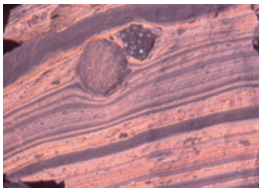
Feature



Pan-glacial—a third state in the climate system

Radiative energy-balance models reveal that Earth could exist in any one of three discrete climate states—'non-glacial' (no continental ice-sheets), 'glacial-interglacial' (high-latitude ice-sheets) or 'pan-glacial' (ice-sheets at all latitudes)—yet only the first two were represented in Phanerozoic time. There is mounting evidence that pan-glacial states existed at least twice in the Cryogenian (roughly 750–635 Ma), the penultimate period of the Neoproterozoic. Consensus is lacking on whether the world ocean was fully glaciated ('snowball' model) or largely unglaciated ('slushball' model). The first appearances of multicellular animal fossils (diapause eggs and embryos in China, and sponge-specific biomarkers in Oman), being closely associated with the last pan-glacial state, revive speculation that environmental forces had a hand in the origin of metazoa.

Paul F. Hoffman
Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA; and School of Earth and Environmental Sciences, The University of Adelaide, Adelaide, South Australia 5004, Australia
paulfhoffman@yahoo.com

In 1926, the British meteorologist and climatologist C.E.P. Brooks explicitly argued that during the Phanerozoic eon, the Earth had been in one or the other of two discrete climate states (Fig. 1): a 'glacial–interglacial' state, like the late Cenozoic, in which one to four continents were draped by dynamic ice-sheets, or a 'non-glacial' state, like the Mesozoic and early Cenozoic, in which no continental ice-sheets existed. But what of the Cryogenian (roughly 750–635 Ma), the penultimate period of the Proterozoic eon, when glacial deposits formed simultaneously on virtually all continents, including those that lay close to the palaeoequator and lacked mountains from which ice might have descended to sea-level from high elevations?

A too probable 'White Earth' disaster

Motivated by the projected disappearance of Arctic summer sea-ice due to increasing concentrations of 'greenhouse' gases from the burning of fossil fuels, climate scientists of the 1950s and 1960s derived mathematical expressions to describe mean annual surface temperatures as a function of latitude and variable radiative forcing. Assuming energy balance between incoming and outgoing radiation, the expressions incorporated the variable angle of incident radiation, simple parameterizations of pole-ward heat transport by atmosphere and ocean dynamics, and both negative and positive feedbacks from clouds and snow/ice, respectively. Leading figures in this effort were Mikhail Budyko in St Petersburg (then Leningrad), Eric Ericsson in Stockholm and William Sellers in Tucson, Arizona. With increased radiative forcing,

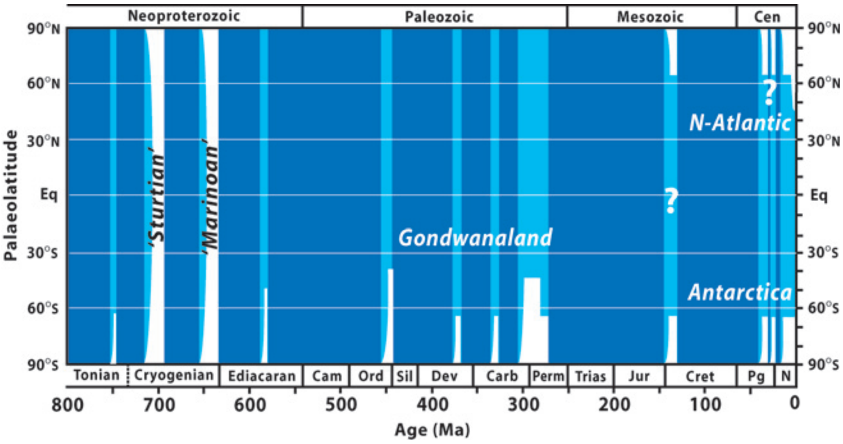


Fig. 1. Meridional extent of ice sheets and annual-average sea-ice (white) from 800 Ma to present, showing the 'glacial-interglacial' (light blue) and 'non-glacial' (dark blue) climate states modified after Brooks (1926), and the two 'pan-glacial' states in the Cryogenian period (base yet to be formally defined) of the Neoproterozoic.

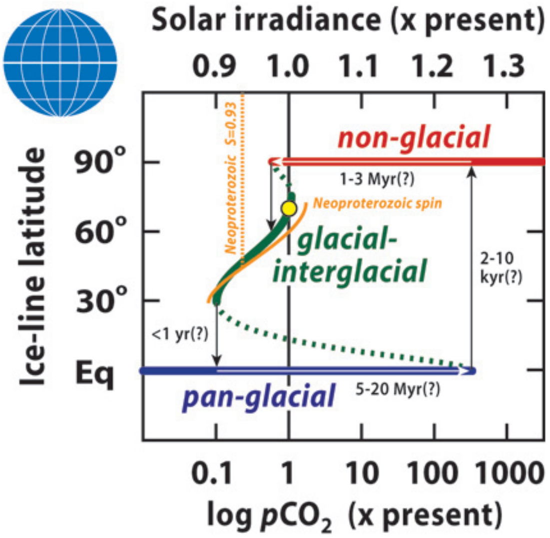


Fig. 2. Ice-line latitude on an idealized aqua-planet as a function of solar irradiance, relative to the present Earth, or equivalent CO_2 concentration, according to a simple energy-balance climate model of the Budyko–Sellers type. Note the three stable branches representing 'glacial-interglacial' (green), 'non-glacial' (red) and 'pan-glacial' (blue) climate states. Dashed green lines are unstable areas. Present irradiance permits all three climate states (yellow dot is the actual state). Thin arrows track the hysteresis loop of a 'snowball' Earth climate cycle, with the estimated duration of each leg of the loop.

the calculations suggested that the demise of Arctic summer sea-ice was not only possible but could occur abruptly, the system 'jumping' across an unstable area separating one stable state from the other (Fig. 2).

When radiative forcing was lowered, the results were remarkable and unanticipated. With a mere 1.5–2.0 per cent decrease in solar radiation, the calculated surface temperatures dropped below freezing everywhere. The area of instability was very broad: if the ice-lines fell within 30–35 degrees latitude of the equator, the advance of ice became self-sustaining and irreversible due to runaway ice–albedo feedback (Fig. 2). This was rightly viewed as a highly problematic result.

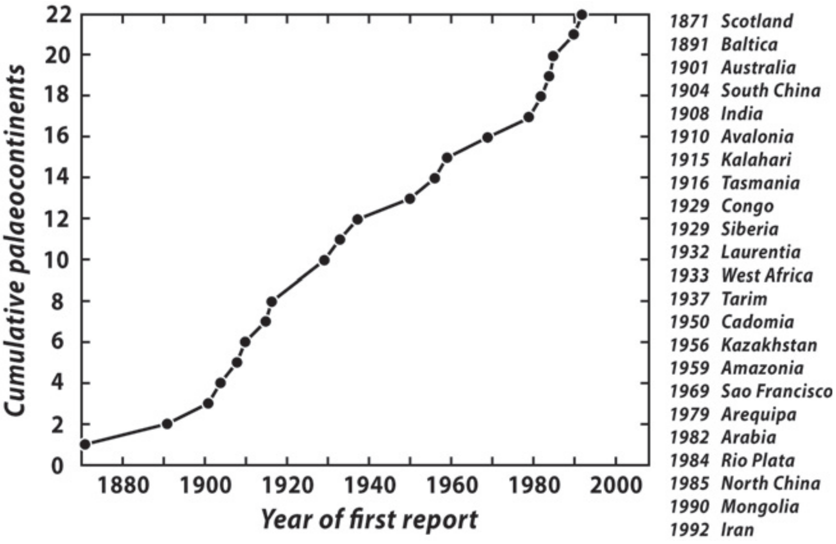
It was known that the Sun's luminosity was 25–30 per cent lower in the early Solar System and has increased almost linearly since that time, due to the progressive accumulation of helium atoms in the Sun's core. The calculations implied that a global ice shell should have cloaked the early Earth, an ice shell that should still exist because an increase in solar irradiance far above the present would be needed to overcome its high albedo (the fraction of incident radiation that is reflected). It was taken for granted that such a 'white Earth' disaster had never occurred because life, if it ever existed, would have been extinguished. It was therefore assumed that the formulation of the climate problem was grossly in error. This stimulated research in the nascent science of climate modeling, but despite substantial improvements in energy-balance climate models in succeeding years, the 'white Earth' problem did not go away.

Maintaining a habitable planet

In 1981, planetary atmospheric scientists James Walker, Paul Hays and Jim Kasting at the University of Michigan in Ann Arbor thought they had found a solution to the 'white earth' problem. They were drawn to the more general paradox of the 'faint young Sun'—how was a habitable planet maintained for billions of years given a large secular increase in solar luminosity? The answer, they suggested, lay in the negative climate feedback provided by the temperature-dependence of silicate rock weathering. As the luminosity rose, silicate weathering reactions consumed carbon dioxide (CO_2) at a faster rate, both because of the direct effect of temperature on chemical reaction kinetics and indirectly through the control of rainfall in humid regions by temperature. Negative climate feedback caused the concentration of atmospheric CO_2, a 'greenhouse' gas, to adjust downwards in compensatory response to the rising solar luminosity. The feedback, they proposed, operates on a million-year timescale and prevents runaway warming or cooling, while allowing (and indeed requiring) limited changes of climate in response to variations in radiative forcing (e.g. rates of 'greenhouse' gas emission or consumption).

In the second last paragraph of their classic 1981 paper (see Suggestions for Further Reading), Walker and colleagues proposed that negative feedback in the geochemical cycle of carbon had prevented a 'white Earth' disaster. But, they went on, if one ever had occurred, it wouldn't be permanent. With the surface frozen, CO_2 could not be consumed by weathering. In the absence of sinks for CO_2, the present rate of volcanic emissions would build up 1.0 bar of CO_2 in ~20 million years, more than enough to melt the ice cover via the 'greenhouse' effect. At some point, the globe would deglaciate on a geological rapid timescale, driven by positive feedbacks (e.g. ice-albedo and ice-elevation feedbacks). Importantly, if a 'white earth' disaster was self-reversing, its occurrence in the distant past could not be ruled out *a priori*.

Fig. 3. Cumulative discoveries of Neoproterozoic glacigenic deposits by palaeocontinent. The large number of palaeocontinents reflects a highly fragmented palaeogeography and its uncertainty. Many of the deposits were not recognized as Neoproterozoic in age at the time of their discovery, although all were identified as glacigenic. Note that Laurentia is counted twice, Scotland (1871) and North America (1932).



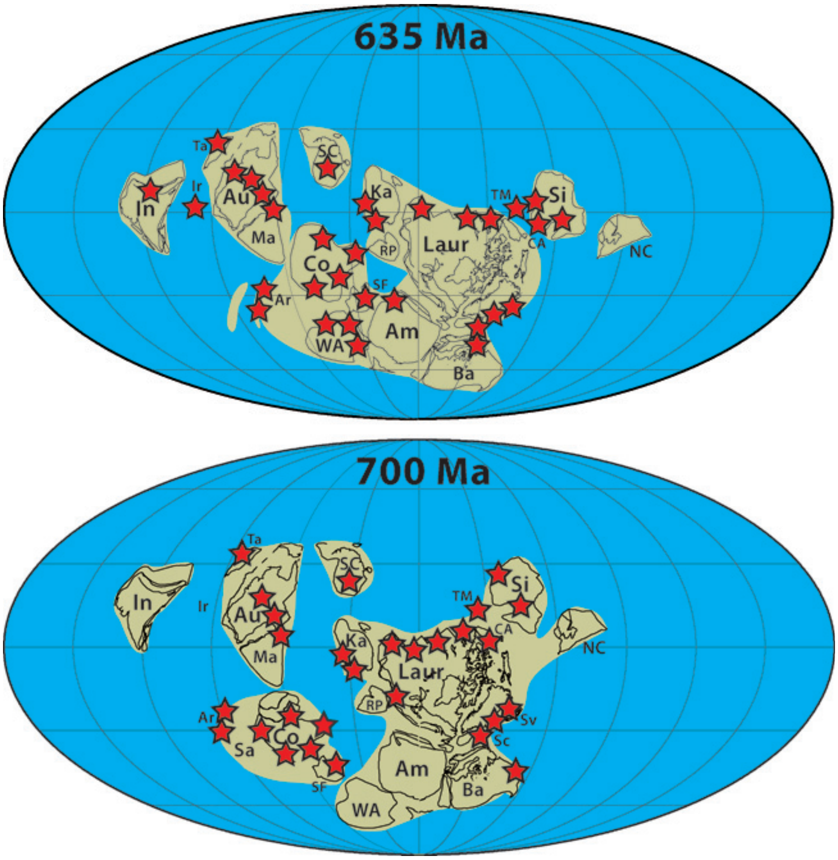


Fig. 4. Distribution of glacigenic deposits (red stars) on palaeogeographic maps for 700 Ma ('Sturtian' deposits) and 635 Ma ('Marinoan' deposits) according to Zheng-Xiang Li (Curtin University of Technology, Perth, Australia).

The geological record of Proterozoic glaciation

Glacigenic deposits are now known from 22 Neoproterozoic palaeocontinents (Fig. 3), more than twice the number of continents and microcontinents in the world today. The first such formation, the Port Askaig Tillite of Islay in the west of Scotland, was described by James Thomson in 1871. By 1937, it was apparent that Neoproterozoic glaciation was at least as extensive as the late Palaeozoic or late Cenozoic ones. In 1948, the South Australian geologist and Antarctic explorer Sir Douglas Mawson pronounced that the severest ice age of all time shortly preceded the Cambrian and that the first animals, recently discovered by his remarkable protegé Reginald Sprigg, had evolved in its wake. Mawson, a fixist, was unduly influenced however by the existence of tillites in Uganda, close to the present equator.

Nevertheless, by the mid-1960s it was known that dynamic Neoproterozoic ice sheets once existed on mountainless marine carbonate platforms, which because of the direct dependence on temperature of carbonate saturation, must represent the warmer parts of the surface ocean. Such glaciated carbonate platforms occur in Namibia, Mongolia and the Caledonides of East Greenland and Svalbard. If the warmer parts of the world were glaciated at sea-level, colder areas must have been frozen as well. It is important to understand that this observation, independent of any presumed correlation of glacial deposits, underpins the hypothesis of simultaneous widespread glaciation. Correlation follows from the premise, but is not its prerequisite.

In 1959, the British geologist Brian Harland attempted to use palaeomagnetism to determine the meridional extent of Neoproterozoic glaciation. An early mobilist, he knew that present latitude was no indication of palaeolatitude. His attempts were thwarted by primitive technology and the susceptibility of sedimentary rocks to secondary remagnetization. It is only since 1987, starting in South Australia with a study of the Elatina Formation by Brian Embleton and George Williams, that reliable palaeomagnetic data have increasingly supported the inference that ice sheets extended to sea-level close to the palaeoequator on at least two occasions in the Neoproterozoic (Fig. 4), and at least once in the Palaeoproterozoic. Strangely, there is little or no record of continental ice-sheets at any palaeolatitude between 2.22 and 0.75 Ga. It is a safe guess that, when the reason for this 1.47-Gyr ice-age gap is finally revealed, the pan-glacial episodes that bracket it will become better understood as well.

The 'Snowball Earth' hypothesis

Until 1989, geologists and climate dynamicists might as well have been on different planets insofar as Proterozoic glaciation was concerned. The latter had no idea there were observations supporting the results of their calculations; the former had no idea there were theories explaining what they saw in their rocks. This state of affairs was worse for geologists: without theory—they had no means to make predictions that could be tested with further observations.

The American palaeomagnetist Joseph Kirschvink had critically reviewed the paper by Embleton and Williams reporting low-inclination palaeopoles from the Elatina Formation. Secondary re-magnetization appeared unlikely because the remanent magnetization was stably carried by detrital haematite. Moreover, South Australia had not been in low palaeolatitudes since the Cambrian. To make sure, Kirschvink had an undergraduate student conduct a soft-sediment fold test. The test, subsequently confirmed by others, was positive: the Elatina Formation, which bears unmistakeable evidence of glaciers in a marine environment, had been deposited within 15 degrees of the palaeoequator.

Kirschvink belonged to a multidisciplinary think-tank called the Precambrian Palaeobiology Research Group (PPRG), organized by the American micropalaeontologist William Schopf. James Walker and Jim Kasting, the atmospheric scientists who had solved the ‘faint young Sun’ problem, were members as well, as were two experts on Precambrian ‘banded iron-formations’ known as BIFs, Nicolas (Nic) Beukes of Johannesburg, South Africa, and Cornelis (Cees) Klein of Albuquerque, New Mexico. At the 1989 meeting of the PPRG, Kirschvink applied the concept of self-reversing global glaciation driven by ice-albedo feedback, developed by Walker and collegues in their classic 1981 paper, to the problem of low-latitude Neoproterozoic glaciation. Alluding to the glaciated planet’s appearance from outer space, he named his hypothesis the ‘snowball Earth’.

Dynamics of a global ice shelf

The snowball Earth hypothesis predicts that the world ocean was covered by a dynamic ice shelf hundreds of metres thick on average (Fig. 5). Its thickness was governed by the geothermal heat flux escaping through the ocean and varied spatially according to the surface air temperature. The ice shelf flowed under its own weight toward the Equator, where it was thinnest, and the flowage was maintained in steady-state by sublimation and melting at low latitudes, and by condensation and freezing in middle and high latitudes. Accordingly, the ice shelf had two components, meteoric ice (compressed snow) and marine ice (frozen seawater). Meteoric ice has higher albedo than mature marine ice because of trapped air bubbles. Consequently, equatorial sea ice would be thin (<10 m) if marine ice was exposed by sublimation, but thick (>100 m) if meteoric ice flowed in from the mid-latitudes. Climate models suggest that atmospheric vapour transport would be sufficient to build up continental ice sheets thick enough to flow in steady state within a few 100 kyr after the ocean first froze over. Two major difficulties confront the hypothesis. The first is that subduction has destroyed the direct sedimentary record of Proterozoic ocean floors. The second concerns the survival of phototrophic primary producers.

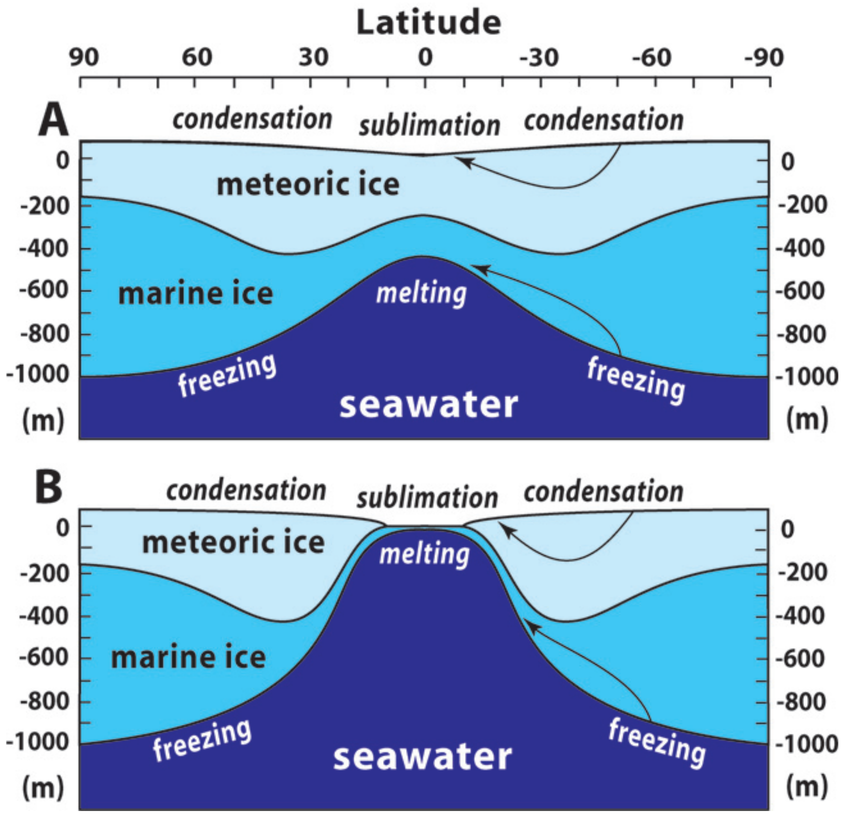


Fig. 5. Schematic portrayal of ‘sea-glacier’ dynamics on a ‘snowball’ Earth, where: **A,** reflective meteoric ice and **B,** darker marine ice is exposed in the equatorial zone. In **B,** the equatorial ice is thin enough (<10 m) to allow sub-ice photosynthesis. Arrows indicate trajectories of ice flowage, maintained by sublimation and condensation at the top of the ice driven by Hadley convection, and by melting and freezing at its base resulting in salinity gradients that drive a weak ocean circulation. Rates of ice flow reach ~50 m/yr in the subtropics.

Banded iron- and iron-manganese formations

The snowball hypothesis was difficult for geologists and geobiologists to swallow. For nearly a decade, only two besides Kirschvink openly supported it, the Banded Ironstone Formation (BIF) experts Nic Beukes and Cees Klein. BIFs and associated sedimentary MnO_2 deposits are common in Archaean successions and occur sporadically in the Palaeoproterozoic until 1.89 Ga, after which they all but disappear from the sedimentary record. The only younger occurrences are within Neoproterozoic glacigenic sequences, where they occur as beds of nearly pure haematite (Fe_2O_3) and in some cases MnO_2 over large areas (Fig. 6A). Because Fe^{3+} is highly insoluble, the reappearance of BIF indicates ocean bottom-water anoxia and their exclusive occurrence in glacigenic sequences suggests that the cause of the anoxia was ice cover.

It has been suggested that ocean bottom waters were anoxic during most of the Proterozoic, but that BIF was excluded because the anoxic waters were euxinic (H_2S-rich), like the modern Black Sea, in which all soluble Fe^{2+} is removed as sedimentary pyrite (FeS_2) as opposed to BIF. As rivers are the major source of sulphate utilized by sulphate-reducing bacteria in the ocean, greatly diminished runoff (as subglacial meltwater) in a snowball Earth is consistent with low sulphide as well as high Fe concentrations in seawater. The snowball Earth hypothesis thus provides an attractive explanation for the comeback of BIFs.

‘Cap’ carbonates

If the oceans were fully glaciated as well as the continents, strong ‘greenhouse’ radiative forcing was required for deglaciation. This has two geologically testable corollaries. First, the glacial intervals were long-lived (millions of years) to allow high concentrations of CO_2 to accumulate in the atmosphere. Second, the glacial interval would be directly followed by an ultra-greenhouse transient, because the melting of the ice would occur faster (a few thousand years)

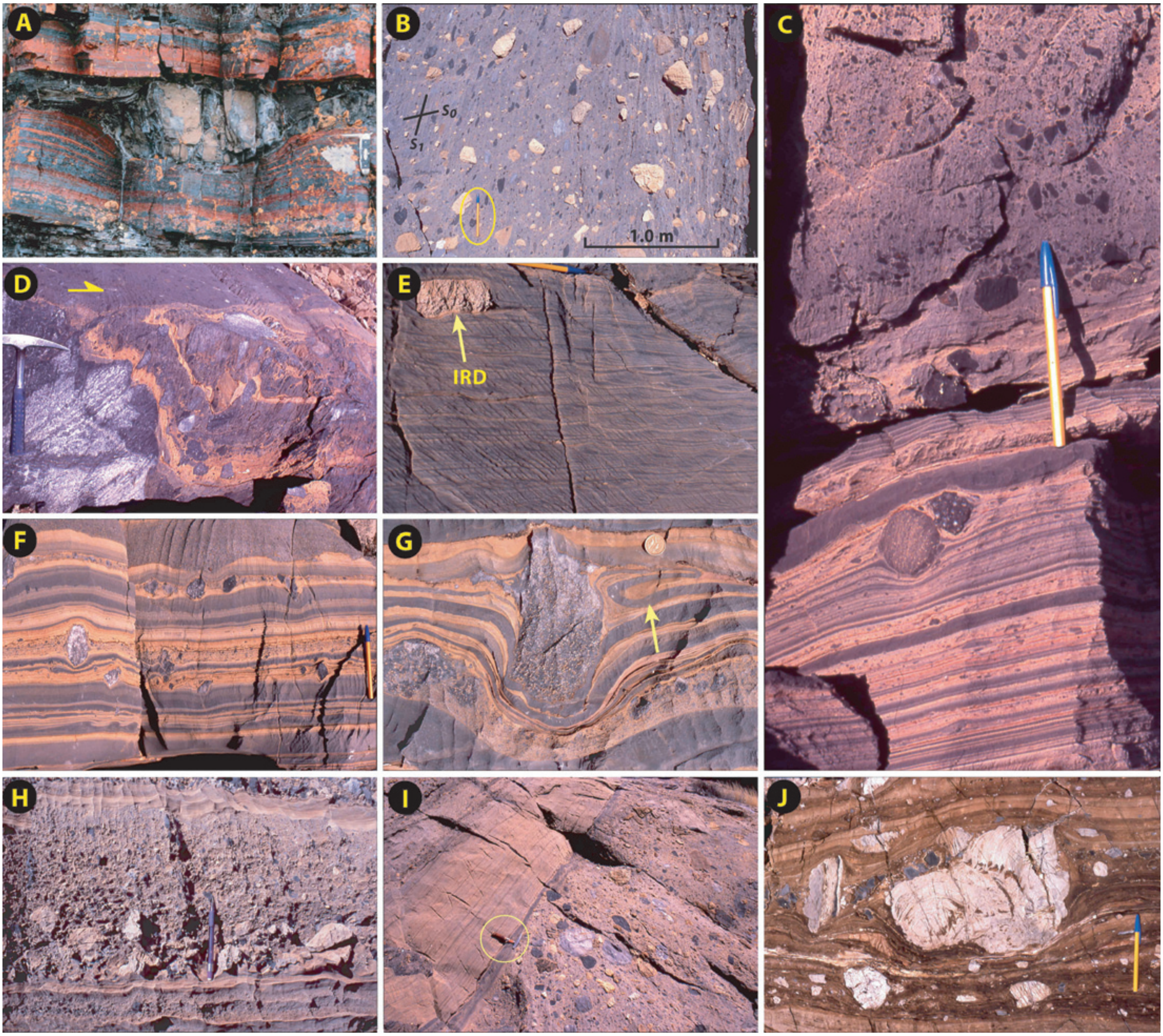


Fig. 6. Glacigenic lithofacies in: **A,** Rapitan Group, NW Canada, and **B–J,** Ghaub Formation, NW Namibia: **A.** Banded haematite-jasper iron-formation with ice-rafted dropstone of dolostone; **B.** Massive carbonate-clast diamictite; **C.** Rain-out diamictite gradationally overlying subaqueous proglacial carbonates with ice rafted dropstones; **D.** Melt-out (ice-contact) diamictite with reactivation surface and soft-sediment deformation related to ice-flowage (arrow); **E.** Climbing-ripples in grounding-line fan with ice-rafted lonestone (arrow); **F.** Slowly-deposited meltwater-plume fallout (tan, laminated) with IRD and rapidly-deposited limestone turbidites (grey, graded) lacking IRD; **G.** Ice-rafted dropstone (oolitic limestone derived from glacial-advance low-stand wedge) with recumbently folded ejection flap (arrow). Note deformed substrata and onlapping superstrata; **H.** Graded debris-flow in stratified subaqueous pro-glacial facies; **I.** Massive diamictite sharply overlain by stratified proglacial silts, sands and gravels recording an abrupt grounding-line retreat and gradual re-advance; **J.** Drape of ferruginous ice-rafted debris associated with ice-sheet terminal collapse on the Otavi platform.

than would the consumption of CO_2 by silicate weathering and carbonate burial (a few million years).

The first corollary provides the most practical falsifying test of the hypothesis. However, one must carefully distinguish the duration of the glacial interval from the duration of preserved glacial deposits. Most preserved glacial deposits record the retreat of an ice sheet from its last maximum limit, but not prior advances.

The second corollary predicts intense weathering in the glacial aftermath due to a combination of high pCO_2, high surface temperatures, and freshly ground-up rock and rock-flour exposed by the retreating ice sheets. The ocean would experience a jolt of alkalinity, driving carbonate production, especially during deglaciation when glacioeustatically lowered sea-level would expose shelf carbonates to weathering. A Harvard University team consisting of Galen P. Halverson, John A. Higgins, Alan J. Kaufman, Daniel P. Schrag and myself related post-glacial weathering to the occurrence of 'cap' carbonates, continuous layers of dolomite and limestone with unusual textures and sedimentary structures, which uniquely drape Neoproterozoic glacial sequences world-wide (Cover Photo). Anaerobic methane oxidation has been proposed as an additional source of alkalinity, but this is questionable if marine sulphate concentrations were low, as suggested by the presence of BIF.

Recently, extraordinarily high CO_2 concentrations have been inferred by Simone Kasemann (University of Edinburgh) and colleagues from boron isotopes in cap carbonates, and by Huiming Bao (Louisiana State University) and colleagues from mass-independent oxygen isotope ratios in early diagenetic barite ($BaSO_4$) from cap carbonates and in trace sulphate from syn-glacial lacustrine limestones (Cover Photo). Cap carbonates, along with BIFs, provide the strongest empirical evidence that the oceans froze over during at least two Neoproterozoic glaciations.

Glacioeustatic consequences

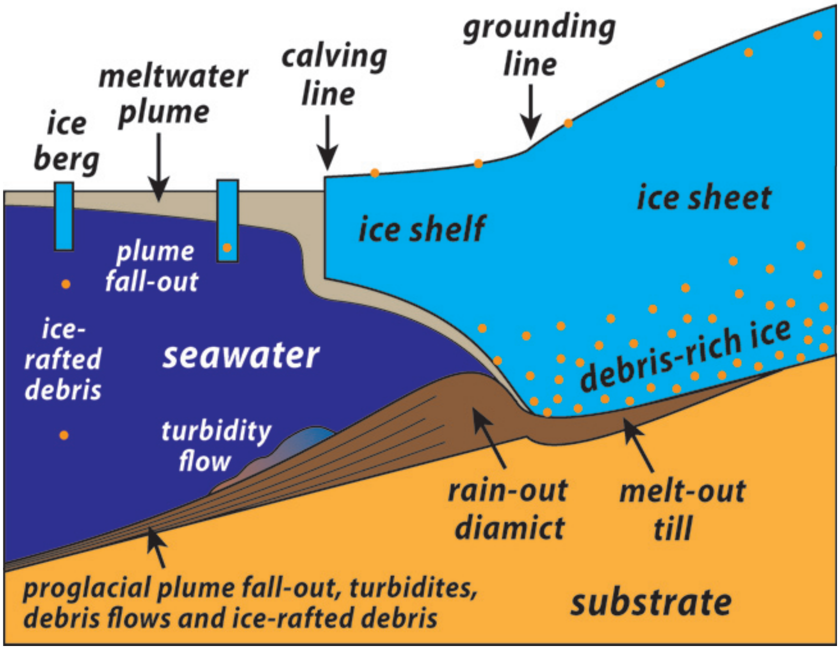
Many Quaternary glacial sedimentologists have examined Proterozoic glacial sequences and there is a consensus that the two are closely similar in terms of lithofacies associations. From this it has often been inferred that Quaternary and Proterozoic glaciations were broadly similar in character. However, if the average ice-sheet thickness on all continents was ~3.0 km, as implied by palaeomagnetic data and the distribution of dynamic glacial deposits (Fig. 4), then the glacioeustatic fall should have been ~1.5 km because the area of the ocean is nearly twice that of the glaciated continents and oceanic plateaus combined. Such a glacioeustatic fall is ~12-fold greater than that at the Last Glacial Maximum, which was ~125 m. Yet, large glacioeustatic falls have not been reported in Proterozoic studies.

In the Pleistocene, it is comparatively easy to determine glacioeustatic falls from the depths of submerged coral-reef terraces around low-latitude ocean islands (e.g. Barbados, Huon Peninsula). When all continents were isostatically depressed by ice sheets and ocean islands no longer exist, the problem is not so straightforward. Provided palaeodepths on an ancient continental margin or marine platform can be reconstructed with reasonable accuracy, it may be possible to estimate changes in base-level (i.e. relative sea-level) during a glacial interval. Glacioeustatic changes might then be estimated from the base-level change if corrections can be made for the glacio-isostatic response to ice loading and unloading, the hydro-isostatic response to the changes in water loads, the changes in local sea-level due to the gravitational 'pull' on the adjacent ocean by the evolving mass of the ice-sheet itself, and tectonic subsidence (or uplift) of a margin over the course of the glacial interval. This is a daunting challenge.

In Namibia, the younger (635 Ma) of two Cryogenian glaciations occurred while the Otavi carbonate platform was undergoing regional thermal subsidence. The platform has a well-defined submarine foreslope on which palaeodepths can be estimated from modern analogues, like the flanks of the Great Bahama Bank, and from 'geoplumb' (palaeovertical) indicators in the rocks themselves, from which the original slopes (with respect to the palaeohorizontal) can be derived. The geoplumb indicators are cement- and/or sediment-filled tubes, resulting from fluid or gas escape, within the syn-deglacial 'cap' dolostone.

The glacial deposits consist of carbonate rock debris derived from the upper slope and the interior of the platform. The debris forms a laterally continuous prism, with an average thickness of 100 m, situated between 5 and 10 km seaward of the top of the slope. Glacial sedimentologist Eugene W. Domack and I have measured 80 stratigraphic sections through the prism, which consists of a complex of melt-out (ice-contact) diamictites (Fig. 6D), massive rain-out diamictites (Fig. 6C), tunnel-mouth grounding-line fans (Fig. 6E), and more distal turbidites (Fig. 6F), meltwater-plume fallout (Fig. 6F), ice-rafted dropstones (Fig. 6F,G) and debris flows (Fig. 6H). Sharp contacts between diamictite and proglacial facies (Fig. 6I) indicate abrupt backsteps of the ice grounding-line, while terminal collapse of the ice-sheet is represented by a drape of ferruginous stratified mate-

Fig. 7. Sedimentary environments and deposits associated with an idealized submarine ice grounding-line.



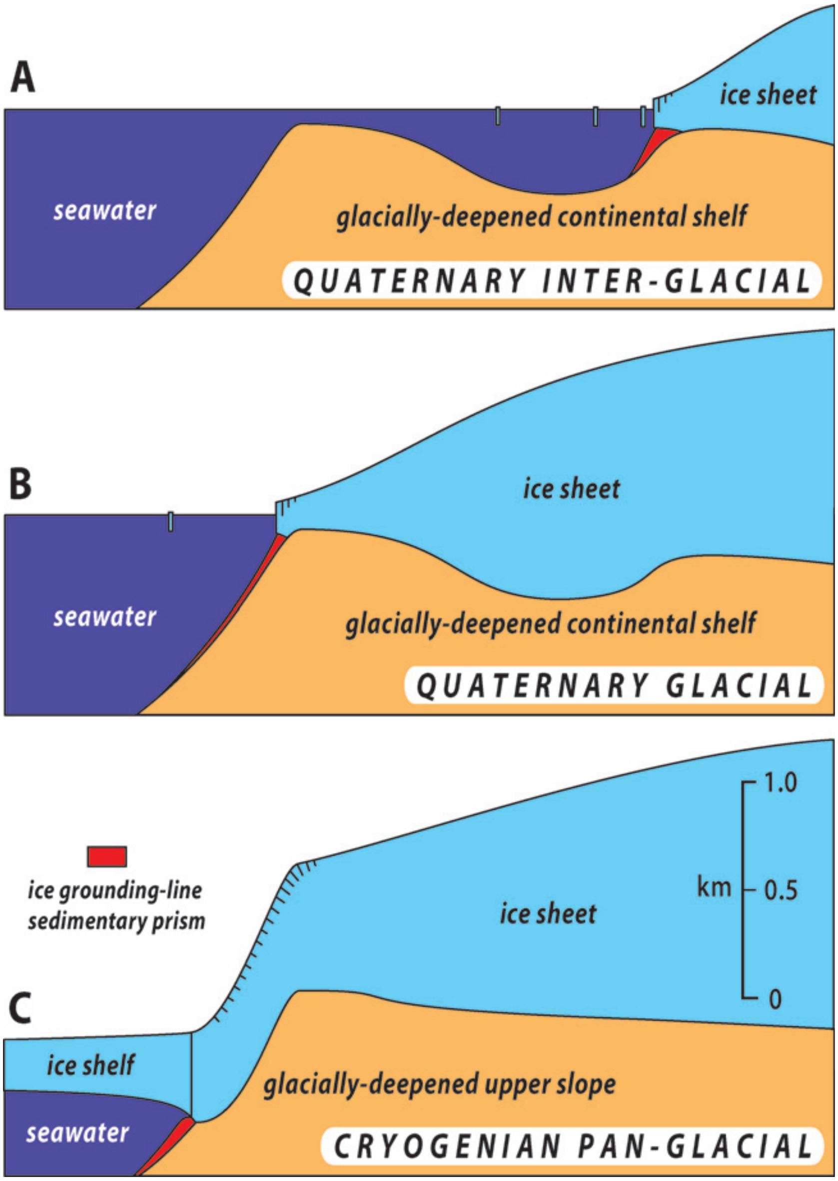


Fig. 8. Schematic locations of ice-grounding lines in East Antarctica during Quaternary **A,** interglacial and **B,** glacial intervals, compared with **C,** the 635-Myr pan-glacial period in Namibia.

rial choked with ice rafted dropstones (Fig. 6J). In terms of lithofacies association and stratal organization, the prism resembles many Quaternary marine ice grounding-line moraines (Fig. 7). In only two respects is it fundamentally different. First, it is composed entirely of carbonate rock debris, save for rare extrabasinal (granite) clasts. Second, it is situated at an estimated palaeodepth of 0.6–0.8 km vertically below the lip of the platform (Fig. 8).

That its position is related to a massive base-level fall is affirmed by a well-developed low-stand wedge—an upward-coarsening stack of carbonate turbidites and oolite debris-flows—directly beneath it, and a syndeglacial 'cap' dolostone with shallow-water sedimentary structures directly above it. The 'cap' dolostone, which continues up the slope and across the platform, was deposited diachronously above wave-base during glacioeustatic flooding of the slope and platform.

The 0.6–0.8 km of base-level change indicated by these relationships is not inconsistent, after adjustments for isostasy, ice-sheet self-gravitation and tectonic subsidence, with a glacioeustatic change of ~1.5 km, as expected if the global average ice-sheet thickness was ~3.0 km.

Response of the biosphere

Not only cyanobacteria, but different groups of extant eukaryotic algae evolved before the Neoproterozoic glaciations and must therefore have survived them. If the snowball hypothesis implies that photons and liquid water nowhere coexisted, the hypothesis is false. I do not believe that this is implicit in the hypothesis. The floating ice shelf on the ocean was dynamic, flowing at rates equivalent to those of mountain glaciers (decametres per year). This means that wherever the floating ice encountered grounded ice, at continental margins and oceanic banks and islands, crack systems would have perpetually existed. Unlike cracks in grounded ice, cracks in floating ice are held open to any depth by the force of liquid water. Because air temperatures on a snowball Earth were everywhere at or below freezing, fresh cracks would immediately freeze over with new sea-ice. New sea-ice is full of brine channels, which are inhabited by eukaryotic algae, protists and prokaryotes, including cyanobacteria. After a few years, the brine drains away and the inhabitants must find a new crack. Crack systems in dynamic shelf ice were perhaps the most extensive and reliable refugia for photoautotrophs on a snowball Earth, outside areas of continuous thin equatorial ice (Fig. 5B), if and where dark marine ice was exposed.

Until 2007, the oldest known multicellular animal fossils were the soft-bodied ('Ediacaran') frondose macrofauna of the Drook Formation in eastern Newfoundland, which appeared ~60 Myr after the last snowball Earth interval ended in 635 Ma (Fig. 9). Recently, diapause cysts of metazoan eggs and embryos have been found abundantly in the Doushantuo Formation of South China, down to within ~3 Myr of the same (Nantuo) glacial termination. And in the subsurface of Oman, a diagnostic sponge biomarker, 24-isopropyl-cholestane, occurs in similar-age strata (Masirah Bay Formation) directly above correlative glacial deposits of the Gadir Manqil Formation (also within and below it, but possibly displaced downward by drilling). These findings raise anew the possibility that the advent of multicellular animal life was somehow promoted by environmental forcing.

It has long been hypothesized that a rise in environmental oxygen levels to 0.01–0.1 PAL (present atmospheric level) might have allowed latent mul-

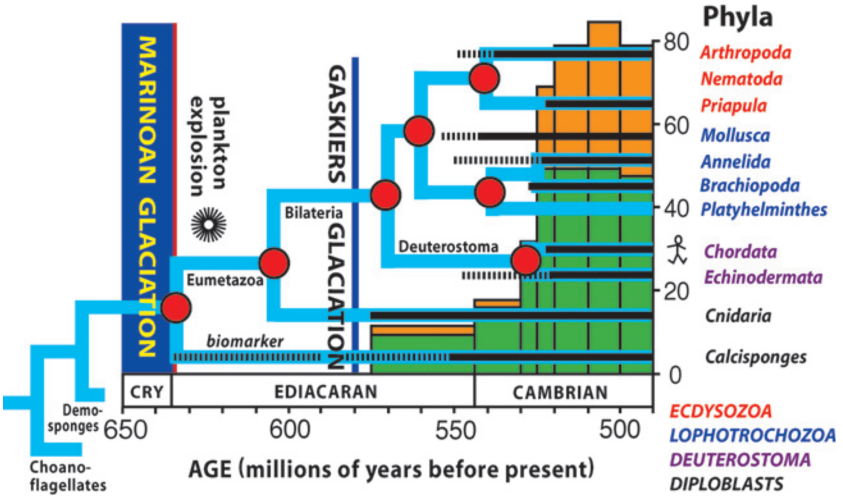


Fig. 9. Phylogeny (blue bars) and branch points (red dots) of early animal evolution based on an invertebrate-calibrated molecular 'clock' analysis by Kevin J. Peterson and Nicholas J. Butterfield, superimposed on fossil data modified from Andrew H. Knoll and Sean B. Carroll. Solid black bars represent crown-group taxa and dashed black bars stem-group taxa. Histograms of diversity are given at the group (green) and order (orange) level.

ticellularity in animals (e.g. choanoflagellates) to realize its potential. One way to raise atmospheric O_2 is to decouple photosynthesis (which releases O_2) from respiration (which consumes it). Rapid melting of a snowball Earth would cover the ocean with a lid of low-density meltwater, creating a stable density stratification that would be enhanced by 'greenhouse' warming. Nutrient-rich upwellings and hence organic productivity would be suppressed, assuming organic particles sank, but respiration might suffer more. 'Greenhouse' warming would lower O_2 concentrations in surface waters and resist downwelling. Low ambient sulphate concentrations would limit anaerobic respiration. The result would be high rates of organic burial, despite lowered productivity, causing a permanent increase in atmospheric O_2. High carbonate burial would mask the isotopic signature of high organic burial.

If BIF deposition was more common during the earlier of the two Cryogenian snowball episodes, as indicated geologically, its presence as a potential electron acceptor on the sea floor may have limited the capacity for organic burial at that time, making the second snowball episode uniquely capable of boosting the budget of atmospheric oxygen.

Pan-glacial, a third climate state

There is now a broad consensus that virtually all continents were simultaneously glaciated in the Cryogenian Period. Consensus is lacking on whether the oceans were also ice covered ('snowball' model) or mostly ice-free ('slushball' model). My own preference is clear: the snowball model provides cogent explanations for cap carbonates, the return of BIFs, and isotopic evidence for greatly elevated pCO_2. The slushball model explains none of these. On the other hand, knowledgeable palaeontologists find the snowball model inconsistent with the fossil record, meagre though it is, and this is the acknowledged motivation on the part of climate modellers to find slushball solutions.

I propose that for now, we accept consensus where it exists—a third state in the climate system—and following C.E.P. Brooks, we call it 'pan-glacial'. We must not rest, however, until each pan-glacial episode is determined to be, or not to be, a snowball Earth.

Acknowledgments

I thank geologist and palaeomagnetist Edward (Ted) Irving for drawing my attention to the book by C.E.P. Brooks and its historical significance. The palaeogeographic maps used in Fig. 4 were kindly provided by Zheng-Xiang Li (Curtin University of Technology, Perth, Australia). The paper was written while I was supported by a Harvard Club of Australia Fellowship, hosted by the School of Earth and Environmental Sciences at The University of Adelaide. Additional support came from the Canadian Institute for Advanced Research (CIFAR), U.S. National Science Foundation grant EAR-0417422, the Geological Survey of Namibia, and Harvard University. David A.D. Evans made comments that improved the manuscript.

Suggestions for further reading

Bendtsen, J. 2002. Climate sensitivity to changes in solar insolation in a simple coupled climate model. *Climate Dynamics*, v.18, pp.595–609.

Brooks, C.E.P. 1926. *Climate Through the Ages*. R.V. Coleman, New York.

Fairchild, I.J. & Kennedy, M.J. 2007. Neoproterozoic glaciation in the Earth System. *Journal of the Geological Society, London*, v.164, pp.895–921.

Harland, W.B. & Rudwick, M.J.S. 1964. The great infra-Cambrian ice age. *Scientific American*, v.211, pp.28–36.

Hoffman, P.F. & Schrag, D.P. 2002. The snowball Earth hypothesis: testing the limits of global change. *Terra Nova*, v.14, pp.129–155.

Hoffman, P.F., Halverson, G.P., Domack, E.W., Husson, J.M., Higgins, J.A. & Schrag, D.P. 2007. Are basal Ediacaran (635 Ma) post-glacial 'cap dolostones' diachronous? *Earth and Planetary Science Letters*, v.258, pp.114–131.

Kirschvink, J.L. 1992. Late Proterozoic low-latitude glaciation: the snowball Earth. In: Schopf, J.W. & Klein, C. (eds) *The Proterozoic Biosphere*, pp.51–52, Cambridge University Press, Cambridge.

Walker, G. 2003. *Snowball Earth: the Story of the Great Global Catastrophe That Spawned Life as We Know It*. Crown Publishers, New York.

Walker, J.C.G., Hays, P.B. & Kasting, J.F. 1981. A negative feedback mechanism for the long-term stabilization of Earth's surface temperature. *Journal of Geophysical Research*, v.86, pp.9776–9782.