Geologic and Climatic Puzzle of the Proterozoic Snowball Earth

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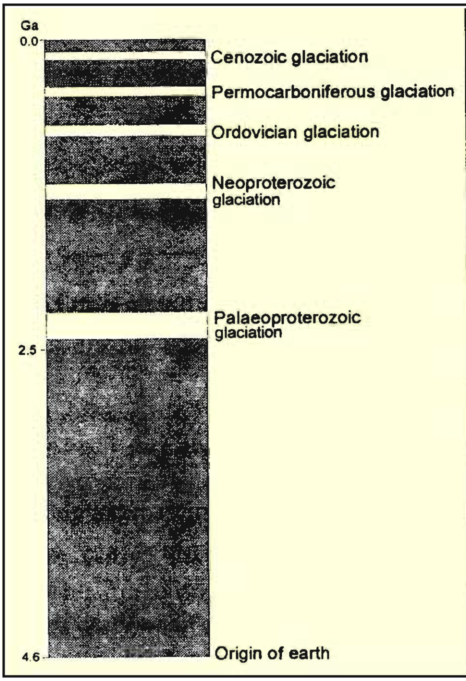
According to the hypothesis of 'snowball earth' the planet was covered *in toto* with ice for millions of years in two major pulses of global glaciation in the Proterozoic era of earth history. The earlier event of snowball earth is less understood but the subsequent one has overwhelming evidence in the geological record of rock strata. Accelerated chemical weathering on tropically positioned continental masses is believed to have withdrawn excess CO_2 from the atmosphere, initiating global cooling and eventually plunging the whole earth under ice cover. Accumulation of volcanically emitted CO_2 in the atmosphere during glacial ice cover melted the ice by greenhouse warming bringing back normalcy.

The Proterozoic Glacial Epochs

When the earth accreted 4.6Ga (1Ga$=10^9$ years) ago it was a red-hot planet and planetesimals and comets continued to bombard it. Soon after this early phase, the earth commenced cooling from >45°C that prevailed in the early Archaean (3.8 to 2.5Ga) to the present day temperature. This long history of cooling was interrupted at periodic intervals by transient colder periods called ice ages or glacial ages. Among such spells of ice ages, the ones that took place during the Proterozoic era (2.5 to 0.544Ga, *Figures* 1 and 2) were very severe and long. These glacial episodes were also unique since such severe glaciation did not occur even in the preceding Archaean era, when solar luminosity was 30% less than today.

Keywords
Proterozoic era, snowball earth, global glaciation.

The Proterozic glaciation took place in two spells – the first one between 2.4 and 2.3 Ga ago in the Palaeoproterozoic and the second between 0.8 and 0.6 Ga ago in the Neoproterozoic. Of these, the latter glaciation was very intense and global and the



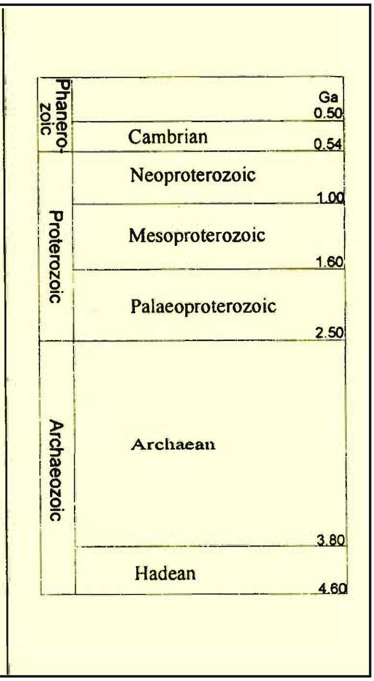


Figure 1 (left). Major glacial events in earth history.

Figure 2 (right). The Precambrian timescale.

ice-sheets were believed to have spread right up to the equator at sea level. Even the tropical seas were frozen and over a kilometer thick ice sheets had blanketed the whole earth for millions of years. Surface temperature had plunged to –50°C and the earth was spinning through space like a cosmic snowball. Today, evidences for these glacial spells, separated by ice-free or interglacial periods, are seen in the form of glacially deposited sediments or tillites (see *Box* 1) and non-glacially deposited interglacial sediments. Such sediments have been recorded from several countries around the world like Canada, USA, Finland, South Africa and western Australia. In India, sedimentary rocks, long

Box 1. Tillite, Diamictite, Dropstones

Flowing ice sheets, like flowing rivers, carry sediment load with them and when they melt, their sediment load is deposited along advancing fronts. Such deposits or 'tills' consist of fine clay, silt or sand embedded with striated, abraded boulders. When these tills get compacted (lithification) they are called tillites. Diamictites are essentially tillites, but highly unsorted, containing jumbled mixtures of pebbles, cobbles and boulders in a matrix of mud. Dropstones are large boulders transported by glaciers, which get dropped over fine sediments on the sea floor.

Box 2. Plate Tectonics

The theory proposed and developed in the 1960s according to which the earth's lithosphere is considered to be a mosaic of rigid blocks or plates, which move horizontally on the surface of the earth in response to thermal upwelling (convection) in the mantle. This theory explains many of the geological processes such as earthquakes, volcanism on land and ocean floor, mountain building, and continental breakup and their motions.

suspected to be glacially derived, occurring in the lower Vindhyan formations in Madhya Pradesh, are now considered non-glaciogenic.

Climatic and Geologic Puzzles of Global Ice Covér

The puzzling and much debated aspect of the Proterozoic glaciation concerns the extent of its spread – whether they were confined to higher latitudes only, like in the ice age episodes of younger geological times or, spread even up to tropical regions as claimed. Brian Harland of the University of Cambridge, as early as 1964, drew attention to the distribution of ice-rafted sediments below the Cambrian strata (0.544 to 0.500Ga) in a number of countries, an occurrence that is possible only if all the countries existed at one place. By then, the plate tectonics concept (see *Box* 2) had gained recognition and based on palaeomagnetic studies (see *Box* 3), he concluded that the earth's continents must have remained near the equator in the Neoproterozoic and that glaciers of the period had covered the tropics. But many considered that this argument was not convincing enough and, therefore, his views did not enjoy wide acceptance.

Box 3. Palaeomagnetism

Certain magnetic minerals such as magnetite crystallizing out of cooling magmas or settling out of water, align themselves in the direction of earth's prevailing magnetic field. They retain this magnetic orientation for billions of years, a feature which helps to derive the palaeolatitude of the sampled site. This field of study is of paramount importance in the reconstruction of paleogeography or former positions of continents.

The fact that lands had indeed clustered together during the Neoproterozoic could not be dismissed in view of the occurrence of abundant glacially derived sedimentary rocks or diamictites (see *Box* 1) of the period in a number of continents, which today lie dispersed. Further, these rocks are bounded above and below by sequences of carbonates, which are marine sedimentary rocks that can form only in warm tropical seas, within 38° latitude. There are a number of other evidences also pointing to the earth's intermittent glacial spells in the Proterozoic. For example, the occurrence of banded iron formations[1] and the presence of carbonate strata abruptly capping glacially-laid sediments (hence called cap carbonates) showing interesting clues through variations in carbon isotope ratios ($^{13}C/^{12}C$) are two evidences stressed by geologists. Though these are claimed to support extensive or global glaciation, a pertinent question asked by many is that if the earth were so cold and globally ice covered, how did it rebound from the cryogenic slumber.

Banded iron formation (BIF) are chemically precipitated marine sedimentary rocks with alternating layers of silica and iron oxide minerals.

The Snowball Earth

As early as the 1960s, Mikhail Budyko, a Russian geophysicist, provided an explanation for tropical glaciation using climate models. According to him, ice has a higher albedo (reflectivity) than water or land and any cooling that extends the coverage of ice over the earth's surface will result in further increase of planetary albedo. This cooling will be greater in the regions of lower latitudes where the surface area per latitude is larger. Eventually, this ice-albedo feedback would run out of control and ice sheets could extend to latitudes lower than 30° S or N of the equator. This mechanism of cooling gradually created a 'snowball earth' an apt description conceived by Joseph Kirschvink of the California Institute of Technology in 1992, while explaining the association of BIF with the Proterozoic glacial sediments. According to him, extensive glaciation and ice cover over the lands in this era had decoupled atmosphere-ocean exchange of gaseous constituents like oxygen and impoverished the deep ocean of dissolved oxygen. Over a period of time, the soluble ferrous iron generated by ocean bottom volcanism along the mid-ocean ridges had steadily increased in the oxygen-poor ocean. This ferrous iron, held in solution, precipitated as insoluble ferric oxide of the BIF as soon as deglaciation commenced and restored the oceanic circulation and atmosphere-ocean exchange of gaseous constituents and the ocean waters once again became oxic.

But how did the deglaciation take place? Several geological developments that occurred while the earth remained totally ice-covered were supposed to have led to deglaciation by greenhouse warming, mainly through accumulation of CO_2 in the atmosphere. The rise in atmospheric CO_2 during glacial periods must have happened due to uninterrupted emissions from volcanoes and the cessation of biologic consumption of this gas by photosynthesizing organisms, which had perished under the frigid conditions. More importantly, the collapse of chemical weathering, in the absence of liquid water on lands and stoppage of atmosphere-ocean exchange of CO_2 also aided the accumulation of CO_2 in the atmosphere. The enforced greenhouse warming melted the ice and liberated the earth from the ice-cover. Caldeira and Kasting, Pennsylvania State University, have estimated that with modern rates of CO_2 release from sub-aerial volcanism, a critical concentration of ~350 times the present level (360 ppm) of CO_2 can be reached in 4Ma (1 Ma = 10^6 years) after the onset of snowball earth conditions. However, Kirschvink's explanation did not address the problem of cap carbonate and the associated carbon isotope anomalies.

In 1998, Paul Hoffman and co-workers of Harvard University and University of Maryland, USA, found fresh geologic evidences in support of the snowball earth hypothesis in the Neoproterozoic rock formations in several countries like Australia, China, western USA, South Africa and the Arctic island of Svalbard. The most convincing evidence favouring this hypothesis came from a thick zone of cap carbonate immediately overlying Neoproterozoic diamictites of the Skeleton coast of Namibia, exhibiting unusual variations in the carbon isotopes. They argued that if the earth were ice-covered, an ultra-high CO_2 atmosphere would be required to raise the temperature for the snow to melt. Once melting began, low-albedo seawater would replace high-albedo ice reversing the runaway freeze and restoring evaporation and enhance warming, since water vapour is also a powerful greenhouse gas. These trends will eventually cause torrential rains and an enhanced water cycle, faster chemical weathering of rocks, transportation of more carbonates, bicarbonates and Ca and Mg ions to the oceans and faster

The most convincing evidence favouring the 'snowball' hypothesis came from a thick zone of cap carbonates in Namibia showing unusual variations in the carbon isotopes.

precipitation of carbonate sediments on the ocean floor over the sediments already laid down there by the melting glaciers. The authors claim that the Namibian cap carbonates were indeed precipitated in this manner rapidly, perhaps in a few thousand years.

The Namibian cap carbonates, like similar cap carbonate occurrences around the world, exhibit an anomalous pattern of variation of the two carbon isotopes ^{12}C and ^{13}C. According to Hoffman and his group, these isotopes in the Namibian cap carbonates, exhibit a pattern of variation, which correlated with the decrease and increase of marine life during the Neoproterozoic when the earth remained under ice and subsequently emerged out of it after millions of years. They developed their postulate thus: Marine biota, algae and bacteria in particular, take up dissolved CO_2 from the ocean to photosynthesize carbohydrates and for this process these organisms preferentially take up the lighter isotope ^{12}C. As a result, the ocean waters would get relatively enriched in the heavier isotope ^{13}C. Carbonates precipitated from such waters would, therefore, be enriched in ^{13}C. They explained how just prior to the onset of the snowball event, global cooling would have reduced biological productivity, which in turn, would have resulted in reduced ^{12}C uptake by marine organisms. Carbonates precipitated at this time would be relatively enriched in ^{12}C. Once ice covered the whole earth, biological activity would completely stop. But no carbonate can precipitate from ice-covered ocean and we cannot record the isotopic trend of the ocean in this interval. However, with the onset of deglaciation, biological productivity would slowly increase and C-isotope ratios of seawater and carbonates precipitated from the oceans would gradually return to normal values. These trends, according to Hoffman and his team, are in agreement with the snowball earth hypothesis.

The isotope variation perhaps correlated with the decrease and increase of marine life when the earth remained under ice and subsequently emerged out of it.

Methane Hydrate Model

In 2001, Martin Kennedy, University of California and coworkers Christie-Blick and Linda Sohl of Columbia University, USA,

Box 4. Gas Hydrates

Gas hydrates are crystalline solids composed of methane (therefore also called methane hydrates) and water formed under specific P-T conditions. They occur widely dispersed within ocean floor sediments under continental rise and slope between water depths of 250 and 530m (e.g., off the SE coast of USA). They are also known to occur under permafrost terrains in higher latitudes. These hydrates are stable only at pressures of >50 bars and temperatures of <7°C and get destabilized into the gas phase if these ambient conditions fail. Methane in gas hydrates is largely biogenic, generated by bacterial reduction of organic matter (decay processes) embedded in sediments.

provided an alternate explanation for the enigmatic cap carbonates. They invoked massive methane release from immense quantities of gas-hydrates (see *Box* 4) entombed under continental permafrost (permanently frozen aggregate of ice and soil in very cold regions) consequent to snowball deglaciation. According to them, methane so liberated produced CO_2 on oxidation and was later deposited as cap carbonates. Since methane is largely biogenic, the -ve $^{13}C/^{12}C$ ratio observed in these carbonates can be easily accounted for as biogenic carbon is depleted in ^{13}C. These authors have cited a number of features in the cap carbonates in support of their model, in particular, the presence of tubular passageways made by escaping methane gas. However, based on field, laboratory and geochemical data, a few critics have discounted these, especially the degree of carbon isotope variations (–ve ^{13}C) reported by Kennedy and others, as they do not support their methanogenic model. Further, the global distribution of cap carbonates requires destabilization of the sea floor/permafrost on a worldwide scale for which methane hydrate model did not provide any mechanism.

High Obliquity Hypothesis

Williams, Pennsylvania State University, advanced another explanation in 1993, for the Neoproterozoic ice-cover over the equatorial zone. Called the 'high obliquity hypothesis', he considered that the earth's axial tilt (the obliquity) exceeded 54° until the end of the Proterozoic after which it returned to the present value of 23.5°. Such an axial tilt would reverse the climatic zones glaciating the tropics while making the polar regions ice-free. However, this model does not explain the association of carbonates and glacial deposits that represent climatically contrasting phenomena, as also the long ice-free events in the mid-Proterozoic. Neither does it offer a satisfactory mechanism for the obliquity to return to the present values. Besides, studies of stromatolites (see *Box* 5), which are known to show heliotropism indicate a planetary obliquity of 26.5° in the Neoproterozoic.

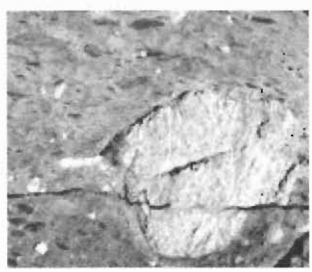
Box 5. Stromatolites, Heliotropism

Stromatolites are certain sedimentary structures constructed in carbonate sediments by photosynthesizing cyanobacteria. They range in geologic age from the early Archaean to the present and are among the early members of life on earth. They exhibit helio-tropism i.e., they grow vertically in response to the noon position of the Sun.

Arguments against Snowball Earth

The snowball earth hypothesis has been criticised by climatologists who feel that the high thermal inertia of the oceans would not have permitted it to freeze completely . Actually, the discovery of thin layers of glacial debris interbedded with marine sediments in Africa, suggests that glaciers still debouched into the oceans and deposited their load, thereby implying that the seas never froze. They were of the view that once the earth became engulfed by ice sheets, it could have never recovered from that state. They have also performed numerical simulation studies, assuming different scenarios of solar flux reductions and sea surface temperatures appropriate to the Neoproterozoic and their results do not favour global ice-cover. Another study based on climate-ice sheet model rejects the assumed extinction of marine life during the global glaciation. This study indicates that an equatorial belt of ice-free ocean would still remain where the marine biota could survive the freeze. A few computer simulation experiments recently performed also rebut the ice-albedo feedback mechanism that accounts for the onset of global cooling. They argue that this would require a solar luminosity reduction of more than 10% of the present value for ice cover to advance towards the equator and that during the Neoproterozoic this was only 7%. In fact, the solar flux was far less in the early Archaean (~30% less) but surprisingly this did not cause any glaciation at that time. Some geologists have conceived diamictites (*Figure* 3) as unsorted ejecta produced by bombarding meteorites, but such an origin cannot explain the enormous volume of diamictite deposits distributed all over the world.

Figure 3. Diamictite showing highly assorted debris.



Snowball Earth and Biological Evolution

The earth witnessed a burst in the evolution to higher forms of life during the early Cambrian (0.53 - 0.52 Ga ago) *i.e.*, immediately after the severe Neoproterozoic ice age. Carson had proposed in 1987 that environmentally-driven stresses promote rapid development of several new species. Successive snowball earth conditions, prior to the Cambrian, obviously acted as bottlenecks in the progress of evolution to higher forms of life, which do not appear to have advanced beyond primitive life forms like the cyanobacteria. The post-snowball earth saw the establishment of ideal conditions with warm and congenial habitats. The stressed and stifled life soon diversified through a great degree of genetic variations within a short time and the earth thus witnessed an explosion of new life forms. Kirschvink and coworkers also envisage a similar mechanism to have operated for the burst of cynobacterial life after an earlier ice-age spell during the Palaeoproterozoic, when abundant Fe-Mn-rich nutrients from ocean floor volcanism enriched the ocean, and produ-ced a bacterial bloom following the glacial melting. It is believed that the oxygen released by these photosynthesizing organisms oxidized the oceans and precipitated the dissolved Fe and Mn to form ore deposits such as the Kalahari Manganese Field in Southern Africa, which overlies glacially deposited sediments.

Break up of Rodinia and Global Ice Cover

What are the likely factors that must have contributed to the climatic deterioration and consequent global ice cover? The answer lies in the secular variation in the atmospheric CO_2 reservoir. Palaeomagnetic data confirm that the continents, which were earlier assembled to form the supercontinent Rodinia, started to breakup and drift, clustering near the equator by the end of the Neoproterozoic. Their location in the tropical belt enhanced extraction of atmospheric CO_2, as rock weathering is faster in the tropics than in higher latitudes. Such rapid chemical weathering of rocks, drawing excess CO_2 from the atmo-

Suggested Reading

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sphere resulted in accelerated sedimentation, facilitating organic carbon burial in continental shelf sediments, which thus served as a sink for CO_2. These events paved the way for the onset of extensive glaciation in the Neoproterozoic.

Why did the Snowball Phenomenon not Recur?

But why did the snowball freeze not return in younger geologic times (Phanerozoic)? There could be several reasons: Higher solar luminosity, dispersion of continents at higher latitudes where rock weathering is less intense, thereby withdrawing less CO_2 from the atmosphere and reduced oceanic primary productivity due to diminished supplies of nutrient iron and phosphorous to the Phanerozoic oceans. Will the snowball earth scenario reappear in the future? Not at least for many millions of years from now because the continents today are dispersed in the middle to higher latitudes where CO_2-absorbing chemical weathering is very slow. Perhaps, in a distant geological future, if plate tectonics again pushes the continents and re-assembles them near the equator, and when the luminosity of the aging sun dwindles, snowball earth conditions may recur. Hopefully, by then *Homo sapiens* may have evolved into some super-intelligent species and colonized elsewhere in the Universe.

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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.

Robert Frost
Fire and Ice