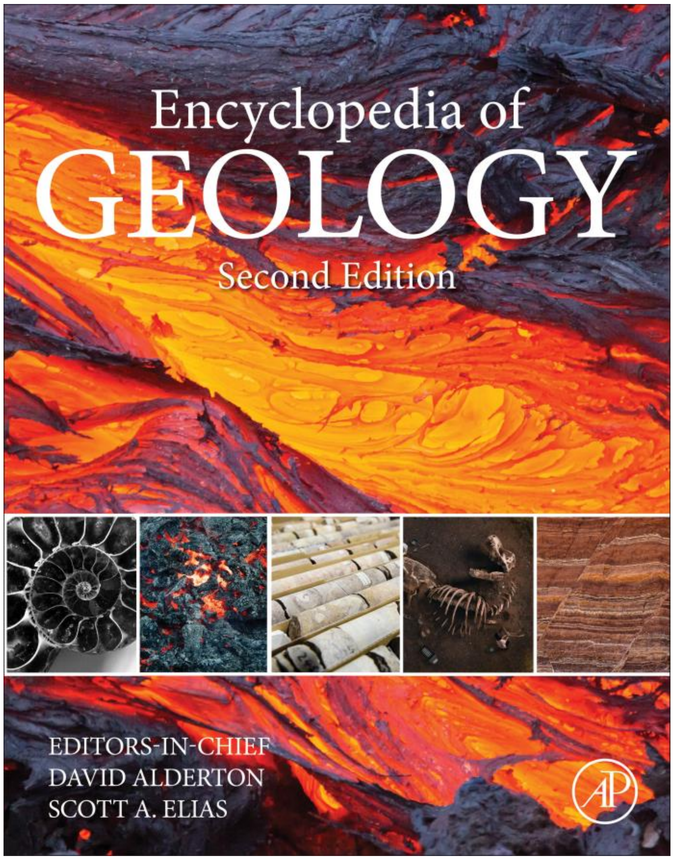

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Neoproterozoic Glaciation—Snowball Earth Hypothesis

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Introduction

Earth's climate has alternated between warmer and cooler episodes. Warmer intervals of sufficient duration (tens to hundreds of millions of years) are called "Greenhouse" episodes and colder intervals are called "Icehouse" episodes. The timing and cause of these episodes are of great interest to scientists. Much of this climate variability reflects changes in solar energy arriving at the Earth's surface. Latitudinal surface temperatures on Earth are largely controlled by its orbital configuration about the Sun [especially the inclination of its rotational axis with respect to the ecliptic (obliquity)] and atmospheric greenhouse gas concentrations, which absorb outgoing reflected solar radiation and infrared radiation given off from the Earth at night that would otherwise be lost to space. Modern Earth has relatively low orbital obliquity (22.1–24.5 degrees) such that incoming solar radiation (insolation) is greater over tropical latitudes than polar latitudes. The latitudinal distribution of continents, ice and clouds (with high albedo) compared to open ocean (with low albedo) further controls Earth's surface temperature. During most of Earth history, greenhouse gas concentrations have been sufficiently high to maintain liquid water (Feulner, 2012). Greenhouse gas concentrations are regulated by the balance of sinks (formation of $CaCO_3$ and photosynthesis) and sources (volcanic emissions, metamorphic decarbonation). Over millions of years, the fixing of CO_2 by silicate weathering buffers greenhouse gas concentrations. Times of enhanced silicate weathering promote atmospheric cooling by reducing greenhouse gas concentrations. This occurs because of increased transfer of carbon from the atmosphere to sediments in the form of carbonates and organic matter. The ensuing cooling reduces the amount of silicate weathering through the buildup of polar ice and reduced intensity of the hydrologic cycle, until CO_2 levels rise through volcanic and metamorphic degassing to resume warming. Over Phanerozoic time, icehouse intervals are tied to plate tectonics. When continental land masses occupied polar latitudes, this fostered development of stable ice sheets. Regional scale glacial stages involved episodic advances of ice sheets to lower latitudes, followed by ice margin retreats to higher latitudes. Such icehouse intervals persisted for several tens of millions of years (myrs) (e.g., Late Paleozoic), but Phanerozoic continental ice sheets did not reach tropical latitudes (Fig. 1B).

The most severe Icehouse intervals are thought to have occurred twice in Earth history during Precambrian time (Paleoproterozoic and Neoproterozoic Eras), when ice sheets may have extended to equatorial latitudes (Fig. 1A). Global energy budget models applied to Earth with modern obliquity indicate that glacial advances into the tropical latitudes (<30–25 degrees) would increase Earth's albedo, cooling it to the point that ice sheets and sea ice would cover the globe. This mode of cooling is sometimes called the "runaway albedo effect." With the Earth largely covered in ice, CO_2 sinks (silicate weathering, photosynthesis) would become less vigorous and perhaps cease to function. Such icehouse states are thought to have persisted for millions of years and have been termed "Snowball Earth" or panglacial episodes, to distinguish them from more common regional scale icehouse episodes, such as those of the Paleozoic and Cenozoic Eras (Fig. 1B).

Geologic evidence is strongest for the younger of the two proposed panglacial intervals, which characterized the Late Neoproterozoic Cryogenian period (ca. 720–635 million years ago, Ma). Cryogenian glaciations stand out for their remarkable intensity and intriguing association with other major changes in the Earth system, including the evolution of complex life, wild swings in carbon isotopic compositions of seawater, and tectonic changes. Their widespread stratigraphic characteristics are also the basis for the newly defined Cryogenian Period, with component glacial episodes assigned as time-equivalent cryochrons (Shields-Zhou et al., 2016). Identifying the causes and sequence of Earth system perturbations that triggered Cryogenian panglacial episodes are essential endeavors of the "Snowball Earth Hypothesis" (SEH) (Kirschvink, 1992; Hoffman et al., 1998; Hoffman and Schrag, 2002). Ongoing interest in the SEH partly reflects the fact that the causes of modern global climate change—specifically the roles of carbon dioxide and methane in the atmosphere—are also important to policy makers and the general public.

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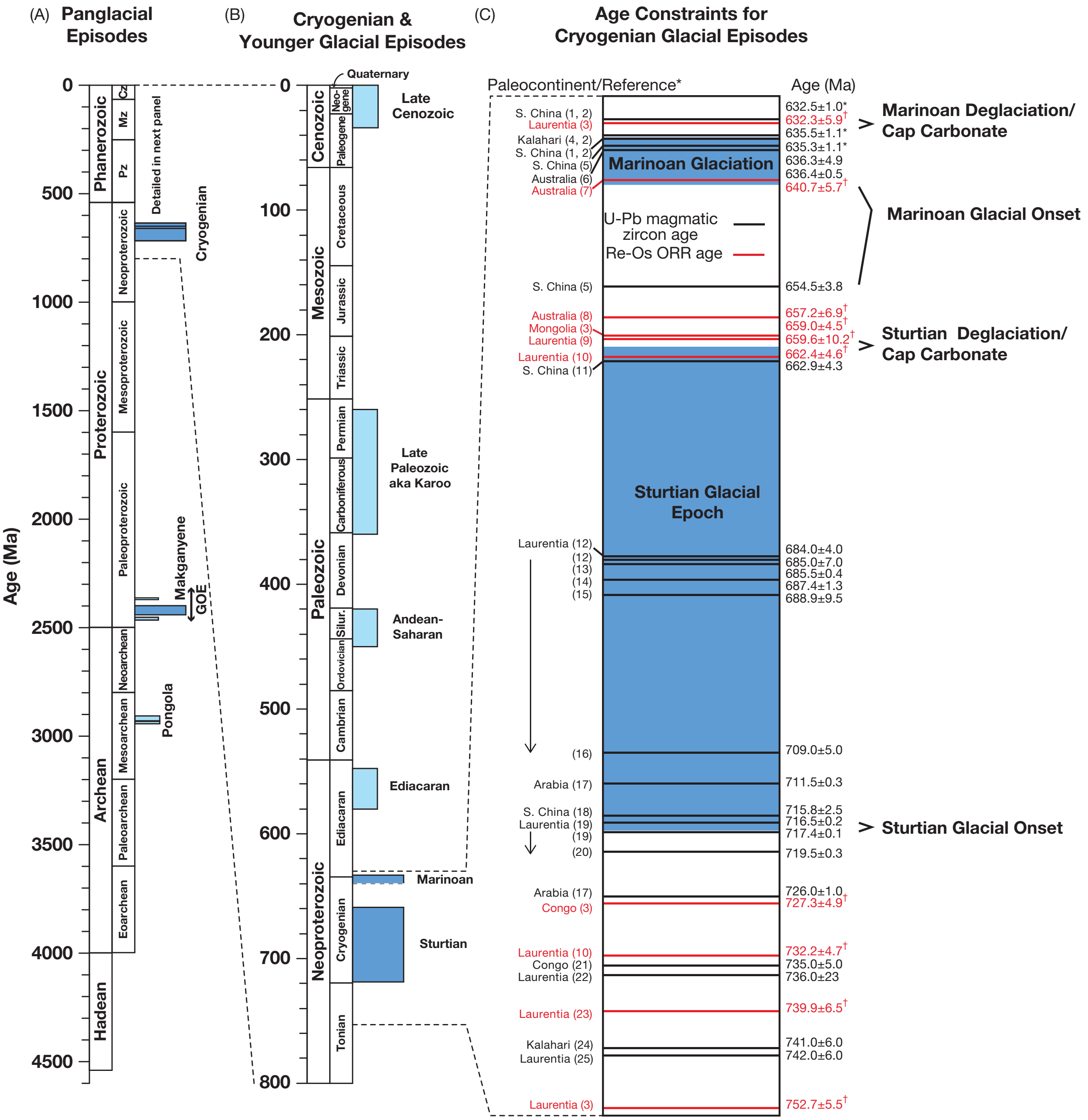

Fig. 1 Occurrence of regional scale (*light blue boxes*) and panglacial (*dark blue boxes*) episodes in Earth history and geochronological constraints supporting the synchroneity and long durations of Cryogenian icehouse episodes. (A) Geological evidence supports two possible panglacial icehouse states, each involving global or near-global glacial episodes lasting multiple millions of years: (1) Paleoproterozoic glacial strata on six cratons are constrained between 2.45 and 2.26 Ga (Hoffman, 2013), a span overlapping with the Great Oxidation Event (GOE); in southern Africa, Makhanyene glacigenic strata conformably underlie Ongeluk volcanics; and (2) Cryogenian glacial units ranging in age between ~720 and 635 Ma are recognized on all (?) continents. (B) Cryogenian (Sturtian and Marinoan) glacial episodes contrast from later Phanerozoic glacial intervals because they include abundant low paleolatitude localities (including glacigenic deposits in marine and marginal marine settings) and have globally distinctive deglacial cap carbonate successions. Phanerozoic glacial intervals correspond with the occurrence of polar continental land masses (e.g., Gondwana, Antarctica), but ice sheet advances did not reach into tropical latitudes. Ediacaran glacial episodes (~581–547 Ma) are documented in a number of paleocontinents, but low latitude settings have yet to be confirmed and durations (e.g., <350 kyrs) are comparable to Paleozoic and Cenozoic glaciations. (C) U-Pb magmatic zircon (non-detrital) and Re-Os (organic rich rock; ORR) ages from different paleocontinents constrain the timing of onsets and deglaciations for the Sturtian and Marinoan panglacial episodes (modified from Rooney, A. D., Strauss, J. V., Brandon, A. D. and Macdonald, F. A. (2015). A Cryogenian chronology: Two long-lasting, synchronous Neoproterozoic snowball earth glaciations. *Geology* **43**, 459–462; supporting references in parentheses below). Such age compilations demonstrate that glacial onsets and deglaciations were essentially synchronous in low latitude settings and that panglacial icehouse states were of extreme duration (Sturtian ~717–659 Ma: ~58 myrs; Marinoan ~650–639 to ~635 Ma; ~4–15 myrs), with a non-glacial interim of <25 myrs (Hoffman et al., 2017; Rooney et al., 2015).

Definition

The SEH was first formulated by Kirschvink (1992), who coined the term "Snowball Earth." Further attention followed from detailed sedimentalogic and carbon isotopic investigations of Cryogenian glacigenic sequences in northern Namibia (Hoffman et al., 1998; Hoffman and Schrag, 2002). The original formulation sought a global climatic mechanism to account for: (1) the abundance of Neoproterozoic glacigenic strata on most continents (Harland, 1964), including evidence of widespread continental glaciers within a few degrees of the paleo-equator; (2) that many glacial intervals were sharply bounded by thick carbonate sequences (including later-defined cap carbonates) or contained carbonate fragments; and (3) that some glacial intervals included a return of sedimentary iron formation (IF) deposition after a billion year absence from the geologic record. In a normal obliquity world, low latitude glacial deposits implied a climatic extreme with ice covering most of the planet. Furthermore, over the past 100 myr, thick carbonate strata have developed mainly in tropical latitudes, so stratigraphic associations with glacial strata suggested that glaciation reached low-latitudes or involved unlikely rapid oscillations of landmasses between lower and higher latitudes. Kirschvink (1992) envisioned that ice covering the continents and most of the oceans—a Snowball Earth—would eventually melt, following the build-up of atmospheric carbon dioxide as a result of volcanism and reduced weathering. Hot and cold climatic swings may have been brief, lasting perhaps a few million years, separated by longer intervals of more temperate climate. Kirschvink (1992) identified three ways to test this hypothesis. First, glacial units for a given episode around the globe should be more or less synchronous. Second, global scale icehouse/greenhouse events should have produced similar shallow marine deposits around the globe, including the cap carbonates discussed below. Finally, protracted oceanic cover by floating ice should inhibit the exchange of oxygen with the atmosphere, leading to stagnant and anoxic seawater and the buildup of ferrous iron. Increased inputs of oxygen during deglaciation should then have promoted deposition of iron-rich deposits including IF.

It is controversial whether or not the entire Earth ever became ice-covered, but it is accepted that Neoproterozoic glaciations were more extensive than late Cenozoic "ice ages." Efforts to test and refine the SEH have progressed through the integration of regional stratigraphy and sedimentology with improved dating of events through radiometric, paleomagnetic, and geochemical techniques. Precise determination of glacial unit age is often difficult because of the absence of datable materials, such as interbedded ash beds, within glacigenic units. Determinations of paleolatitude face comparable preservational challenges, but paleomagnetic evidence now supports that substantial volumes of glacial debris were deposited in low-latitude settings (Harland, 1964; Hoffman and Schrag, 2002; Evans and Raub, 2011). Early work raised the possibility of multiple (2–4) panglacial episodes between ~800 and 580 Ma, but the development and application of high-precision geochronology, along with paleolatitude studies, now support just two panglacial events: the older "Sturtian" and younger "Marinoan" glaciations; named for glacigenic successions in Australia but extended globally in modern usage. The common occurrence of thick "cap-carbonate" sequences directly overlying glacigenic sediments further suggests that cap limestone and dolomite successions may have been deposited very rapidly, as the warming deglacial ocean became intensely supersaturated in carbonate. The SEH concept continues to evolve as scientists collect and evaluate evidence.

Timing

Since the seminal publication of Kirschvink (1992), tests of the Snowball Earth Hypothesis have sought evidence supporting or refuting the occurrence and number of panglacial episodes during the Late Neoproterozoic. The present consensus (Fig. 1C) benefits from the recent addition of high resolution U-Pb and Re-Os ages (e.g., Rooney et al., 2015) and supports two panglacial episodes, the Sturtian (ca. 717–659 Ma) and the Marinoan (ca. 645–635 Ma). Evidence for pre-Sturtian (ca. 740 Ma) panglacial intervals, suggested for localities on cratons including the Kalahari (Kaigas glaciation), Tarim (Bayisi diamictite), Egypt and Congo (Kundelungu Basin), are controversial because of questionable age constraints, glacigenic origins, and/or demonstrable overlap with nonglacial sedimentation in Laurentia (Rooney et al., 2015). The Sturtian episode (717–659 Ma) seems to have encompassed a time span that was nearly as long as the Cenozoic era, whereas the Marinoan episode (~650–640 to 635 Ma) was briefer, lasting for ~15–5 myr. The likelihood that Late Neoproterozoic panglacial episodes may have served as evolutionary bottlenecks for the appearance of Ediacaran biota has stimulated paleontological investigations of post-Marinoan glacial strata. The occurrence of Ediacaran glacial deposits on multiple paleocontinents (Evans and Raub, 2011), including some with apparent low-paleolatitudes, led to the concept of a post-Marinoan panglacial event—the so-called "Gaskiers" glaciation (after deposits in eastern Newfoundland). With the addition of high-precision radiometric age constraints, many of these localities have since been shown to be diachronous or to have had short durations inconsistent with multimillion year durations required for panglacial episodes. Considering the broad distribution of Ediacaran glacial localities, including some with possible low paleolatitudes, the "Gaskiers" glacial episode may have been stimulated by causes similar to those triggering the Sturtian and Marinoan panglacial episodes (e.g., greenhouse gas drawdown cycles related to chemical weathering of juvenile crust/flood basalt).

Evidence

Glaciation is a strong agent of erosion, and material that is eroded must be deposited somewhere. Continental glaciation also transfers water from ocean to land ice, lowering sea level and exposing emergent continental shelf regions to erosion. Continental ice sheets as envisioned for SEH would have deposited eroded detritus on the seafloor, especially on continental shelves where the ice sheets terminated. The waxing and waning of global ice is also reflected in changing seawater composition, and these changes should be preserved in marine sediments. These considerations are reflected in the five principal lines of evidence for the SEH: glacial deposits (diamictites and dropstones), the Great Unconformity, cap carbonates, banded iron formations, and low paleolatitude of glacial deposits. These are discussed further below.

a. Glacial deposits: Glaciers erode a wide range of rocks of various sizes and dump these to form moraines where the ice terminates, often where the ice sheet flows into the sea. Glacial moraines are poorly sorted polymict conglomerates and breccias and contain a wide range of clast sizes and shapes carved and carried by ice. Ancient deposits are often called diamictites when deposition by glacial processes cannot be confirmed, but diamictites can form in many ways other than by glacial activity—for example as debris flows and as ejecta blankets from meteorite impacts (Eyles and Januszczak, 2004). Sedimentary units identified as diamictites therefore warrant scrutiny in considerations of prospective glacigenic associations. Diamictites that result from glacial activity encompass a variety of peri- and subglacial environments, including terminal and lateral moraines, deposited in both marine and subaerial environments. Because rocks plucked by the action of glaciers are rarely rounded, an abundance of angular clast shapes supports an interpretation of glacial origin, but these may be common only in marine sedimentary environments. Rounded cobbles can also result from terrestrial glaciation, because rock fragments deposited by glaciers must be transported by melt streams from upland moraines to depositional basins. The most unequivocal evidence for a glacial deposit is the identification of dropstones. Dropstones form as drifting icebergs melt in the ocean, releasing embedded stones. These fall through the water column and plunge into sediments on the seafloor. If impacted sediments are laminated, the sinking stone will disrupt the laminae and then be covered by younger, undisturbed sediments.
b. The Great Unconformity: Global glaciation will cause intense erosion of the continents, and this erosion will be preserved as a break in the stratigraphic record, or unconformity. The Great Unconformity marks one or more episodes of Neoproterozoic erosion and/or nondeposition on the continents (Keller et al., 2018). The Great Unconformity is well exposed in the Grand Canyon, but this geomorphic surface, which records the erosion and weathering of continental crust followed by sediment accumulation, can be traced across Laurentia and globally, including Africa, Scandinavia, North America, and Siberia, making it the most widely recognized and distinctive stratigraphic surface in the rock record. Keller et al. (2018) argued that the Great Unconformity formed in association with large excursions of oxygen and hafnium isotopic compositions in magmatic zircon that suggest enhanced crustal erosion and sediment subduction. The lack of preservation of small, older impact craters and the first-order pattern of Phanerozoic sedimentation can be explained, along with the Great Unconformity, by Neoproterozoic glacial erosion averaging 3–5 vertical kilometers.
c. Cap carbonates: These are thin (~3–20 m) carbonate (dolomite and/or limestone) sedimentary rocks that directly overlie some marine glacial deposits. Cap carbonates are significant because thick carbonate sedimentary rocks are generally deposited in warm (tropical) seawater. They are interpreted to have formed from supersaturated surface waters during the main marine deglacial transgression, the latter caused by melting of ice sheets and thermal expansion of warming oceans. Deglaciations should have been associated with increased chemical weathering on land, as well as changing physical and chemical stratification of the oceans due to the development of a km-thick meltwater lid (Hoffman et al., 2017). The associated alkalinity increase from chemical weathering, coupled with CO_2-charged surface waters in equilibrium with the extreme greenhouse atmosphere (with pCO_2 levels 25–250× modern levels), drove carbonate precipitation to form cap carbonates. Probable ice-rafted debris is occasionally found at the lowest levels of cap carbonate units, suggesting that deglaciation followed directly from glacial conditions (Hoffman and Macdonald, 2010). Deglacial transgressions may have been rapid, but some cap carbonate units preserve paleomagnetic reversals which is more consistent with slow deposition (Hoffman et al., 2017). According to Hoffman et al. (2017), cap carbonates are globally widespread and synchronous, with sharp basal contacts, overthickened depositional sequences, and C-isotope excursions beginning from negative mantle-like values. That cap carbonates have no known equivalents within underlying glacigenic deposits supports the hypothesis that they are a unique phenomenon associated with panglacial episodes. Structures common to many cap carbonates include breccia and veined zones near the base, laminations and fine bedding, and algal accumulations known as stromatolites. Marinoan cap carbonates tend to be beige or pinkish dolostone, with peloidal textures and structures indicating wave action (giant wave ripples, low angle cross-stratification, normal and reverse grading), and stromatolites (tubestone- and guttertype) indicating algal growth in the surface layer of the ocean that receives sunlight, i.e., the photic zone. They also widely host barite cements and occasionally also aragonite crystal fans deposited on or near the seafloor; no similar sea floor cements are known in Sturtian cap carbonates. Cap carbonates above Marinoan glacial successions are especially common. Sturtian cap carbonates have sedimentalogic characteristics suggesting deeper water deposition (e.g., dark, organic-rich, micritic limestone with graded calcilutite turbidites or hummocky cross-stratification, possible nonphototrophic stromatolites/microbialaminates). The significance of the negative $\delta^{13}C$ of cap carbonates is a topic of debate. For instance, some scientists suggest that this isotopic signal indicates that life was almost extinguished by Snowball Earth episodes (Hoffman et al., 1998).
d. Iron Formations (IFs): IFs are iron-rich (15–40 wt% Fe) and siliceous (40–60 wt% SiO_2) chemical sedimentary rocks that precipitated from seawater; nearly all IFs were deposited in Precambrian time. Most were deposited between 2800 and 1850 Ma in the Neoarchaean and Palaeoproterozoic, when Earth's atmosphere and oceans became increasingly enriched in oxygen due to the proliferation of photosynthetic cyanobacteria (Konhauser et al., 2017). Increasing oxygen levels in seawater converted

soluble Fe^{2+} into insoluble Fe^{3*}, which settled on the seafloor to form IF. IF deposition ended by 1850 Ma but returned during Neoproterozoic time as a result of Snowball Earth events (Cox et al., 2013). Most Neoproterozoic IFs are Sturtian in age and nonvolcanic, indicating oxidation of deep-ocean anoxic ferruginous seawater. In the classical SEH (Kirschvink, 1992), global ice-cover resulted in anoxic ferruginous oceans, leading to increased abundance of soluble Fe^{2+} in seawater. Dissolved Fe may have increased over tens of millions of years in association with the break up of the Rodinian supercontinent that led to an episode of increased volcanism and basalt weathering (e.g., Horton, 2015; Cox et al., 2013, 2016). When the ice melted or cyanobacteria activity increased sufficiently, seawater would have become re-oxygenated, converting soluble Fe^{2+} into insoluble Fe^{3*}, which settled on the seafloor to form IF. However, deposits of Sturtian IF are a regional phenomenon that tends to occur in restricted basinal settings and in lower portions of glacigenic successions (e.g., boulder-bearing stratified diamictite) rather than being associated with cap carbonates. Oxidants may have been introduced to these settings as subglacial meltwater discharge (Hoffman et al., 2017).

e. Globally synchronous low-latitude glaciation and globally synchronous deglaciation at all latitudes: Earth has experienced several long-duration (tens to hundreds of million years) regional scale glacial episodes involving ice accumulation at high and mid-latitude land masses (Fig. 1B). Panglacial episodes also included sea ice formation at or near the equator. Transitions to and from panglacial episodes should correspond with instabilities in Earth's normal climate regime (with constant insolation and active CO_2 regulation via silicate weathering), each offering unique, testable hypotheses. Global energy balance models (e.g., Budyko, 1969; Sellers, 1969) that support the SEH indicate that global cooling resulting from runaway albedo (driven by a reduction in solar flux and/or atmospheric CO_2 levels) should have triggered rapid advancement of terrestrial-based ice sheets and sea ice to equatorial latitudes, and that resulting global-scale ice cover should then have endured over multi-million year intervals until greenhouse gas concentrations supplied by volcanic and metamorphic outgassing increased to the point of melting the ice in tropical latitudes. The atmospheric CO_2-regulating silicate weathering feedback would have stalled with global-scale ice cover and concomitant reduction in hydrologic cycle activity. The concentration of CO_2 required to resume tropical melting is very high, at 25–250 times the modern level (e.g., 10^4–10^5 ppm; Hoffman et al., 2017), and once melting began, the amount of reflected solar radiation (albedo) would have progressively decreased, enhancing the hydrologic cycle and resuming the silicate weathering CO_2 feedback. This combination would have resulted in super greenhouse warming and a loss of glacial ice at all latitudes within millennia (Walker et al., 1981). Thus, evidence supporting the occurrence of panglacial episodes should include both (1) globally synchronous low-latitude glaciation and (2) globally synchronous deglaciation at all latitudes. These predictions are now supported by paleomagnetic assessments of Cryogenian glacigenic deposits, which indicate an abundance of such deposits in the tropical paleolatitudes (Evans and Raub, 2011). The application of refined U-Pb and Re-Os geochronology methods (e.g., Rooney et al., 2015) capable of ~1 myr age resolution, now tightly constrains the timing of the onsets and terminations of glaciations, as evidenced by glacial strata on different paleocontinents (Fig. 2C).

What Caused Neoproterozoic Snowball Earth?

For about 1600 million years after a major glacial episode at ~2400 Ma and before Neoproterozoic Snowball Earth began, Earth's climate seems to have been warm (Fiorella and Sheldon, 2017), so something must have disrupted this climate equilibrium to cause Neoproterozoic Snowball Earth. Many explanations have been offered and it is useful to keep the admonition of Roberts (1976, p. 56) in mind: "The evidence bearing on the glaciation issue as a whole is so complex . . . that it seems best to concentrate on one theory at a time." The many hypotheses advanced to explain Neoproterozoic Snowball Earth are summarized in Table 1, where they are parsed into four groups: extraterrestrial, geodynamic, oceanographic, and biotic. Five explanations concern external forcings originating in outer space. There are 11 geodynamic explanations that reflect changes in the behavior of the solid Earth. The three oceanographic causes are explained by changes in the functioning of the ocean. Finally, the three biotic explanations reflect changes in the behavior of life and its products. The two Neoproterozoic panglacial episodes may have had different causes, and multiple causes are also possible. A fifth class of explanation is also worth considering: that the Earth experienced a major change in its tectonic behavior in Neoproterozoic time, triggering multiple geodynamic, oceanographic, and biotic changes. Each of the 22 mechanisms are briefly discussed below before we briefly discuss how the transition from a single lid tectonic regime to plate tectonics could have been responsible.

Extraterrestrial Causes

One or both of the Neoproterozoic panglacial events could have been caused by phenomena that originated in space. Five phenomena have been suggested in the peer-reviewed scientific literature:

a. Fainter Neoproterozoic Sun: Harland (1964) suggested that Neoproterozoic glaciations may have resulted from lower insolation. Stellar evolution models indicate that the Sun was about 25–30% less luminous 4570 Ma compared to today (Newman and Rood, 1977) and would have been ~6–7% less luminous during the Cryogenian (Hoffman et al., 2017). The increase in luminosity is modeled as a regular, slightly accelerating, increase with small (0.1%) recent variability over decadal and millennial scales. Simple radiative energy-balance calculations, in which solar irradiance is reduced by only a few percent from modern levels, however, produce runaway albedo scenarios that lead to an ice-covered planet (e.g., Sellers, 1969;

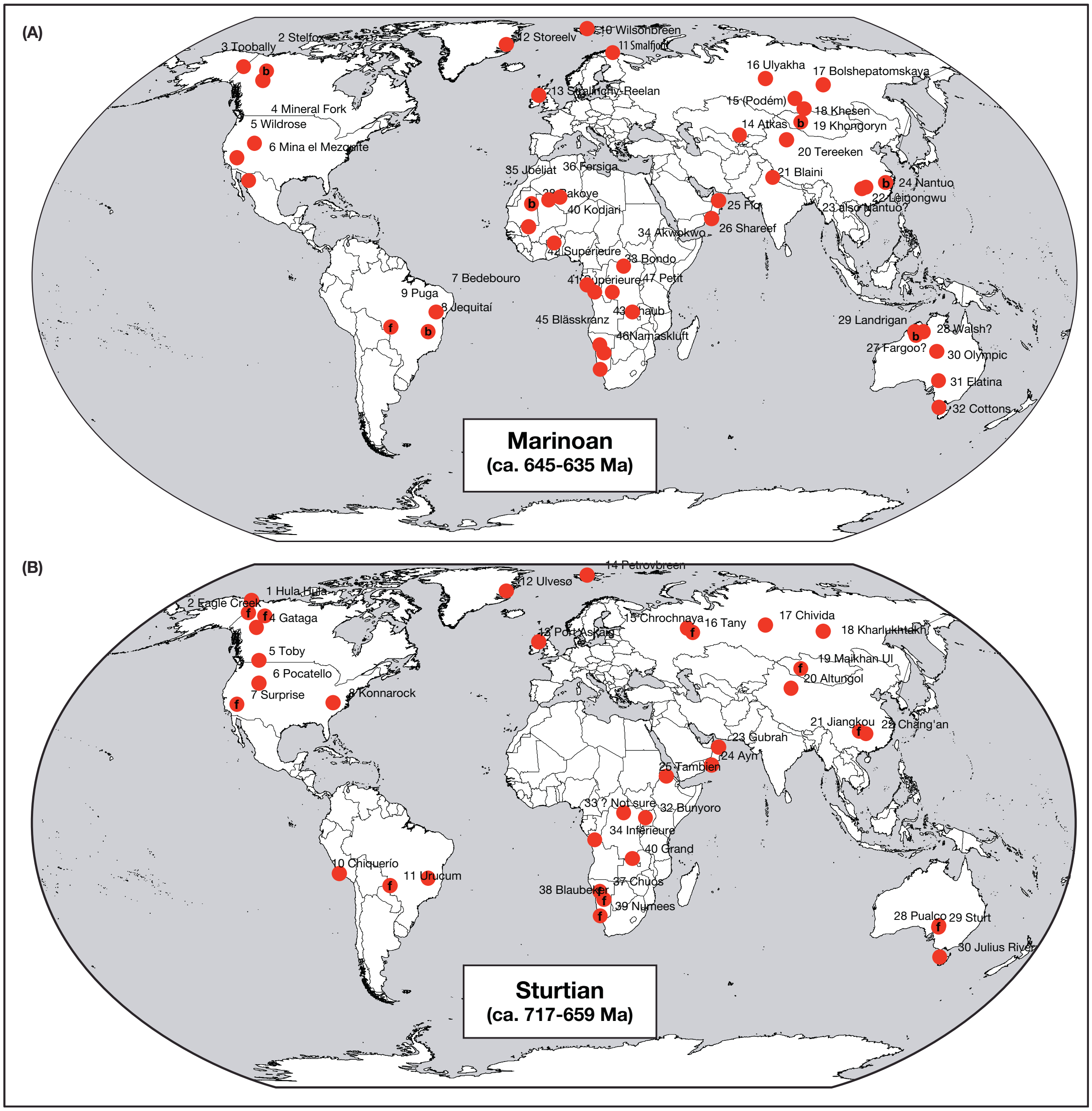

Fig. 2 Modern distribution of regional scale Cryogenian glacigenic deposits. (A) The Marinoan glacial episode (ca. 645–635 Ma) concluded with formation of distinctive cap carbonates, including the precipitation of (primary/authigenic) barite on or near the sea floor in some areas (*dots* with b's). (B) The Sturtian glacial episode (ca. 717–659 Ma) was particularly prolonged (~58 myrs) and glacial-periglacial deposition in some localities was accompanied by sedimentary Fe oxide formation (*dots* with f's). Modified after Hoffman et al. (2017).

Budyko, 1969). However, Earth's early (Archean-Proterozoic) geologic record is replete with evidence for liquid water and also indicates that glacial episodes were relatively rare. These lines of evidence for a warm climate coincide with a time interval when solar output was insufficient to prevent a panglacial climate. These contradictory findings are known as the faint young Sun paradox/problem (Feulner, 2012). Higher concentrations of greenhouse gases (CO_2, CH_4, NH_3) that diminished over time as solar luminosity increased may account for the geologic evidence. Although stellar evolution models are inconsistent with a reduction in luminosity over time, reduced solar forcing could have been brought about by other causes (see b–e below).

b. Collapse of orbiting ice rings into Earth's atmosphere: To explain the recurrence of Neoproterozoic glaciations, Sheldon (1984) hypothesized that Archaean Earth once had dense ice rings, the orbits of which slowly decayed as the moon moved away from Earth, eventually entering Earth's atmosphere in the Proterozoic. He speculated that the ice ring shadows caused cooling (shade for the hemisphere experiencing winter) and ice ages on Earth, but as each ice ring was progressively destroyed in the

Table 1 Possible causes of Neoproterozoic snowball earth.

Class—Proposed events promoting cooling	*Main cooling mechanism(s)*	*Refs*	*Caused by TPT?*
1. Extraterrestrial			
a. Fainter Neoproterozoic sun	Lower(ed) insolation	H64	No
b. Collapse of orbiting ice rings into Earth's atmosphere	Lower(ed) insolation	S84	No
c. Variation in cosmic ray flux	Lower(ed) insolation	MM04	No
d. Variation in Earth's interaction with interstellar dust	Lower(ed) insolation	P05	No
e. Cooling by impact ejecta (dust) in the atmosphere	Lower(ed) insolation	BB02	No
2. Geodynamic			
a. Colder, more seasonal, tropics due to high obliquity	High obliquity	W16	Yes
b. Low-latitude Rodinia after $\sim$800 Ma true polar wander episode	Enhanced albedo and C sequestration	Li04	Yes
c. Low-latitude Rodinia (unspecified)	Enhanced albedo and C sequestration	HS02	Yes
d. Rodinia break-up and weathering	Enhanced C sequestration	D04	Yes
e. Rodinia break-up (Zipper-rift model)	Tectonic uplift, active rift margins	EJ04	Yes
f. Rodinia break-up + basalt weathering	Enhanced C sequestration	G03	Yes
g. Rodinia break-up + basalt weathering + ocean fertilization	Enhanced C sequestration	H15, G16	Yes
h. Clathrate reservoir (tectonic?) exhumation and depletion	Loss of atmospheric methane	H02	Yes
i. Atmospheric sulfur aerosols from explosive volcanism	Lower(ed) insolation	S08	Yes
j. Atmospheric sulfur aerosols—LIP emplacement within S evaporite	Lower(ed) insolation	MW17	Yes
k. Reduced continent-volcanic arc activity	Lull in volcanic CO_2 outgassing	M16	No
3. Oceanographic			
a. Ocean stagnation and enhanced organic burial	Enhanced C sequestration	K93	Yes
b. Carbonate burial depletes $P\text{CO}_2$	Enhanced C sequestration	R76	Yes
c Hypsometric effect—deeper CCD depletes $P\text{CO}_2$	Enhanced C sequestration	R03	Yes
4. Biotic			
a. Methane destroyed by a Neoproterozoic oxidation event	Loss of atmospheric methane	P03	Yes
b. Biocatalyzed weathering enhances $P\text{CO}_2$ drawdown	Enhanced C sequestration	K06	Yes
c. Enhanced organic export production and anaerobic mineralization	Enhanced C sequestration	T11	Yes
5. Transition to plate tectonics (TPT)			
Multiple potential causes (see column "Caused by TPT?)	—	S18	—

References are intended to be representative, not exhaustive: H64: Harland, 1964. S84: Sheldon, 1984. MM04: Marcos and Marcos, 2004. P05: Pavlov et al., 2005. BB02: Bendtsen and Bjerrum, 2002. W16: Williams et al., 2016. Li04: Li et al., 2004. HS02: Hoffman and Schrag, 2002. D04: Donnadieu et al., 2004. EJ04: Eyles and Januszczak, 2004. G03: Goddéris et al., 2003. H15: Horton, 2015. G16: Gernon et al., 2016. H02: Halverson et al., 2002. S08: Stern et al., 2008. MW17: Macdonald and Wordsworth, 2017. M17: McKenzie et al., 2016. K93: Kaufman et al., 1993. R76: Roberts, 1976. R03: Ridgwell et al., 2003. P03: Pavlov et al., 2003. K06: Kennedy et al., 2006. T11: Tziperman et al., 2011. S17: Stern and Miller, 2018.

atmosphere, the shadows decayed and Earth recovered, entering a greenhouse state until the next ring's orbit decayed. After the final ring had decayed, the tropics were finally shadowless and the ice ages ended.

c. Variation in cosmic ray flux: Marcos and Marcos (2004) suggested that variations in rates of supernova and star formation in our galaxy resulted in changing fluxes of cosmic rays. Higher supernova and star formation rates would have increased the cosmic ray flux to the planet, and this may have generated more clouds in Earth's troposphere, enhancing albedo and cooling climate.

d. Variation in Earth's interaction with interstellar dust clouds: Pavlov et al. (2005) argued that dramatic climate change could have been caused when the Earth encountered a giant molecular "dust" cloud so that interstellar dust accumulated in Earth's atmosphere. The stratospheric dust layer from such interstellar particles would have reflected enough solar radiation to cool the planet, causing the Snowball Earth.

e. Cooling due to impact ejecta (dust) in the atmosphere: Bendtsen and Bjerrum (2002) argued that if Earth was struck by a sufficiently large meteor or comet, enough dust and aerosols could have been ejected into the atmosphere to block the level of solar radiation sufficient to cool the planet and cause Snowball Earth.

Geodynamic Causes

Eleven mechanisms related to solid Earth behavior have been proposed for triggering Neoproterozoic Snowball Earth episodes. The breakup of the Neoproterozoic supercontinent Rodinia figures prominently in many of the geodynamic scenarios.

a. True Polar Wander and High Obliquity: True polar wander (TPW) would happen if Earth's axis of rotation shifted position so dramatically that the geographic locations of the north and south poles would change, or "wander." In a rotating body, the largest moment of inertia axis is aligned with the spin axis. When these axes differ, true polar wander will occur as the rotation axis is realigned with the largest moment of inertia axis. Mass redistribution, for example by drifting continents and/or formation of new subduction zones, can change the location of the Earth's largest moment of inertia axis. TPW contrasts with apparent polar wander, which is a paleomagnetic technique used to reconstruct the positions of different continents in the past. TPW was suggested by Kirschvink (1992) to explain evidence for low-latitude glaciations in Neoproterozoic time, and these ideas are supported by subsequent research (e.g., Robert et al., 2018). Such a reorientation of Earth's rotation axis would have substantial effects on climate, many of which are currently incalculable. Williams et al. (2016) argued that low-latitude glaciation did not require the entire Earth to be locked in ice. They argued instead that unusually large seasonal changes of temperature occurred near the equator because Earth's rotation axis was tilted >54 degrees, much more than the modern tilt (23.5 degrees). Such a high obliquity would have caused more seasonality at low latitudes so that the equator would be cooler than the poles, on average, and global seasonality would be greatly amplified, allowing ice to form near sea level at equatorial latitudes. The lack of known high-paleolatitude glacial localities (Evans and Raub, 2011) could be consistent with this theory.

b. Low-latitude Rodinia after ~800 Ma true polar wander episode: Li et al. (2004) used paleomagnetic and geochronological data to suggest that at ~800 Ma, the Neoproterozoic supercontinent Rodinia was the site of a major mantle plume and this caused an episode of true polar wander (TPW) that brought the entire supercontinent into equatorial latitudes. The unusually large land area and extensive regions of exposed basalt at low latitudes increased global albedo and weathering, which reduced atmospheric CO_2 and led to cooling that triggered the Sturtian glaciation.

c. Low-latitude Rodinia (unspecified): Hoffman and Schrag (2002) followed Kirschvink (1992) in speculating that a preponderance of continents in middle to low latitudes created conditions favorable for Neoproterozoic Snowball Earth. The reason for such a distribution of landmasses was unspecified. Such a continental configuration might have given rise to polar sea-ice caps large enough to significantly increase Earth's albedo and cool the planet further.

d. Rodinia break-up and weathering: Donnadieu et al. (2004) used coupled climate-geochemical modeling to argue that the break-up of the supercontinent Rodinia ~750 Ma (located near the equator) led to uplift, eruption rift-related basalts, and thereby increased precipitation. Continental weathering was enhanced by these changes, resulting in greatly decreased atmospheric carbon dioxide concentrations, leading to the Sturtian glacial episode.

e. Rodinia break-up (Zipper-rift model): Eyles and Januszczak (2004) challenged the idea that glaciation was globally synchronous and proposed instead the "Zipper-rift" model. They emphasized that the reorganization of the Earth's surface as a result of breaking up the supercontinent Rodinia from ~750 to ~610 Ma would have generated the climatic effects associated with uplifted rift flanks. They also argued that and the resulting sedimentary record deposited in newly formed rift basins. They argued that Neoproterozoic glaciations were likely regional or hemispheric in scope and latitudinally constrained.

f. Rodinia break-up and basalt weathering: Goddéris et al. (2003) focused on the climatic effects of intense basaltic magmatism between 825 and 755 Ma, associated with the break-up of Rodinia. They emphasized that these basaltic provinces would be easily weathered and that this would have enhanced a draw-down of atmospheric CO_2, cooling climate. Goddéris et al. (2003) speculated that the Laurentian magmatic province was responsible for triggering the Sturtian glaciation, since it had drifted to a near-equatorial location where weathering was especially intense.

g. Rodinia break-up, basalt weathering and ocean fertilization: Horton (2015) recognized that phosphorus in the oceans is a limiting nutrient for photosynthetic organisms. He used this insight to show how weathering of extensive regions of 850–720 Ma basalts would have increased the influx of P from the land to the sea for millions of years, elevating oceanic primary production and thereby drawing down atmospheric CO_2 sufficient to cause cooling. Changes to ocean chemistry related to basalt weathering may also have contributed to other enigmatic phenomena associated with the SEH. Gernon et al. (2016), for example, considered how the alteration of submarine basaltic glasses formed at spreading ridges during the breakup of Rodinia could have increased Ca- and Mg-saturation over the course of the glaciation, potentially stimulating cap carbonate deposition when glaciation ended. Basalt weathering may also have contributed to BIF deposition by increasing dissolved iron, phosphorous, and silica concentrations.

h. Clathrate reservoir exhumation and depletion: Schrag et al. (2002) suggested that large (11–15%) negative shifts in $\delta^{13}C$ in shallow marine carbonates directly underlying Neoproterozoic glacial deposits could be explained by prolonged methane release. They speculated that voluminous release of methane from destabilizing sediments rich in methane hydrates (clathrates) might result from tectonic uplift. In their hypothesis, this release of methane into the atmosphere was responsible for the destabilization of climate that led to Neoproterozoic glaciation. Such tectonic movements would be expected accompany the breakup of Rodinia.

i. Atmospheric sulfur aerosols from explosive volcanism: Stern et al. (2008) argued that explosive volcanism was intense in Neoproterozoic time, especially about the time that Snowball Earth episodes occurred. Explosive eruptions are common for arc volcanoes, which produce sulfur-rich magmas. Such eruptions can inject fine ash and sulfuric acid aerosols into the stratosphere, and the aerosols may persist there for several years, reflecting incoming solar and cooling the planet's surface, perhaps enough to cause Snowball Earth episodes.

j. Atmospheric sulfur aerosols: Macdonald and Wordsworth (2017) proposed that the Sturtian glaciation was initiated by injection of sulfate aerosols into the stratosphere by eruption of the ~717 Ma Franklin large igneous province basalt, which assimilated older evaporite sediments, including significant quantities of sulfur. Eruption of the S-enriched magma would therefore have led to elevated SO_2 and H_2S outgassing in eruption plumes. The largest of these may have risen into the stratosphere, where sulfate aerosols formed, reflecting insolation and thereby cooling the planet's surface, triggering the Sturtian glaciation.

k. Reduced continent-volcanic arc activity: McKenzie et al. (2016) compiled ~120,000 detrital zircon U-Pb ages from the Cryogenian period to the present and used these as a proxy for continental arc volcanism. On this basis they inferred a negative relationship between global arc activity and glaciations: reduced continental arc activity corresponds with Cryogenian, Late Ordovician, Late Paleozoic, and Cenozoic glaciations. They concluded from this relationship that continental volcanic outgassing has controlled changes in atmospheric CO_2 levels over the past ~720 Ma, and thus affected climate, including Neoproterozoic Snowball Earth episodes.

Oceanographic Causes

Three scenarios leading to Snowball Earth climatic conditions have been proposed in relation to changes in Cryogenian ocean circulation or carbonate chemistry.

a. Ocean stagnation and enhanced organic burial: Kaufman et al. (1993) used Sr and C isotopic data to constrain rates of erosion, hydrothermal alteration and organic C burial in Neoproterozoic time. They interpreted the great increase in the Sr isotopic composition of marine carbonates over Neoproterozoic time as due to continent-continent collisions. High Neoproterozoic erosion rates, coupled with high organic productivity and anoxic bottom-water conditions, may have increased the burial rate of organic C, thereby drawing down atmospheric CO_2 and leading to cooling.
b. Carbonate burial due to depleted atmospheric CO_2: Roberts (1976) suggested that extensive deposition of carbonate sediments depleted atmospheric CO_2 and caused an "anti-greenhouse" sufficient to cause the cooling that led to Neoproterozoic glaciation.
c. Hypsometric effect—deeper carbonate compensation depth in the ocean depleted atmospheric CO_2: Formation of $CaCO_3$ is especially important for controlling concentrations of CO_2 in seawater and thus in the atmosphere. Ridgwell et al. (2003) argued that because calcareous plankton (which live in the open ocean) had not yet evolved, atmospheric greenhouse gas concentrations were much more sensitive to sea level changes during the Neoproterozoic than they are in modern times. This is because the buffering of Neoproterozoic seawater to balance erosional fluxes from the continents was mostly controlled by shelf carbonate deposition. When Neoproterozoic glacial episodes began, the loss of shallow-water environments greatly affected atmospheric CO_2 and thus climate and growth of ice sheets. Ridgwell et al. (2003) hypothesized that initial cooling was enhanced by this mechanism, which was responsible for the severity and duration of these ice ages. Ridgwell et al. (2003) speculate that tectonic changes such as breakup of Rodinia may have been responsible for initial cooling to start the process.

Biotic Causes

Three scenarios involving the action of organisms have been advocated as potential triggers of Neoproterozoic Snowball Earth episodes.

a. Methane destroyed by a Neoproterozoic oxidation event: Pavlov et al. (2003) argued that a methane (CH_4)-rich atmosphere helped keep climate warm for ~1.5 billion years (2.3–0.75 Ga). Methane is a strong greenhouse gas that is rapidly oxidized in the presence of significant atmospheric O_2, which is created by photosynthetic organisms. Pavlov et al. (2003) argued that Neoproterozoic glaciation was caused by the destruction of atmospheric methane due to an oxidation event ~0.75 Ga. This oxidation event reflected the proliferation of photosynthetic organisms.
b. Biocatalyzed weathering enhances PCO_2 drawdown: Kennedy et al. (2006) used mineralogical and geochemical evidence to argue for increased clay mineral deposition in the Neoproterozoic. They noted that clay minerals today mostly form in biologically active soils and concluded that microbial biomass on land increased greatly in Neoproterozoic time. More effective weathering resulted in increased deposition of shales and burial of organic carbon. This, in turn, led to a drawdown of atmospheric CO_2 leading to cooling.
c. Enhanced organic export production and anaerobic mineralization: Tziperman et al. (2011) addressed the large swings in C isotopic composition in marine sediments. They evaluated how proliferating and diversifying life in Neoproterozoic time could have led to increased burial of organic carbon sufficient to draw down atmospheric CO_2 to a level that would have triggered Neoproterozoic ice ages. They argued that sulfate reduction, followed by pyrite formation, increased oceanic alkalinity, enhancing $CaCO_3$ precipitation. Diversification of marine eukaryotes may have resulted in more organic matter forming particulate aggregates that can sink through the water column and be buried on the seafloor faster. This led to a drawdown of atmospheric CO_2, leading to cooling.

Did the Start of Plate Tectonics Cause Neoproterozoic Snowball Earth?

There is a controversy about when plate tectonics started and what was Earth's tectonic condition before this time. Many geoscientists consider that plate tectonics have been operating for 2–3 billion years or more, but a minority argues that this transition occurred in Neoproterozoic time. If the transition to plate tectonics occurred in Neoproterozoic time, it could have caused Snowball Earth. Stern and Miller (2018) outlined geodynamic considerations and summarized evidence for the occurrence in time of distinctive rock associations that are only formed by plate tectonic processes, specifically ophiolites, blueschists, ultrahigh pressure metamorphic rocks, and certain gemstones (jadeitite and ruby). These distinctive rock associations are, with few exceptions, only found in Neoproterozoic and younger rocks. Stern (2018) argued that Earth's tectonic condition before plate tectonics started was some variant of single lid tectonics, like that of the other active silicate bodies in the Solar System: Venus, Mars, and Io. The transition to plate tectonics required rupturing of the lid, perhaps by a large mantle plume, which allowed the lithosphere around it to founder, forming the first subduction zone. Formation of the first subduction zone initially resulted in the creation of just two plates, but formation of a complete global plate mosaic like that of today would have taken tens to hundreds of millions of years more.

The transition from a single lid tectonic regime to a full global mosaic could have caused nearly all of the geodynamic, oceanographic, and biotic mechanisms listed in Table 1. Formation of new subduction zones would have changed Earth's moment of inertia axis and likely caused true polar wander. Formation of new subduction zones and plates could have caused rifting of the supercontinent Rodinia, with attendant uplift, and also could have triggered mantle plumes and large basaltic eruptions. Increased erosion and weathering could have stimulated oceanographic and biotic mechanisms listed in Table 1.

Conclusions

We have made excellent progress in our efforts to understand the nature, timing and possible causes of Neoproterozoic Snowball Earth. The integration of high-precision geochronologic and paleomagnetic techniques with regional stratigraphic studies contribute to a broad concensus that the Sturtian and Marinoan glaciations were each synchronous on nearly all paleocontinents and together define Earth's late Neoproterozoic Cryogenian period. Many controversies persist, however, such as the extent of marine ice cover—ranging from extensive (hard snowball) to partial (slushball). The predictions offered by the (hard) Snowball Earth hypothesis conceivably account for the synglacial deposition of iron formation, the formation of cap carbonates upon deglaciation, rapid low latitude glaciation and rapid deglaciation at all latitudes, and the very long multi-million-year durations of low latitude glaciations. However, to account for the survival of photosynthetic life and evidence of an active hydrologic cycle during deposition of some Cryogenian glacial strata, some workers think that portions of the ocean must have remained ice-free. More work is required to resolve such inconsistencies. Because climate and tectonics are intimately connected, a better understanding of Earth's tectonic evolution may be the key to understanding what caused this very unusual episode in Earth's climate history.

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