual deposits of iron-rich rock. These deposits should have been able to form only if the Neoproterozoic oceans and atmosphere contained little or no oxygen, but by that time the atmosphere had already evolved to nearly the same mixture of gases as it has today. To confound matters, rocks known to form in warm water seem to have accumulated just after the glaciers receded. If the earth were ever cold enough to ice over completely, how did it warm up again? In addition, the carbon isotopic signature in the rocks hinted at a prolonged drop in biological productivity. What could have caused this dramatic loss of life?



Image: DANIEL P. SCHRAG

**AUTHORS SCHRAG AND HOFFMAN** point to a rock layer that represents the abrupt end of a 700-million-year-old snowball event. The light-colored boulder in the rock between them probably once traveled with an iceberg and fell to the muddy seafloor when the ice melted.

minerals lie just above the glacial debris and harbor the chemical evidence of the hothouse that followed. After hundreds of millions of years of burial, these now exposed rocks tell the story that scientists first began to piece together 35 years ago.

Each of these long-standing enigmas suddenly makes sense when we look at them as key plot developments in the tale of a "snowball earth." The theory has garnered cautious support in the scientific community since we first introduced the idea in the journal *Science* a year and a half ago. If we turn out to be right, the tale does more than explain the mysteries of Neoproterozoic climate and challenge long-held assumptions about the limits of global change. 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 on genetic change and could help account for this evolutionary burst.

The search for the surprisingly strong evidence for these climatic events has taken us around the world. Although we are now examining Neoproterozoic rocks in Australia, China, the western U.S. and the Arctic islands of Svalbard, we began our investigations in 1992 along the rocky cliffs of Namibia's Skeleton Coast. In Neoproterozoic times, this region of southwestern Africa was part of a vast, gently subsiding continental shelf located in low southern latitudes. There we see evidence of glaciers in rocks formed from deposits of dirt and debris left behind when the ice melted. Rocks dominated by calcium- and magnesium-carbonate

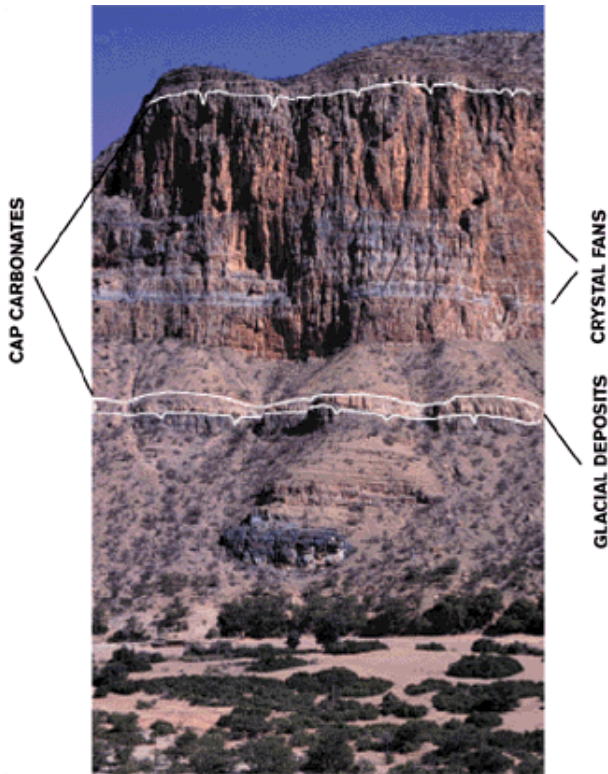


Image: GALEN PIPPA HALVERSON

**ROCKY CLIFFS** along Namibia's Skeleton Coast have provided some of the best evidence for the snowball earth hypothesis.

In 1964 W. Brian Harland of the University of Cambridge pointed out that glacial deposits dot Neoproterozoic rock outcrops across virtually every continent. By the early 1960s scientists had begun to accept the idea of plate tectonics, which describes how the planet's thin, rocky skin is broken into giant pieces that move atop a churning mass of hotter rock below. Harland suspected that the continents had clustered together near the equator in the Neoproterozoic, based on the magnetic orientation of tiny mineral grains in the glacial rocks. Before the rocks hardened, these grains aligned themselves with the magnetic field and dipped only slightly relative to horizontal because of their position near the equator. (If they had formed near the poles, their magnetic orientation would be nearly vertical.)

Realizing that the glaciers must have covered the tropics, Harland became the first geologist to suggest that the earth had experienced a great Neoproterozoic ice age [see "The Great Infra-Cambrian Glaciation," by W. B. Harland and M.J.S. Rudwick; *Scientific American*, August 1964]. Although some of Harland's contemporaries were skeptical about the reliability of the magnetic data, other scientists have since shown that Harland's hunch was correct. But no one was able to find an explanation for how glaciers could have survived the tropical heat.

At the time Harland was announcing his ideas about Neoproterozoic glaciers, physicists were developing the first mathematical models of the earth's climate. Mikhail Budyko of the Leningrad Geophysical Observatory found a way to explain tropical glaciers using equations that describe the way solar radiation interacts with the earth's surface and atmosphere to control climate. Some geographic surfaces reflect more of the sun's incoming energy than others, a quantifiable

characteristic known as albedo. White snow reflects the most solar energy and has a high albedo, darker-colored seawater has a low albedo, and land surfaces have intermediate values that depend on the types and distribution of vegetation.

The more radiation the planet reflects, the cooler the temperature. With their high albedo, snow and ice cool the atmosphere and thus stabilize their own existence. Budyko knew that this phenomenon, called the ice-albedo feedback, helps modern polar ice sheets to grow. But his climate simulations also revealed that this feedback can run out of control. When ice formed at latitudes lower than around 30 degrees north or south of the equator, the planet's albedo began to rise at a faster rate because direct sunlight was striking a larger surface area of ice per degree of latitude. The feedback became so strong in his simulation that surface temperatures plummeted and the entire planet froze over.

## Frozen and Fried

Budyko's simulation ignited interest in the fledgling science of climate modeling, but even he did not believe the earth could have actually experienced a runaway freeze. Almost everyone assumed that such a catastrophe would have extinguished all life, and yet signs of microscopic algae in rocks up to one billion years old closely resemble modern forms and imply a continuity of life. Also, once the earth had entered a deep freeze, the high albedo of its icy veneer would have driven surface temperatures so low that it seemed there would have been no means of escape. Had such a glaciation occurred, Budyko and others reasoned, it would have been permanent.

The first of these objections began to fade in the late 1970s with the discovery of remarkable communities of organisms living in places once thought too harsh to harbor life. Seafloor hot springs support microbes that thrive on chemicals rather than sunlight. The kind of volcanic activity that feeds the hot springs would have continued unabated in a snowball earth. Survival prospects seem even rosier for psychrophilic, or cold-loving, organisms of the kind living today in the intensely cold and dry mountain valleys of East Antarctica. Cyanobacteria and certain kinds of algae occupy habitats such as snow, porous rock and the surfaces of dust particles encased in floating ice.



Image: DANIEL P. SCHRAG

**PURE CARBONATE LAYERS** stacked above the glacial deposits precipitated in the warm, shallow seas of the hothouse aftermath.

The key to the second problem--reversing the runaway freeze--is carbon dioxide. In a span as short as a human lifetime, the amount of carbon dioxide in the atmosphere can change as plants consume the gas for photosynthesis and as animals breathe it out during respiration. Moreover, human activities such as burning fossil fuels have rapidly loaded the air with carbon dioxide since the beginning of the Industrial Revolution in the late 1700s. In the earth's lifetime, however, these carbon sources and sinks become irrelevant compared with geologic processes.

Carbon dioxide is one of several gases emitted from volcanoes. Normally this endless supply of carbon is offset by the erosion of silicate rocks: The chemical breakdown of the rocks converts carbon dioxide to bicarbonate, which is washed to the oceans. There bicarbonate combines with calcium and magnesium ions to

These "cap" carbonates are the only Neoproterozoic rocks that exhibit large crystal fans, which accompany rapid carbonate accumulation.

produce carbonate sediments, which store a great deal of carbon [see "Modeling the Geochemical Carbon Cycle," by R. A. Berner and A. C. Lasaga; Scientific American, March 1989].

In 1992 Joseph L. Kirschvink, a geobiologist at the California Institute of Technology, pointed out that during a global glaciation, an event he termed a snowball earth, shifting tectonic plates would continue to build volcanoes and to supply the atmosphere with carbon dioxide. At the same time, the liquid water needed to erode rocks and bury the carbon would be trapped in ice. With nowhere to go, carbon dioxide would collect to incredibly high levels--high enough, Kirschvink proposed, to heat the planet and end the global freeze.

Kirschvink had originally promoted the idea of a Neoproterozoic deep freeze in part because of mysterious iron deposits found mixed with the glacial debris. These rare deposits are found much earlier in earth history when the oceans (and atmosphere) contained very little oxygen and iron could readily dissolve. (Iron is virtually insoluble in the presence of oxygen.) Kirschvink reasoned that millions of years of ice cover would deprive the oceans of oxygen, so that dissolved iron expelled from seafloor hot springs could accumulate in the water. Once a carbon dioxide-induced greenhouse effect began melting the ice, oxygen would again mix with the seawater and force the iron to precipitate out with the debris once carried by the sea ice and glaciers.

With this greenhouse scenario in mind, climate modelers Kenneth Caldeira of Lawrence Livermore National Laboratory and James F. Kasting of Pennsylvania State University estimated in 1992 that overcoming the runaway freeze would require roughly 350 times the present-day concentration of carbon dioxide. Assuming volcanoes of the Neoproterozoic belched out gases at the same rate as they do today, the planet would have remained locked in ice for up to tens of millions of years before enough carbon dioxide could accumulate to begin melting the sea ice. A snowball earth would be not only the most severe conceivable ice age, it would be the most prolonged.

## **Carbonate Clues**

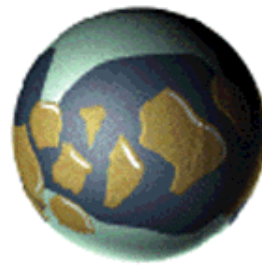
Kirschvink was unaware of two emerging lines of evidence that would strongly support his snowball earth hypothesis. The first is that the Neoproterozoic glacial deposits are almost everywhere blanketed by carbonate rocks. Such rocks typically form in warm, shallow seas, such as the Bahama Banks in what is now the Atlantic Ocean. If the ice and warm water had occurred millions of years apart, no one would have been surprised. But the transition from glacial deposits to these "cap" carbonates is abrupt and lacks evidence that significant time passed between when the glaciers dropped their last loads and when the carbonates formed. Geologists were stumped to explain so sudden a change from glacial to tropical climates.

Pondering our field observations from Namibia, we realized that this change is no paradox. Thick sequences of carbonate rocks are the expected consequence of the extreme greenhouse conditions unique to the transient aftermath of a snowball earth. If the earth froze over, an ultrahigh carbon dioxide atmosphere would be needed to raise temperatures to the melting point at the equator. Once melting begins, low-albedo seawater replaces high-albedo ice and the runaway freeze is reversed [see illustration below]. The greenhouse atmosphere helps to drive surface temperatures

upward to almost 50 degrees C, according to calculations made last summer by climate modeler Raymond T. Pierrehumbert of the University of Chicago.

Resumed evaporation also helps to warm the atmosphere because water vapor is a powerful greenhouse gas, and a swollen reservoir of moisture in the atmosphere would drive an enhanced water cycle. Torrential rain would scrub some of the carbon dioxide out of the air in the form of carbonic acid, which would rapidly erode the rock debris left bare as the glaciers subsided. Chemical erosion products would quickly build up in the ocean water, leading to the precipitation of carbonate sediment that would rapidly accumulate on the seafloor and later become rock. Structures preserved in the Namibian cap carbonates indicate that they accumulated extremely rapidly, perhaps in only a few thousand years. For example, crystals of the mineral aragonite, clusters of which are as tall as a person, could precipitate only from seawater highly saturated in calcium carbonate.

Cap carbonates harbor a second line of evidence that supports Kirschvink's snowball escape scenario. They contain an unusual pattern in the ratio of two isotopes of carbon: common carbon 12 and rare carbon 13, which has an extra neutron in its nucleus. The same patterns are observed in cap carbonates worldwide, but no one thought to interpret them in terms of a snowball earth. Along with Alan Jay Kaufman, an isotope geochemist now at the University of Maryland, and Harvard University graduate student Galen Pippa Halverson, we have discovered that the isotopic variation is consistent over many hundreds of kilometers of exposed rock in northern Namibia.



### **EVOLUTION OF A SNOWBALL EARTH EVENT**

Carbon dioxide moving into the oceans from volcanoes is about 1 percent carbon 13; the rest is carbon 12. If the formation of carbonate rocks were the only process removing carbon from the oceans, then the rock would have the same fraction of carbon 13 as that which comes out of volcanoes. But the soft tissues of algae and bacteria growing in seawater also use carbon from the water around them, and their photosynthetic machinery prefers carbon 12 to carbon 13. Consequently, the carbon that is left to build carbonate rocks in a life-filled ocean such as we have today has a higher ratio of carbon 13 to carbon 12 than does the carbon fresh out of a volcano.

The carbon isotopes in the Neoproterozoic rocks of Namibia record a different situation. Just before the glacial deposits, the amount of carbon 13 plummets to levels equivalent to the volcanic source, a drop we think records decreasing biological productivity as ice encrusted the oceans at high latitudes and the earth teetered on the edge of a runaway freeze. Once the oceans iced over completely, productivity would have essentially ceased, but no carbon record of this time interval exists because calcium carbonate could not have formed in an ice-covered ocean. This drop in carbon 13 persists through the cap carbonates atop the glacial deposits and then gradually rebounds to higher levels of carbon 13 several hundred meters above, presumably recording the recovery of life at the end of the hothouse period.

Abrupt variation in this carbon isotope record shows up in carbonate rocks that represent other times of mass extinction, but none are as large or as long-lived. Even the meteorite impact that killed off the dinosaurs 65 million years ago did not bring about such a prolonged collapse in biological activity.

Overall, the snowball earth hypothesis explains many extraordinary observations in the geologic record of the Neoproterozoic world: the carbon isotopic variations associated with the glacial deposits, the paradox of cap carbonates, the evidence for long-lived glaciers at sea level in the tropics, and the associated iron deposits. The strength of the hypothesis is that it simultaneously explains all these salient features, none of which had satisfactory independent explanations. What is more, we believe this hypothesis sheds light on the early evolution of animal life.

### Survival and Redemption of Life

In the 1960s Martin J. S. Rudwick, working with Brian Harland, proposed that the climate recovery following a huge Neoproterozoic glaciation paved the way for the explosive radiation of multicellular animal life soon thereafter.

Eukaryotes--cells that have a membrane-bound nucleus and from which all plants and animals descended--had emerged more than one billion years earlier, but the most complex organisms that had evolved when the first Neoproterozoic glaciation hit were filamentous algae and unicellular protozoa. It has always been a mystery why it took so long for these primitive organisms to diversify into the 11 animal body plans that show up suddenly in the fossil record during the Cambrian explosion [see illustration below].

A series of global freeze-fry events would have imposed an environmental filter on the evolution of life. All extant eukaryotes would thus stem from the survivors of the Neoproterozoic calamity. Some measure of the extent of eukaryotic extinctions may be evident in universal "trees of life." Phylogenetic trees indicate how various groups of organisms evolved from one another, based on their degrees of similarity. These days biologists commonly draw these trees by looking at the sequences of nucleic acids in living organisms.

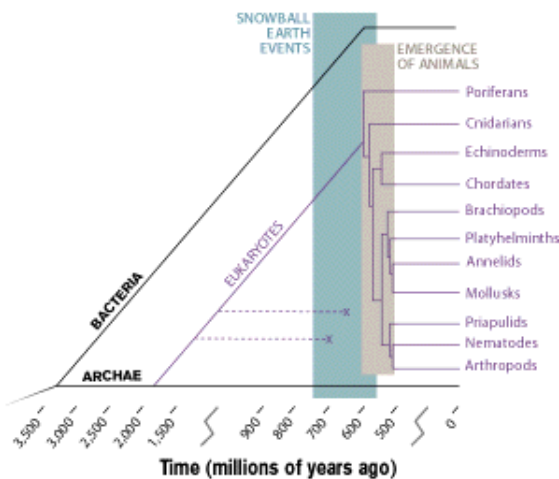


Image: HEIDI NOLAND

#### ALL ANIMALS

descended from the first eukaryotes, cells with a membrane-bound nucleus, which appeared about two

billion years ago. By the time of the first snowball earth episode more than one billion years later, eukaryotes had not developed beyond unicellular protozoa and filamentous algae. But despite the extreme climate, which may have "pruned" the eukaryote tree (dashed lines), all 11 animal phyla ever to inhabit the earth emerged within a narrow window of time in the aftermath of the last snowball event. The prolonged genetic isolation and selective pressure intrinsic to a snowball earth could be responsible for this explosion of new life-forms.

Most such trees depict the eukaryotes' phylogeny as a delayed radiation crowning a long, unbranched stem. The lack of early branching could mean that most eukaryotic lineages were "pruned" during the snowball earth episodes. The creatures that survived the glacial episodes may have taken refuge at hot springs both on the seafloor and near the surface of the ice where photosynthesis could be maintained.

The steep and variable temperature and chemical gradients endemic to ephemeral hot springs would preselect for survival in the hellish aftermath to come. In the face of varying environmental stress, many organisms respond with wholesale genetic alterations. Severe stress encourages a great degree of genetic change in a short time, because organisms that can most quickly alter their genes will have the most opportunities to acquire traits that will help them adapt and proliferate.

Hot-spring communities widely separated geographically on the icy surface of the globe would accumulate genetic diversity over millions of years. When two groups that start off the same are isolated from each other long enough under different conditions, chances are that at some point the extent of genetic mutation will produce a new species. Repopulations occurring after each glaciation would come about under unusual and rapidly changing selective pressures quite different from those preceding the glaciation; such conditions would also favor the emergence of new life-forms.

Martin Rudwick may not have gone far enough with his inference that climatic amelioration following the great Neoproterozoic ice age paved the way for early animal evolution. The extreme climatic events themselves may have played an active role in spawning multicellular animal life.

We have shown how the worldwide glacial deposits and carbonate rocks in the Neoproterozoic record point to an extraordinary type of climatic event, a snowball earth followed by a briefer but equally noxious greenhouse world. But what caused these calamities in the first place, and why has the world been spared such events in more recent history? The first possibility to consider is that the Neoproterozoic sun was weaker by approximately 6 percent, making the earth more susceptible to a global freeze. The slow warming of our sun as it ages might explain why no snowball event has occurred since that time. But convincing geologic evidence suggests that no such glaciations occurred in the billion or so years before the Neoproterozoic, when the sun was even cooler.

The unusual configuration of continents near the equator during Neoproterozoic times may better explain how snowball events get rolling [see illustration]. When the continents are nearer the poles, as they are today, carbon dioxide in the atmosphere remains in high enough concentrations to keep the planet warm. When global temperatures drop enough that glaciers cover the high-latitude continents, as they do in Antarctica and Greenland, the ice sheets prevent chemical erosion of the rocks beneath the ice. With the carbon burial process stifled, the carbon dioxide in the atmosphere stabilizes at a level high enough to fend off the advancing ice sheets. If all the continents cluster in the tropics, on the other hand, they would remain ice-free even as the earth grew colder and approached the critical threshold for a runaway freeze. The carbon dioxide "safety switch" would fail because carbon burial continues unchecked.

We may never know the true trigger for a snowball earth, as we have but simple theories for the ultimate forcing of climate change, even in recent times. But we should be wary of the planet's capacity for extreme change. For the past million years, the earth has been in its coldest state since animals first appeared, but even the greatest advance of glaciers 20,000 years ago was far from the critical threshold needed to plunge the earth into a snowball state.

Certainly during the next several hundred years, we will be more concerned with humanity's effects on climate as the earth heats up in response to carbon dioxide emissions [see "The Human Impact on Climate Change," by Thomas R. Karl and Kevin E. Trenberth; Scientific American, December 1999]. But could a frozen world be in our more distant future?

We are still some 80,000 years from the peak of the next ice age, so our first chance for an answer is far in the future. It is difficult to say where the earth's climate will drift over millions of years. If the trend of the past million years continues and if the polar continental safety switch were to fail, we may once again experience a global ice catastrophe that would inevitably jolt life in some new direction.

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