The Snowball Earth

Many lines of evidence support a theory that the entire Earth was ice-covered for long periods 600-700 million years ago. Each glacial period lasted for millions of years and ended violently under extreme greenhouse conditions. These climate shocks triggered the evolution of multicellular animal life, and challenge long-held assumptions regarding the limits of global change.

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Introduction

Geology tells us that the Earth's climate is subject to change on various timescales, but what are the limits to climatic variability? Over the last million years that constitute the Pleistocene epoch, the time in which humans evolved, continents bordering the North Atlantic Ocean were periodically glaciated at intervals governed by changes in the Earth's orbit around the Sun. At the height of the last ice age, a mere 21,000 years ago, much of North America and Europe were covered by glaciers over 2 kilometers thick, causing sea level to drop by 120 meters. The chill was global: land and sea ice combined to cover 30 percent of the Earth's surface, more than at any other time in the last 500 million years. Although these are dramatic examples of the variability of Earth's climate, they pale by comparison with climatic events near the end of the Neoproterozoic eon (1000-543 million years ago), events that immediately preceded the first appearance of recognizable animal life around 600 million years ago.

In 1964, Brian Harland at Cambridge University postulated that the Earth had experienced a great Neoproterozoic ice age. He pointed out that Neoproterozoic glacial deposits, similar in type to those of the Pleistocene, are widely distributed on virtually every continent. Harland could only speculate on the positions of continents in Neoproterozoic time and could not rule out the possibility that various continents were glaciated at different times as they drifted close to the poles. Nevertheless, he inferred that ice lines penetrated the tropics from the occurrence of glacial deposits within types of marine sedimentary strata characteristic of low latitudes. What could cause glaciers to reach sea level near the Equator? Climate physicists were just developing mathematical models of the Earth's climate, providing a new perspective on the limits to glaciation. The Earth's climate is fundamentally controlled by the way that solar radiation interacts with the Earth's surface and atmosphere. We receive ~343 watts per square meter of radiation from the Sun. Some of this is reflected back to space by clouds and by the Earth's surface, but approximately two thirds is absorbed by the Earth's surface and atmosphere, increasing the average temperature. Earth's surface emits radiation at longer wavelengths (infrared), balancing the energy of the radiation that has been absorbed. If more of the solar radiation were reflected back to space, then less radiation would be absorbed at the surface and the Earth's temperature would decrease. The surface albedo is a measure of how much radiation is reflected; snow has a high albedo (~0.8), seawater has a low albedo (~0.1), and land surfaces have intermediate values that vary widely depending mainly on the types and distribution of vegetation. When snow falls on land or ice forms at sea, the increase in the albedo causes greater cooling, stabilizing the snow and ice. This is called ice-albedo feedback, and it is an important factor in the waxing (and waning) of ic e sheets.

At the same time that Harland was examining Neoproterozoic glacial deposits, Mikhail Budyko at the Leningrad Geophysical Observatory, working with simple two-dimensional energy-balance climate models, found that the ice-albedo feedback created an instability in the Earth's climate system. Budyko showed that if the Earth's climate were to cool, and ice were to form at lower and lower latitudes, the planetary albedo would rise at a faster and faster rate because there is more surface area per degree of latitude as one approaches the Equator. In his model, once ice formed beyond a critical latitude (around 30 degrees north or south, equivalent to half the Earth's surface area), the positive feedback became so strong that temperatures of the surface plummeted, yielding a completely frozen planet. The relatively small amount of heat escaping from the Earth's interior is sufficient to prevent the oceans from freezing to the bottom, but would still allow a kilometer thick cap of sea ice to form, thicker at the poles and thinner at the Equator.

Frozen and Fried

Budyko's model results helped stimulate interest in the science of climate modeling, but few believed that the Earth had ever actually experienced a runaway ice albedo. First, it was assumed that such a catastrophe would have extinguished all life, contrary to microscopic evidence of extant life forms in rocks as old as 3500 million years. Second, once the Earth became totally ice-covered, the high albedo would drive surface temperatures so low that there seemed no means of escape. Had such a glaciation ever occurred, Budyko 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 deep-sea hydrothermal (hot water) vents, and later in the extremely cold, dry, mountain valleys of East Antarctica. Some of these organisms appeared capable of surviving global glaciation and their existence in the Neoproterozoic was unquestioned—molecular studies showed that they disproportionately represent the oldest branches in the universal tree of life.

The key to the second problem—reversing the ice-albedo feedback—is plate tectonics. Climate scientists have long known that the amount of carbon dioxide in the atmosphere plays an important role in determining the Earth's temperature because it is a "greenhouse" gas, meaning that it absorbs infrared radiation emitted from the Earth's surface. Over time scales of human lifetimes, the amount of atmospheric carbon dioxide can be affected by biological processes such as photosynthesis or respiration, and by human activities such as the burning of tropical forests and fossil fuels. Over time scales of millions of years, the amount of carbon dioxide in the ocean-atmosphere system is adjusted to maintain a balance between its supply by volcanoes, both on land and in the ocean, and its removal by chemical weathering reactions with silicate rocks, which convert the carbon dioxide to calcium carbonate which is then buried in sediments.

In the late 1980s, Joe Kirschvink at the California Institute of Technology pointed out that during a global glaciation, what he termed a "snowball" Earth, the supply of carbon dioxide to the atmosphere and oceans from volcanism would continue because of plate tectonics. However, if the Earth were so cold that there were no liquid water on the continents, weathering reactions would effectively cease, allowing carbon dioxide to build up to incredibly high levels. Eventually, the carbon-dioxide-induced warming would offset the ice albedo, and the glaciation would end. Given that solar luminosity 600-700 million years ago was about six percent lower than today due to stellar evolution, Ken Caldeira and Jim Kasting at The Pennsylvania State University estimated that roughly 0.12 bar of carbon dioxide (about 350 times the present concentration) would have been required to overcome the albedo of a snowball Earth. Assuming current rates of volcanic carbon dioxide emissions, a Neoproterozoic "snowball" Earth would have lasted for millions to tens of million of years before the sea ice would begin to melt at the Equator. A "snowball" Earth would not only be the most severe glaciation conceivable, it would be the most prolonged.

Sea Ice at the Equator

Joe Kirschvink had found the escape route from a "snowball" Earth, but was it a route ever taken? Kirschvink pointed to the results from paleomagnetism, a technique that Harland had employed in attempting to estimate the latitudes of Neoproterozoic glaciation. The latitude at which certain rocks formed can be estimated from the inclination, corrected for subsequent disturbances, of their natural remnant magnetization (NRM), which varies systematically from vertical at the magnetic poles to horizontal at the magnetic equator. Today, the magnetic and geographic poles do not coincide, nor have they at most times in the past. However, the poles do coincide when averaged for the secular "drift" of the magnetic poles on a time scale of 10,000 years. In practice, a large number of rock samples closely separated in age must be measured from each location, in order to eliminate statistically the effects of short-term secular variation of the magnetic field. Harland and coworkers found shallow inclinations for Neoproterozoic glacial deposits at a number of sites, which seemed to confirm that glaciation had occurred at low latitudes.

In the 1960s, it was generally assumed that NRMs were acquired when rocks formed, so long as they had not subsequently been heated above their Curie temperature (580-680 degrees Celsius). However, it was subsequently learned that many rocks, particularly sedimentary rocks, may be chemically remagnetized at much lower temperatures if subjected to prolonged groundwater percolation. Many of the early paleomagnetic measurements were shown to be from remagnetized samples and the rest were suspect. Kirschvink decided to reexamine favorable sites and carry out various tests designed to select only primary NRMs. He reasoned that South Australian Neoproterozoic glacial deposits giving shallow inclinations had the least chance of being remagnetized because South Australia was never at low latitude in the last 400 million years. Furthermore, George Williams at the University of Adelaide had proved that the glacial deposits in South Australia formed close to sea level because of their intimate association with sediments of tidal origin. This was important because glaciers exist in the tropics today, but not below 5000 meters above sea level. Even at the last Pleistocene glacial maximum, equatorial ice lines in the Andes were no lower than 4000 meters above sea level. The tests that Kirschvink carried out, later replicated and extended in other laboratories, were positive and confirmed that the shallow inclinations in South Australia are primary. The paleomagnetic evidence seems irrefutable: Neoproterozoic ice lines reached sea level within a few degrees of the Equator. Recently, Linda Sohl and colleagues at Lamont-Doherty Earth Observatory of Columbia University have documented as many as six polarity reversals in the South Australian glacial deposits. The frequency of polarity reversals of the Earth's magnetic field is such that the glacial deposits must represent a minimum of several 100,000s and more likely millions of years, consistent with the time scale of a "snowball" Earth.

Can the paleomagnetic evidence be explained without recourse to a "snowball" Earth? George Williams, who more than anyone else put the South Australian glacial deposits on the map, had a different but equally imaginative idea. He proposed that the Earth's obliquity—the angle between the spin axis and the axis of the ecliptic plane—was greater than 54 degrees until the end of the Proterozoic eon, when it rapidly changed to relatively low values near today's 23.5 degrees. An obliquity greater than 54 degrees would dramatically alter Proterozoic climate. Williams noted that glaciation would occur preferentially at low latitudes. Mean annual insolation would be higher in the polar regions than in the tropics, due mainly to extremely hot polar summers when the Sun would be perpetually high in the sky. At the Equator, the solstices would be very cold with the Sun bobbing on the polar horizon. Strong surface winds would flow from the winter to the summer hemisphere. But the equinoxes would be hot at the Equator. The Sun would pass daily high overhead, just as it does with low obliquity. At all latitudes, seasonality would be greatly increased and Williams pointed to the presence in South Australia of structures like ice-wedge polygons, produced by seasonal temperature variations in frozen soil. Such structures should not form at the Equator if the Neoprotoerozoic obliquity was low. However, strong seasonality is a double-edged sword because it makes it more difficult for glaciers to develop. Glaciation depends on a net accumulation of winter snow after summer ablation. Strong seasonality increases summer ablation, and also decreases winter snowfall because colder air is drier. Detailed investigations show that summer insolation is the key to the growth and decay of Pleistocene ice sheets. The high-obliquity hypothesis faced an uphbill battle for other reasons as well. To initiate it would seem to require a giant impact on the Earth of a body crossing the ecliptic plane at a high angle. Thi s is incompatible with the orbit of the Moon, unless the widely accepted theory of its origin through a giant impact is abandoned.

Iron is the paleomagnetists' favorite element, and iron gave Joe Kirschvink another reason to favor the "snowball" Earth. Several examples of Neoproterozoic glacial deposition in marine waters are unusually rich in iron oxides and sulfides. In fact, they were the object of international iron-ore exploration after World War II, and belong to a class of sedimentary ore deposits called banded iron-formation or BIF, which is otherwise restricted to a much earlier time in Earth history. Modern seawater contains less than one part per billion of iron because iron in its oxidized form (Fe^{3+}) is quite insoluble. However, in its reduced form (Fe^{2+}), iron is relatively soluble. Most BIF occurs in rocks older than 1850 million years and is believed to have formed at a time when the atmosphere had little free oxygen, and seawater in the deep ocean contained abundant iron. This iron precipitated in upwelling zones when it encountered more oxidizing surface waters. The transitory return of BIF, invariably associated with glacial deposits, after a hiatus of over a billion years is remarkable. Kirschvink reasoned that during the millions of years of ice-covered oceans, the amount of gas exchange between the ocean and atmosphere would be reduced, and the deep ocean would quickly become anoxic, allowing reduced iron to build up to high concentrations. Once the glaciation ended, the ocean would quickly become oxidized, and the iron would precipitate out in close association with the deposits of sediment-laden icebergs. The high-obliquity hypothesis provides no explanation for the association of glacial deposits in BIF.

The Acid Test

Joe Kirschvink was unaware of two emerging lines of evidence that would strongly support his "snowball" Earth hypothesis. Ironically, both were first highlighted by the intrepid George Williams. All across Australia, Williams reported, from the Kimberleys to the Flinders, Neoproterozoic glacial intervals are blanketed by peculiar "cap" dolostones (equimolar calcium-magnesium carbonate). The transition from glacial deposits to "cap" dolostone is abrupt and lacks evidence of significant hiatus. Williams argued that the "cap" dolostones are primary, or nearly so, and imply high surface temperatures based on laboratory experiments and modern occurrences. He concluded that Neoproterozoic glacial epochs closed with "abrupt climatic warmings". It was soon apparent that Neoproterozoic "cap" dolostones are a world-wide phenomenon, particularly striking in regions where carbonate rocks are otherwise absent. The "paradoxical" association of glacial and warm-water deposits was widely acknowledged.

To appreciate the special significance of "cap" dolostones, recall the transient conditions unique to the end of a "snowball" Earth. An ultra-high carbon dioxide atmosphere is needed to raise temperatures to the melting point at the Equator. Once melting begins, the ice-albedo feedback is reversed and combines with the extreme greenhouse atmosphere to drive surface temperatures upward. The warming proceeds rapidly because the change in albedo begins in the tropics, where insolation and surface area are maximal. With the resumption of evaporation, the addition of water vapor to the atmosphere adds powerfully to the greenhouse effect. Calculations by Raymond Pierrehumbert at the University of Chicago suggests that tropical sea-surface temperatures would reach almost 50 degrees Celsius in the aftermath of a "snowball" Earth, driving an intense hydrologic cycle. Sea ice hundreds of meters thick globally would disappear within a few 100s of years. Intense chemical weathering of silicate rocks and dissolution of carbonate rocks would result from the strong hydrologic cycle, the low pH of carbonic acid rain, and the large surface area of frost-shattered rock and rock "flour" produced by the grinding action of glaciers. The products of chemical weathering reactions, cations and bicarbonate, would be delivered by rivers to the ocean, where they would neutralize the acidity of the surface waters and drive massive precipitation of inorganic carbonate sediment in the rapidly warming surface ocean. Typically, "cap" dolostones pass upward into much thicker, deeper-water clays or limestones, perhaps reflecting a rise in sea level as continental ice sheets melt, and suggesting that the cap carbonates precipitated extremely rapidly, perhaps in only a few hundred years. This idea is supported by textures in the dolostones and limestones such as gas-escape tubes and crystal fans consistent with precipitation from seawater highly supersaturated in calcium carbonate. "Cap" dolostones are no paradox; they are the expected consequence of the "ultra-greenhouse" conditions unique to the transient aftermath of a "snowball" Earth.

The "cap" carbonates contain additional evidence supporting the Snowball Earth hypothesis found in an unusual pattern of variation in the ratio of two naturally occuring, stable (i.e., non-radioactive) isotopes of carbon (carbon-13 and carbon-12). The carbon supplied to the ocean and atmosphere comes from outgassing of carbon dioxide by volcanoes, and contains about 1% carbon-13 and 99% carbon-12. If the removal of carbon from the ocean were accomplished only by burial of calcium carbonate, then the calcium carbonate must have the same fraction of carbon-13 as what comes out of volcanoes (simply because of conservation of mass). However, carbon is also removed from the ocean in the form of organic matter, the soft tissues of algae and bacteria growing in seawater. Most organic carbon is depleted in carbon-13 relative to calcium carbonate by approximately 2.5%. Today (and over most of the last 500 million years), approximately 20% of the carbon entering the ocean is removed as organic matter, which requires that modern calcium carbonate is enriched in carbon-13 by approximately 0.5% relative to the volcanic source.

The Neoproterozoic carbon isotopic record is very different, not only because the amounts of carbon-13 are generally much higher than modern sediments, but also because the rocks immediately surrounding the glacial deposits show huge excursions towards much lower levels of carbon-13. These patterns are observed world-wide, but the most complete records come from northern Namibia. In Neoproterozoic times, this region of southwest Africa was part of a vast, gently subsiding, continental shelf, located in low southern latitudes and subject to nearly unbroken carbonate sedimentation, similar to the Bahama Banks in the tropical Atlantic. After hundreds of millions of years of burial, the carbonate rocks are now exposed high on the escarpment along the Skeleton Coast. Carbon isotopic records are well preserved in these carbonate rocks (limestone and dolostone) because carbon makes up 10 percent of the rock and represents a huge reservoir that resists alteration by fluids containing only a tiny fraction of the carbon, even in rocks this old. Extensive work by the first author, along with Jay Kaufman at University of Maryland and Galen Halverson at Harvard University, have demonstrated that the patterns of isotopic variation are consistent over many hundreds of kilometers of exposure, and accurately record variability in the Neoproterozoic carbon cycle.

The carbonate rocks beneath the glacial deposits are enriched in carbon-13 by as much as 1.5% relative to volcanoes, much more than modern carbonate sediments. This enrichment extends over many 100s of meters of section, interpreted as representing at least 10 million years. This implies that burial of organic carbon in the Neoproterozoic accounted for nearly half the total carbon removed from the ocean. But just before the glacial deposits, the amount of carbon-13 plummets to levels equivalent to the volcanic source. This drop persists through the cap carbonates atop the glacial deposits, and then slowly rebounds to higher levels of carbon-13 several hundred meters above. Such a rapid excursion in the carbon-13 content of calcium carbonate is seen at other intervals in the geologic record, but none are nearly as large. It can only be explained by an abrupt drop in the fraction of carbon leaving the ocean as organic matter, persisting for long enough to change the composition of the entire reservoir of dissolved inorganic carbon (DIC) in seawater. Even mass extinction events, like the 65-million-year-old meteorite impact event at the Cretaceous-Tertiary boundary, caused only short-term collapses in biological activity in the surface ocean. The amount of carbon-13 in sediments dropped, but not nearly as much as in Neoproterozoic excursions because the time scale fell far short of the time required to alter the total ocean DIC reservoir (100,000s of years).

The drop in carbon-13 content just before the glaciations can be explained as a drop in biological productivity as ice formed over the oceans at high latitudes, and the Earth teetered on the edge of a runaway ice-albedo feedback. Once ice covered the oceans entirely, biological productivity would have essentially ceased, although no record of this time interval exists as calcium carbonate would not have precipitated from seawater in an ice-covered state. After a long hiatus represented by the glacial deposits, the isotopic record begins again at the base of the "cap" dolostone. This distinctive stratigraphic unit is unusually complete in Namibia because the "cap" dolostone continues upward into deeper water limestones 10s and 100s of meters thick on the slope and shelf, respectively. Like the immediate pre-glacial carbonates, the "cap" dolostone and succeeding limestones are strongly depleted in carbon-13. The lowest sustained values are equivalent to those of mantle carbon emitted from volcanoes, and imply a system at steady state with an exclusively inorganic carbon burial flux. This is consistent with the unusual primary structures indicating extremely high carbonate sedimentation rates in both the "cap" dolostone (gas-escape tubes) and deepwater limestones (sea-floor crystal fans). Biological productivity at this time might have been substantial, as life rebounded in the aftermath of the Snowball, but would still be small relative to the rates of carbonate precipitation and burial.

Overall, the geological record of the Neoproterozoic hosts multiple extraordinary observations that can all be explained by the "snowball" Earth hypothesis. The ultimate strength of the hypothesis is not that it provides a plausible explanation for the extraordinary carbon isotopic excursions associated with Neoproterozoic glacial deposits, or that it resolves the "paradox" of "cap" dolostones, or that it accounts for the unique association of ice-rafted dropstones in BIF, or that is it affirms the paleomagnetic evidence for low-latitude ice lines at sea level, or the great duration of the glacial events. The strength of the hypothesis is that it simultaneously explains all of these salient features of the Neoproterozoic record, none of which had satisfactory independent explanations. But what about the most portentous feature of the Neoproterozoic record? What light might the hypothesis shed on the origin and early evolution of animal life?

Survival and Redemption of Life

What implications would a series of global "freeze-fry" episodes have for the evolution of life? In the 1960's, Martin Rudwick, working with Harland, proposed that the climatic recovery following a huge Neoproterozoic glaciation paved the way for the explosive radiation of metazoan (multicellular) animal life that followed soon thereafter. To begin to assess this claim, we must examine what life forms existed at the time and what were their chances of survival? The bacteria and archaea associated with hydrothermal (hot-water) vents in the deep sea were once viewed as likely survivors. Volcanic activity at mid-ocean ridges, hot spots and island arcs would continue unabated in a "snowball" Earth. Temperature gradients that support the organic activity would also continue, although chemical gradients that are exploited metabolically, such as redox (reduction-oxidation) and pH (acid-base) gradients, might be weakened. Prospects seem even rosier for "psychrophilic" (cold-loving) organisms of the kind living today in the intensely cold and dry mountain valleys of East Antarctica. Under conditions not too different from those on a "snowball" Earth, various prokaryotic organisms, including cyanobacteria, and certain eukaryotic algae, occupy habitats including snow, porous rock, and the surfaces of dust particles encased in floating ice. Eukaryote survival is a necessity because rocks older than the Neoproterozoic glacial deposits contain microfossils that are closely homologous in form to a variety of eukaryotic algae living today.

Near-surface hot springs are promising refuges for photosynthetic eukaryotes. Hot springs close to sea level such as those in Iceland, Hawaii and New Zealand would be viable, although elevated hot springs like Yellowstone would soon run dry. Individual hot springs seldom last beyond 1000s of years, so organisms must be capable of surviving transport by winds between hot springs within a particular volcanic field, or be transported in seawater beneath the ice from one volcanic opening to another. The fields themselves are active over millions of years, but are very sparsely distributed on the surface of the Earth. Thus, organic communities clinging precariously to particular volcanic fields might maintain a high degree of genetic isolation for millions to tens of millions of years. Moreover, the steep and variable temperature chemical gradients endemic to hot springs on an ice-covered planet would select for fitness in the hellish aftermath to come. This is not to underestimate the carnage, of which the carbon isotopic record bears witness. The relative poverty of the contemporaneous fossil record makes it difficult to compare Neoproterozoic and later mass extinctions. There are indications of major evolutionary turnovers of "acritarchs"—spheroidal, organic-walled microfossils, possibly the remains of non-skeletal protists or the reproductive cysts of eukaryotic algae. Some measure of the extent of eukaryotic extinctions may be evident in universal "trees" of life, based on molecular sequencing of living organisms. Most such "trees" depict eukaryotic phylogeny as a delayed radiation crowning a long unbranched stem. Chances are that the eukarya-archaea divergence occurred more than 2000 million years ago, so the under-expression of deep eukaryotic branching in modern organisms could mean that most early eukaryotic lineages were "pruned" 600-700 million years ago. All extant eukaryotes would stem from the survivors of the Neoproterozoic calamity.

The body plans of nearly all living animals appeared in a very short interval between 600 and 525 million years ago, and have remained essentially unchanged ever since. This has long been considered a sticking point for evolutionary biology. Beginning with Lyell and Darwin, attempts have been made to recast the evidence as drastic Neoproterozoic record failure, but there is no evident jump in the quantity or quality of the stratigraphic record to support this view. More recently, it was proposed that animals originated earlier as tiny free-floating organisms that left no fossil record. This would be consistent with evidence from molecular "clocks" that place divergence times for various pairs of metazoan phyla well before 600 million years ago. However, the divergence times are estimated using gene substitution rates extrapolated from younger times. Are the extrapolated substitution rates appropriate for gauging the tempo of early animal evolution under Neoproterozoic conditions? A series of global "freeze-fry" events would cause population "bottlenecks and flushes", observed to accelerate evolutionary rates in some species. The crash in population size accompanying a global glaciation would be followed by millions of years of comparative genetic isolation in high-stress environments. This is a favorable scenario for genomic reorganization and the evolution of new body plans. Finally, repopulations following each glaciation would occur in transient selective environments quite different from those preceding the glaciation, favoring the emergence of new life forms. It is not clear, however, if the Neoproterozoic events would favor the branching of major clades of life as distinct from the development of new body plans within existing clades. The former must always precede the latter in any given radiation. Thus, divergence times based on molecular sequences will always be older than first appearances in the fossil record, which reflect new adult body plans. 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 a more active role in spawning multicellular animal life.

Snowball Episodes and Earth History

We have shown how the great glacial deposits in Neoproterozoic rocks world-wide and the strata adjacent to them point to an extraordinary type of climatic event, a "snowball" Earth followed by a briefer but equally noxious ultra-warm "greenhouse" world. There is clear evidence that this sequence happened more than once, perhaps as many as four times between 750 and 580 million years ago. But what caused these calamities in the first place, and why has the biological world been spared such events in more recent geological history? One factor was clearly that the Neoproterozoic sun was weaker by approximately 6%, making the Earth more susceptible to glaciation. The slow warming of our sun since that time might explain why no "snowball" event has occurred since the Neoproterozoic, but the geological evidence is compelling that such glaciations did not occur for at least one billion years prior to the Neoproterozoic when the sun was even cooler. Recent findings by Kirschvink and his former student, David Evans, suggest that global glaciations may have occurred around 2.3 billion years ago, but not in the intervening period.

A potential explanation for the rare occurrence of "snowball" events in Earth history is an unusual continental configuration. Paleomagnetic evidence suggests that there were few if any continents at high latitudes 600-700 million years ago. When most continents are close to the Equator, the Earth is deprived of a mechanism that keeps the amount of carbon dioxide in the atmosphere above a critical level. If carbon dioxide in the atmosphere were to slowly drop over millions of years due to a slow reduction in volcanic activity, global temperatures would drop and glaciers would cover the high-latitude continents, just as ice sheets cover Antarctica and Greenland today. The ice sheets prevent chemical weathering, the process that converts carbon dioxide to carbonate, from proceedin. This stabilizes the levels of carbon dioxide in the atmosphere. But if all the continents were in the tropics, such a "safety switch" would not work, as the continents would remain ice-free even as the Earth grew colder, approaching the critical threshold for a snowball. Such a theory is speculative, although some unusual behavior of the carbon cycle is implicated by the unusually high amount of carbon-13 in sediments of Neoproterozoic time. We may never know the true cause, as we have but simple theories for the ultimate forcing of climate change even in recent times. But clearly a successful answer must explain both why a glacial runaway happens and why it is such a rare event.

Could the Earth become a "snowball" in future? For the last million years, the Earth has been in its coldest state since the Neoproterozoic. We are now living in a relatively warm episode, some

80,000 years from the next glacial maximum, but some evidence suggests that each successive glaciation over the last several cycles has been getting stronger and stronger. During the most recent glacial event, 20,000 years ago, the deep ocean cooled to near its freezing point, and sea ice reached latitudes as low as 40 to 45 degrees north and south, still far from the critical threshold needed to plunge the Earth into a snowball state. But could such a state be in our future? Certainly over time scales of hundreds to thousands of years, we are more concerned with anthropogenic effects on climate, as the Earth heats up in response to emissions of carbon dioxide. But only time will tell where the Earth's climate will drift over millions of years. If the trend of the last million years of Earth history is continued and if the polar continental "safety switch" were to fail, we may once again experience a global ice catastrophe which would inevitably jolt life in some new direction. Perhaps Robert Frost foresaw this in his poem, "Fire and Ice":

Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.

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