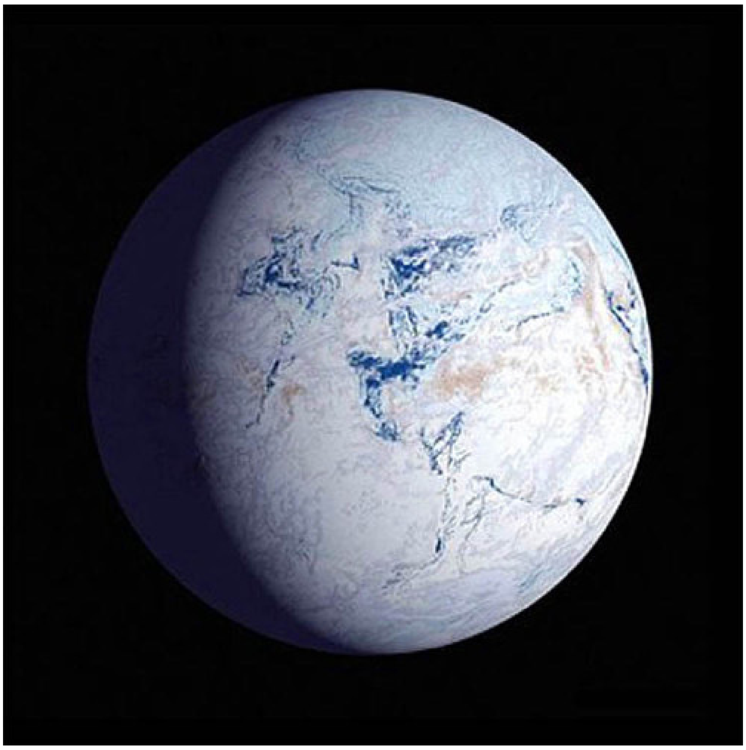
Climate change and palaeoclimatology

Sea-level rise following a Snowball Earth (*May 2018*)

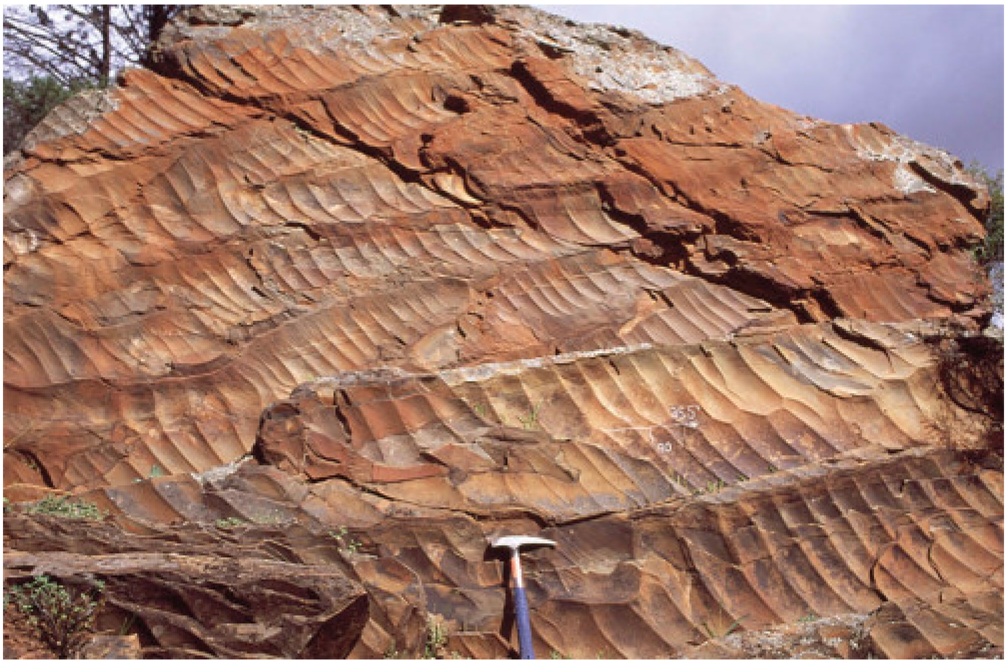
The Cryogenian Period (850 to 635 Ma) of the Neoproterozoic is named for the intense glacial episodes recorded in strata of that age. There were two that palaeomagnetism in glaciogenic sedimentary rocks indicates that ice covered all of the continents including those in the tropics, and a third, less extreme one. These episodes, when documented in the 1990s, became dubbed, aptly enough, as 'Snowball Earth' events. But evidence for frigidity does not pervade the entire Cryogenian, the glacial events being separated by long periods with no sign anywhere of tillites or glaciomarine diamictites shed by floating ice. Each Snowball Earth episode is everywhere overlain by thick carbonate deposits indicating clear, shallow seas and a massive supply of calcium and magnesium ions to seawater. The geochemical change is a clear indicator of intense chemical weathering of the exposed continents. The combination of Ca and Mg with carbonate ions likewise suggests an atmosphere rich in carbon dioxide. For frigidity episodically to have pervaded the entire planet indicates a distinct dearth of the greenhouse gas in the atmosphere during those events. The likely explanation for Snowball Earths is one of booms in the abundance of minute marine organisms, perhaps a consequence of the high phosphorus levels in the oceans during the Neoproterozoic when seawater was alkaline. The carbon-isotope record suggests that there were periodic, massive bursts of organic matter that would have drawn down atmospheric CO_2, which coincide with the evidence for global frigidity, although marine life continued to flourish.



Artist's impression of the glacial maximum of a Snowball Earth event. (Source: NASA)

Under such ice-bound conditions the build-up of continental glaciers would have resulted in huge falls in global sea level, far exceeding the 150 m recorded during some late-Pleistocene glacial maxima. The end of each Snowball Earth would have led to equally dramatic rises and continental flooding. Such scenarios are well accepted to have occurred when accumulation of volcanic CO_2 during full ice cover reached a threshold of global warming potential that could overcome the reflection of solar radiation by the high albedo of ice extending to the tropics. That threshold has been estimated to have been between 400 to 500 times the CO_2 content of the atmosphere at present. Yet it has taken an intricate analysis of sedimentary structures that are commonplace in marine sediments of any age – ripple marks – to quantify the pace of sea-level rise at the end of a Snowball Earth event (Myrow, P.M. *et al*. 2018. Rapid sea level rise in the aftermath of a Neoproterozoic snowball Earth. *Science*, v. **360**, p. 649-651; doi:10.1126/science.aap8612).

The Elatina Formation of South Australia, deposited during the Marinoan (~635 Ma) glaciation, is famous for the intricacy of its sedimentary structures especially in the clastic sedimentary rocks beneath the cap carbonate that marks the end of glacial conditions. Among them are laminated silts and fine sands that were originally thought to be the equivalent of modern varved sediments that form annually as lakes or shallow seas freeze over and then melt with the seasons. Since they contain ripple marks the laminates of the Elatina Formation clearly formed as a result of current flow and wave action – the sea surface was therefore ice free while these sediments accumulated. Careful study of the larger ripples, which are asymmetrical, shows that current-flow directions periodically reversed, suggesting that they formed as a result of tidal flows during the bi-monthly cycle of spring and neap tides in marine deltas. Data from experiments in wave tanks shows that the shapes (expressed as their amplitude to wavelength ratio) of wave ripples depend on the orbital motion of water waves at different depths. The smaller ripples are of this kind. So Myrow and colleagues have been able to tease out a time sequence from the tidal ripples and also signs of any variation in the water depth at which the smaller wave ripples formed.



Ripples on a bedding surface in the Elatina Formation, South Australia. They formed under the influence of tidal current flow. (Credit, University of Guelph)

Just over 9 metres of the tidal laminate sequence that escaped any erosion was deposited in about 60 years, giving a sedimentation rate of 27 cm per year. This is extremely high by comparison with those in any modern marine basins, probably reflecting the sediment-charged waters during a period of massive glacial melting. Throughout the full 27 m sequence smaller, wave ripples consistently show that water depth remained between 9 to 16 m for about a century. Over such a short time interval any tectonic subsidence or sag due to sediment load would have been minuscule. So sea-level rise kept pace with deposition; i.e. at the same rate of 27 cm per year. That is at least five times faster than during any of the Pleistocene deglaciations and about a hundred times faster than sea-level rise today that is caused by melting of the Greenland and Antarctic ice caps and thermal expansion of ocean water due to global warming. It has been estimated that the Marinoan ice sheets lowered global sea level by between 1.0 to 1.5 km – ten times more than in the last Ice Age – so deglaciation to the conditions of the cap carbonates, shallow, clear seas at around 50°C, would have taken about 6,000 years at the measured rate.

To read more on the Snowball Earth hypothesis and other early glacial epochs click here

Late Palaeozoic glacial features in Chad (*May 2018*)

The longest and most extreme glacial epoch during the Phanerozoic took place between 360 and 260 Ma ago, when it dominated the Carboniferous and Permian sedimentary sequences across the planet. On continents that lay athwart the Equator during these times, sedimentation was characterised by cycles between shallow marine and terrestrial conditions. These are epitomised by the recurring 'Coal-Measure' cyclothem of, from bottom to top: open-sea limestone; near-shore marine mudstone; riverine sandstone; coal formed in swamps. This sequence represents a rapid rise in sea level as ice sheets melted, sustained during an interglacial episode and then falling sea level as ice once again accumulated on land to culminate in a glacial maximum when coal formed in coastal mires. During the Late Palaeozoic Era a single supercontinent extended from pole to pole. The break-up of Pangaea was charted by Alfred Wegener in 1912, partly by his using glacial deposits and ice-gouged striations on the southern continents. With the present widely separated configuration of major landmasses glacial sediments and the directions of inferred ice movements could only be reconciled by reassembling Africa, India, South America, Antarctica and Australia in the form of a single, congruent southern continent that he called Gondwanaland. In Wegener's reconstruction the glacial features massed together on Gondwanaland with the striations radiating outwards from what would then have been the centre of a huge ice cap.

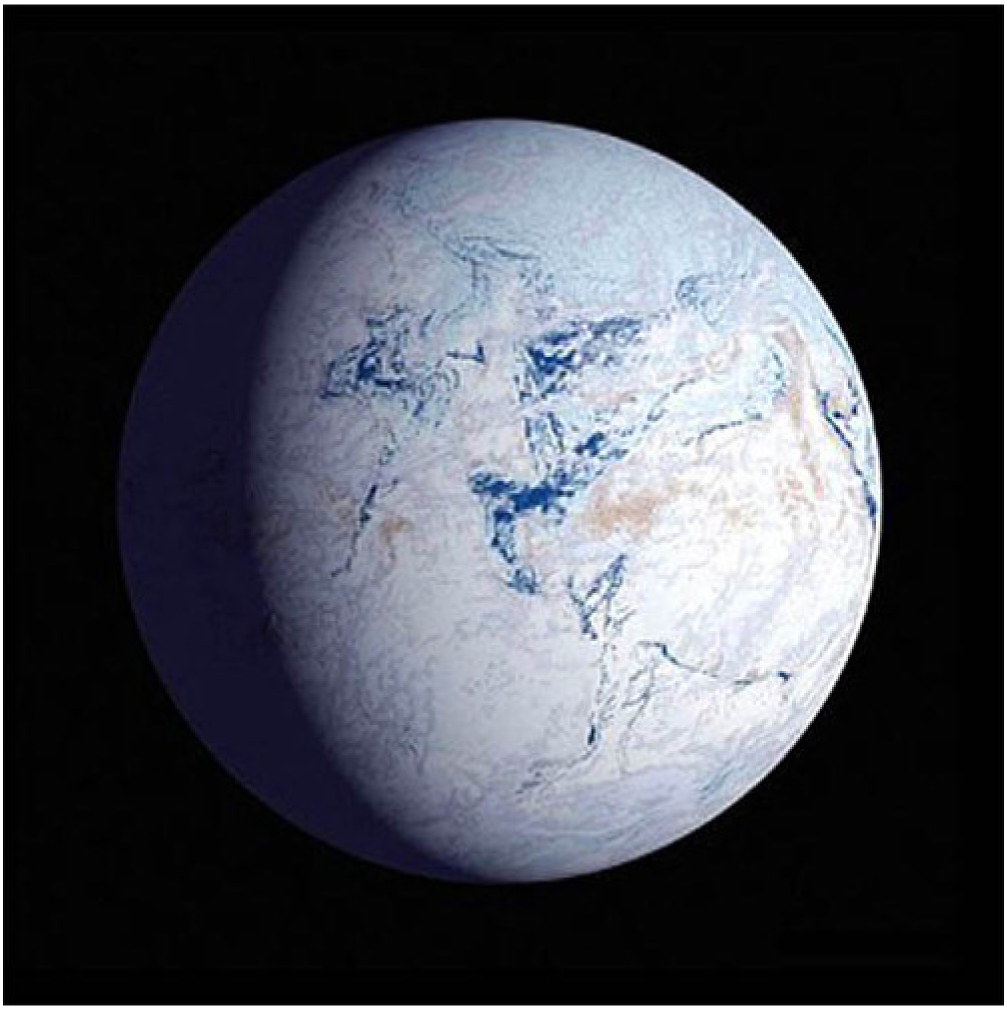
There are many localities on the present southern continents where such striations can be seen on the surface of peneplains etched into older rocks that underlie Carboniferous to Permian tillites, but later erosion has removed the continuity of the original glacial landscape. There are, however, some parts of central Africa where it is preserved. By using the high-resolution satellite images (with pixels as small as 1 m square) that are mosaiced together in Google Earth, Daniel Paul Le Heron of Royal Holloway, University of London has revealed a series of 1 to 12 km wide sinuous belts in a 6000 km^2 area of eastern Chad that are superimposed unconformably on pre-Carboniferous strata (Le Heron, D.P. 2018. An exhumed Paleozoic glacial landscape in Chad. *Geology*, v.**46(1)**, p. 91-94; doi:10.1130/G39510.1). They comprise irregular tracts of sandstone to the south of a major Carboniferous sedimentary basin. Zooming in to them (try using 17.5° N 22.25°E as a search term in Google Earth) reveals surfaces dominated by wavy, roughly parallel lines. Le Heron interprets these as mega-scale glacial lineations, formed by ice flow across underlying soft Carboniferous glacial sediments as seen in modern glacial till landforms in Canada. In places they rest unconformably on older rocks, sometimes standing above the level of the sandstone plateaux as relics of what may have been nunataks. There are even signs of elliptical drumlins.

An oblique Google Earth view looking to the south-east shows mega-scale glacial lineations from a glacial flow way in eastern Chad. The lower-right quadrant shows the unconformity atop older bedded strata that are dipping to the west. Click on the image to see a full resolution view. (Credit: Google Earth)

Glacial tillites and glaciofluvial sediments of Late Palaeozoic age are common across the Sahara and in the Sahelian belt, but in areas as remote as those in eastern Chad. So a systematic survey using the resolving power of Google Earth may well yield yet more examples. It is tedious work in such vast areas, unless, of course, one bears in mind Alfred Wegener, the founder of the hypothesis of continental drift and 'Big' Earth Science as a whole, who would have been gleeful at the opportunity.

Snowball Earth: A result of global tectonic change? (*August 2018*)

The Snowball Earth hypothesis first arose when Antarctic explorer Douglas Mawson (1882-1958)speculated towards the end of his career on an episode of global glaciations, based on his recognition in South Australia of thick Neoproterozoic glacial sediments. Further discoveries on every continent, together with precise dating and palaeomagnetic indications of the latitude at which they were laid down, have steadily concretised Mawson's musings. It is now generally accepted that frigid conditions enveloped the globe at least twice – the Sturtian (~715 to 660 Ma) and Marinoan (650 to 635 Ma) glacial episodes – and perhaps more often during the Neoproterozoic Era. Such an astonishing idea has spurred intensive studies of geochemistry associated with the events, which showed rapid variations in carbon isotopes in ancient seawater, linked to the terrestrial carbon cycle that involves both life- and Earth processes. Strontium isotopes suggest that the Neoproterozoic launched erratic variation of continental erosion and weathering and related carbon sequestration that underpinned major climate changes in the succeeding Phanerozoic Eon. Increased marine phosphorus deposition and a change in sulfur isotopes indicate substantial change in the role of oxygen in seawater. The preceding part of the Proterozoic Eon is relatively featureless in most respects and is known to some geoscientists as the 'Boring Billion'.



Artist's impression of the glacial maximum of a Snowball Earth event (Source: NASA)

Noted tectonician Robert Stern and his colleague Nathan Miller, both of the University of Texas, USA, have produced a well-argued and -documented case (and probably cause for controversy) that suggests a fundamental change in the way the Precambrian Earth worked at the outset of the Neoproterozoic (Stern, R.J. & Miller, N.R. 2017. Did the transition to plate tectonics cause Neoproterozoic Snowball Earth. *Terra Nova*, v. **30**, p. 87-94; DOI: 10.1111/ter.12321). To the geochemical and climatic changes they have added evidence from a host of upheavals in tectonics. Ophiolites and high-pressure, low-temperature metamorphic rocks, including those produced deep in the mantle, are direct indicators of plate tectonics and subduction. Both make their first, uncontested appearance in the Neoproterozoic. Stern and Miller ask the obvious question; Was this the start of plate tectonics? Most geologists would put this back to at least the end of the Archaean Eon (2,500 Ma) and some much earlier, hence the likelihood of some dispute with their views.

They consider the quiescent billion years (1,800 to 800 Ma) before all this upheaval to be evidence of a period of stagnant 'lid tectonics', despite the Rodinia supercontinent having been assembled in the latter part of the 'Boring Billion', although little convincing evidence has emerged to suggest it was an entity formed by plate tectonics driven by subduction. But how could the onset of subduction-driven tectonics have triggered Snowball Earth? An early explanation was that the Earth's spin axis was much more tilted in the Neoproterozoic than it is at present (~23°). High obliquity could lead to extreme variability of seasons, particularly in the tropics. A major shift in axial tilt requires a redistribution of mass within a planetary body, leading to true polar wander, as opposed to the apparent polar wander that results from continental drift. There is evidence for such an episode around the time of Rodinia break-up at 800 Ma that others have suggested stemmed from the formation of a mantle superplume beneath the supercontinent.

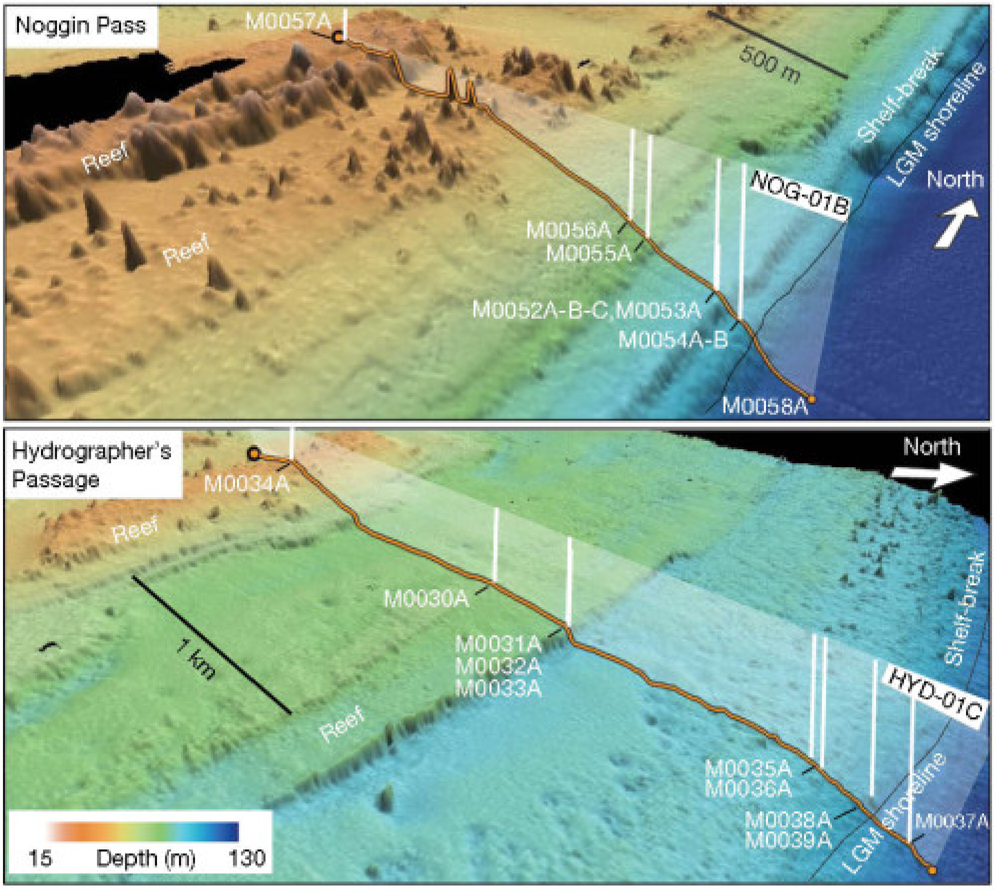
Considering seventeen possible geodynamic, oceanographic and biotic causes that have been plausibly suggested for global glaciation Stern and Miller link all but one to a Neoproterozoic transition from lid- to plate tectonics.

The Great Barrier Reef and the Last Glacial Maximum (LGM) (*August 2018*)

The 2,300 km stretch of coral reefs and islands in the Coral Sea off the coast of Queensland, Australia is the largest single structure on Earth built by living organisms. The dominant reef builders are four hundred species of coral, most of which are a symbiosis that conjoins marine invertebrates in the class Anthozoa – part of the phylum Cnidaria – and photosynthesising single-celled eukaryotes known as dinoflagellates. These algae are mainly free-living marine plankton, some species of which evolved to be co-opted by corals. Their role in the symbiosis is complex; on the one hand providing energy in the form of sugars, glycerol and amino acids; on the other consuming the coral polyps' carbon dioxide output. The latter is fixed, in the case of hard corals, by the secretion of calcium carbonate: the key to reef formation.

Marine photosynthesisers demand clear water in the upper few tens of metres of the sea, together with sunlight least affected by the atmosphere, as in the tropics where the sun rises to the zenith year round. The coral animal-algae connection limits reef growth to shallow seas, the top of the reef being close to mean sea level, sometimes rising above it at low tide. Hence the formation of fringing and barrier reefs. In the case of atoll reefs, a connection with sea-floor volcanoes that rose from hotspots on the oceanic abyssal plains to form active volcanic islands that began to sink once they became extinct. The pace at which reefs can grow is generally able to match that of crustal subsidence so that atolls remain throughout the Western Pacific. Reef growth is also capable of coping with global sea-level changes, so that the present top level of the Great Barrier Reef has been in balance with the generally static sea level of the Holocene since the ice caps of the last glaciation melted back to roughly their present extent about seven thousand years ago.

There are many cases of different reef levels on and around islands that match the sea-level fluctuations during the last Ice Age. High-resolution bathymetry produced by multi-beam sonar across the eastern edge of parts of the Great Barrier Reef reveals a series of submerged terraces down to almost 120 m below modern sea-level (Yokoyama, Y. and 17 others 2018. Rapid glaciation and a two-step sea level plunge in the Last Glacial Maximum. *Nature*, v. **559**, p. 603-607; doi:10.1038/s41586-018-0335-4). Globally, the LGM began at around 31 ka when sea level fell by about 40 metres, thanks to massive accumulation of glacial ice at high latitudes. Previous studies to chart the changes in global mean sea level during the LGM suggested a steady fall until about 20 ka, followed by rapid rise as ice caps melted back. The multinational team led by Yusuke Yokoyama of the University of Tokyo, obtained precise ages of coral samples from different depths in drill cores through the coral terraces. These data revealed a more complex pattern of sea-level change, in particular a hitherto unsuspected plunge between 21.9 and 20.5 ka of 20 m to reach -118 m. This immediately preceded the warming-related rise that continued to Holocene levels.

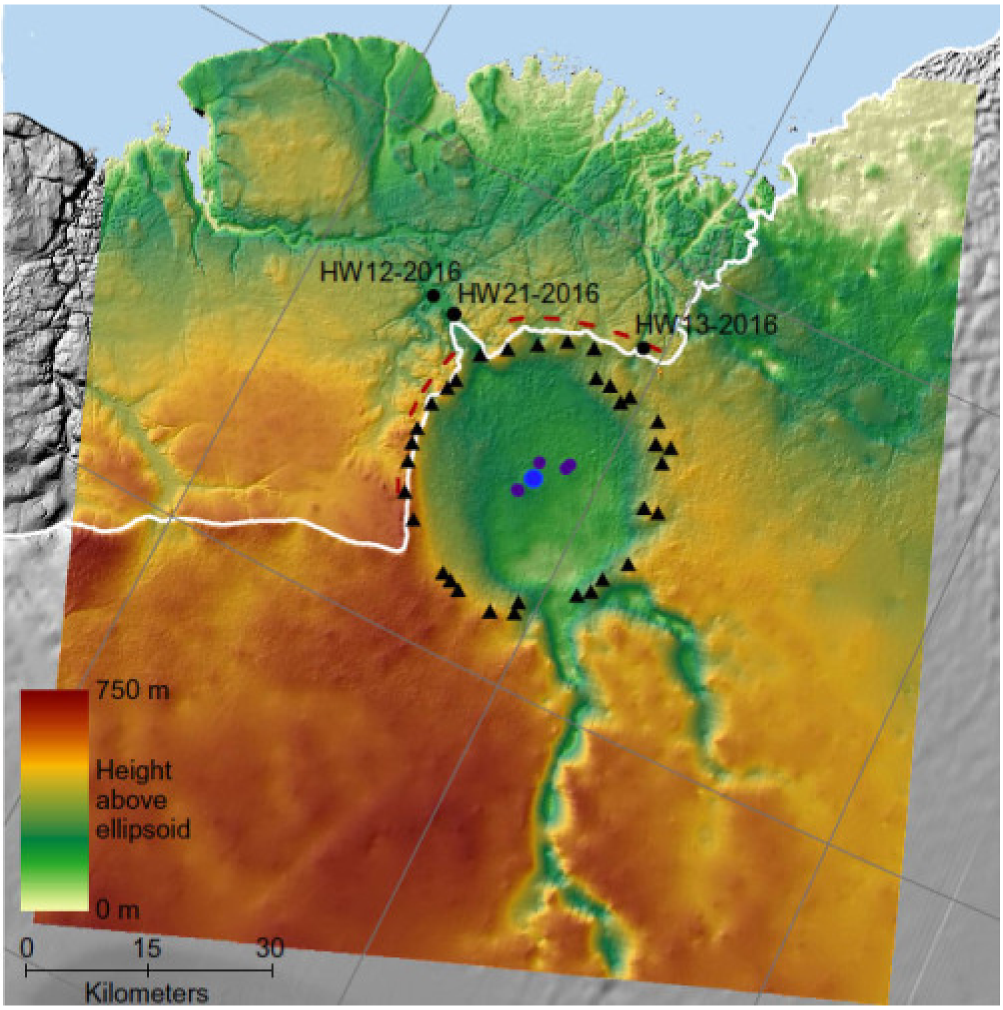


High-resolution sonar images of the sea floor at two sites on the eastern edge of Australia's Great Barrier Reef. They show terraces associated with, the lowest of which corresponds to the Last Glacial Maximum. (Credit: Yokoyama et al. 2018, Figure 1)

Curiously, this massive phenomenon is not shown by sea-level estimates derived from the records of changing oxygen isotopes in ocean-floor sediments and ice cores. The team's complex modelling incorporated global changes in land and sea-bed levels, and thus changes in the volume of the ocean basins, due to the changing isostatic effects of both ice-cap and ocean masses. From these it is possible to reach an interesting conclusion (Whitehouse, P. 2018. Ancient ice sheet had a growth spurt. *Nature*, v. **603**, p. 487-488; doi:10.1038/d41586-018-05760-3). Rather than an increase in snowfall onto ice-caps, their retreat may have been hindered by thickening of marginal floating ice shelves that created buttresses around Antarctica and the northern ice sheets. Slowed glacial flow to the oceans could have promoted ice sheet growth for a time as melting of calved icebergs was hindered, especially in the case of the ice sheet over northern North America. Certainly, this crucial climatic turning point was a lot more complex than previously believed.

Subglacial impact structure in Greenland: trigger for Younger Dryas? (*November 2018*)

Radar microwaves are able to penetrate easily through several kilometres of ice. Using the arrival times of radar pulses reflected by the bedrock at glacial floor allows ice depth to be computed. When deployed along a network of flight lines during aerial surveys the radar returns of large areas can be converted to a grid of cells thereby producing an image of depth: the inverse of a digital elevation model. This is the only means of precisely mapping the thickness variations of an icecap, such as those that blanket Antarctica and Greenland. The topography of the subglacial surface gives an idea of how ice moves, the paths taken by liquid water at its base, and whether or not global warming may result in ice surges in parts of the icecap. The data can also reveal topographic and geological features hidden by the ice (see The Grand Greenland Canyon Geomorphology September 2013).



Colour-coded subglacial topography from radar sounding over the Hiawatha Glacier of NW Greenland (Credit: Kjaer et al. 2018; Fig. 1D)

Such a survey over the Hiawatha Glacier of NW Greenland has showed up something most peculiar (Kjaer, K.H. and 21 others 2018. A large impact crater beneath Hiawatha Glacier in northwest Greenland. *Science Advances*, v. **4,** eaar8173; DOI: 10.1126/sciadv.aar8173). Part of the ice margin is an arc, which suggests the local bed topography takes the form of a 31km wide, circular depression. The exposed geology shows no sign of a structural control for such a basin, and is complex metamorphic basement of Palaeoproterozoic age. Measurements of ice-flow speeds are also anomalous, with an array of higher speeds suggesting accelerated flow across the depression. The radar image data confirm the presence of a subglacial basin, but one with an elevated rim and a central series of small peaks. These are characteristic of an impact structure that has only been eroded slightly; i.e. a fairly recent one and one of the twenty-five largest impact craters on Earth.. Detailed analysis of raw radar data in the form of profiles through the ice reveals that the upper part is finely layered and undisturbed. The layering continues into the ice surrounding the basin and is probably of Holocene age (<11.7 ka), based on dating of ice in cores through the surrounding icecap. The lower third is structurally complex and shows evidence for rocky debris. Sediment deposited by subglacial streams where they emerge along the arcuate rim contain grains of shocked quartz and glass, as well as expected minerals from the crystalline basement rocks. Some of the shocked material contains unusually high concentrations of transition-group metals, platinum-group elements and gold; further evidence for impact of extraterrestrial material – probably an iron asteroid that was originally more than 1 km in diameter. The famous Cape York iron meteorite, which weighs 31 t – worked by local Innuit to forge harpoon blades – fell in NW Greenland about 200 km away.

The central issue is not that Hiawatha Glacier conceals a large impact crater, but its age. It certainly predates the start of the Holocene and is no older than the start of Greenland glaciation about 2.6 Ma ago. That only Holocene ice layers are preserved above the disrupted ice that rests immediately on top of the crater raises once again the much-disputed possibility of an asteroid impact having triggered the Younger Dryas cooling event and associated extinctions of large mammals in North America at about 12.9 ka (see *Impact cause for Younger Dryas draws flak* May 2008). Only radiometric dating of the glassy material found in the glaciofluvial sediments will be able to resolve that particular controversy.