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Did an asteroid impact cause temporary warming during snowball Earth?

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ABSTRACT

The ca. 717 Ma low-latitude Sturtian "snowball Earth" glaciation lasted ~56 Myr. However, sedimentological evidence for transient, open ocean conditions during the glaciation appears to contradict the concept of a global deep freeze. We demonstrate multiple lines of geologic evidence from five continents for a temporary, localized sea-ice retreat during the middle of the Sturtian glaciation, which coincides with one, perhaps two, asteroid impacts, and arguably more terrestrial impacts as inferred from the lunar impact record. The well-dated Jänisjärvi impact (ca. 687 Ma) is synchronous with repeated volcanic ash falls whose deposition is most parsimoniously interpreted to indicate a partially ice-free ocean. Temporary greenhouse warming caused by the vaporization of sea ice can explain localized glacial retreat within restricted seaways between these continents, where ice flow would have been constricted and sea ice thinnest before impact.

1. Introduction

The snowball Earth hypothesis of global ice cover explains the occurrence of low-latitude glaciation and other geologic observations like the reprisal of banded iron formation (BIF) and ^{13}C-depleted "cap" carbonates (Hoffman et al., 1998; Kirschvink, 1992). Due to the high planetary albedo of an ice-covered Earth, the freezing temperatures would create sea ice hundreds of meters thick (Creveling and Mitrovica, 2014). In this “hard” snowball state, it is thought that open ocean conditions are unsustainable, as the sea ice would gravitationally flow and thicken any areas where the ice is thinner. Nonetheless, evidence of dynamic ice-sheets and open ocean conditions, particularly for the Sturtian glaciation, appear to be inconsistent with the snowball Earth hypothesis (Le Heron et al., 2013; Le Heron et al., 2011). In the Wilyerpa Formation of South Australia, numerous sandstone units with hummocky-cross stratification (Le Heron et al., 2011) most likely formed by oscillatory wave action produced during storms (Dumas and Arnott, 2006), requiring locally open ocean conditions. In the Chuos Formation of Namibia, open ocean conditions and glacial retreat is evidenced by a clast-free shale unit marking a maximum flooding surface (Le Heron et al., 2013). These observations have been used to argue that an interglacial period occurred within the Sturtian (Le Heron et al., 2014b).

Such questions, including the requirement of refugia in which evolving Metazoa could survive, inspired “waterbelt” climate models (a.k.a. “slushball” or “soft” snowball solutions) that explore whether a nearly global snowball with equatorial patches of open ocean was theoretically plausible (Hoffman et al., 2017). However, such models are technically challenging since they must closely approach ice-albedo runaway without falling victim to it. Furthermore, they are arguably problematic due to a lack of compatibility with cap carbonate and BIF formation (Hoffman et al., 2017). Reconciliation of the apparent evidence for an at least spatially and temporally isolated open ocean with the hard snowball model thus remains problematic. Here we present multiple lines of evidence for transient open ocean conditions, as well as a new hypothesis to explain the mechanism controlling its occurrence: temporary, localized glacial retreat of snowball Earth due to greenhouse warming from an asteroid impact.

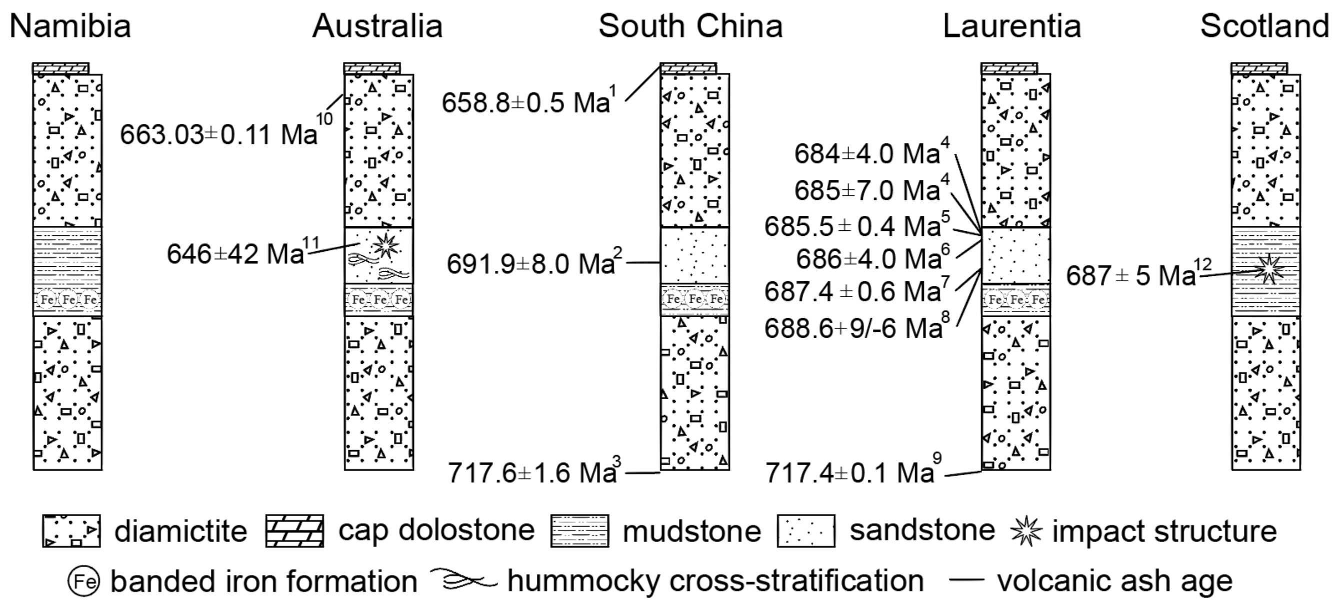

Fig. 1. Schematic stratigraphic columns of five basins exhibiting sedimentological evidence for glacial retreat and re-advance during the middle of the Sturtian glaciation. We compiled the dated volcanic ash layers occurring near the middle of the Sturtian glaciation on two continents (Laurentia and South China), two dated impact structures occurring during the glaciation, and tuff ages constraining Sturtian onset and termination in the basins studied. The references for the ages numbered are as follows: (1) Zhou et al. (2019), (2) Lan et al. (2015), (3) Lan et al. (2020), (4) Lund et al. (2009), (5) Keeley et al. (2013), (6) Fanning and Link (2008), (7) Condon and Bowring (2011), (8) Ferri et al. (1999), (9) Macdonald et al. (2010), (10) Cox et al. (2018), (11) Spray et al. (1999), and (12) Jourdan (2012).

2. Evidence for temporary and localized glacial retreat

From ca. 717-661 Ma, the ~56-Myr-long Sturtian glaciation (Rooney et al., 2020) is the most protracted snowball episode in Earth history. Sedimentological evidence for glacial retreat during the Sturtian glaciation comes from five continents: Australia, Baltica (Scotland), Congo (Namibia), Laurentia, and South China (Fig. 1). Firstly, each of these five continents records a temporary reprise from the deposition of glacial diamictites (Fig. 1). Instead, the sections consist of mudstone, fine to medium-grained sandstones with hummocky cross-stratification, dolostone that was precipitated *in situ* (Hood et al.), and importantly, lack ice-rafted debris (Le Heron, 2015). However, the lack of glacial diamictites does not necessarily mean glacial retreat. Alternatively, it could indicate that the ice sheets were cold-based and not active. Nevertheless, Le Heron (2015) discussed how these intervals are associated with retrogradation packages, indicating they occurred during glacial retreat.

In addition, during this glacial hiatus in the middle Sturtian, these continents record stratigraphically thick intervals of BIF, mudstone, and sandstone deposited in the middle of the Sturtian glaciation (Fig. 1). Although the buildup of an oceanic pool of dissolved Fe^{2+} for BIF requires hard snowball conditions (Kirschvink, 1992), BIF deposition itself represents its oxidation due to air-sea-gas exchange (Lechte et al., 2019; Mitchell et al., 2021), which is impossible under a completely sealed snowball ocean. Sedimentology and $^{56}\delta Fe$ isotopes indicate that BIF deposition occurred across a strong redox gradient both at and near the grounding line of continental ice sheets (Lechte et al., 2019). Thus, although BIF deposition required ventilation, it was highly localized on discrete continental margins. In Australia, the observed hummocky cross-stratification in sandstone units requires oscillating wave action in open ocean conditions following BIF deposition (Le Heron et al., 2011). Furthermore, in successions spanning all five continents (Fig. 1), such siliciclastic interruptions of Sturtian diamictites do not require glaciation to have occurred at that time and have been interpreted as due to glacial retreat followed by a re-advance of a second phase of the Sturtian glaciation

(Arnaud, 2004; Hu and Zhu, 2020; Lan et al., 2015; Le Heron et al., 2014a; Le Heron et al., 2013; Le Heron et al., 2011).

It has been suggested that volcanic activity would have continued largely unaffected by snowball Earth (Kirschvink, 1992). In addition to the sedimentological observations that require temporary glacial retreat and open ocean conditions (Fig. 1), we also suggest that the preservation of zircon-bearing volcanic ash layers (tuffs) that require evolved crustal magmatism (i.e., subaerial eruption) would not be deposited as uniform layers if the ocean was completely frozen over. Snowball deglaciation is thought to require a critical threshold of carbon dioxide from volcanic emissions to overcome the high planetary albedo (Donnadieu et al., 2004). Despite ongoing volcanism, thick sea ice would have prevented ash falls from being deposited in sedimentary basins. However, basins in western Laurentia and South China preserve ash fall layers during the middle of the Sturtian glaciation; moreover, these tuffs are coeval with each other within age uncertainty (Figs. 1 and 2).

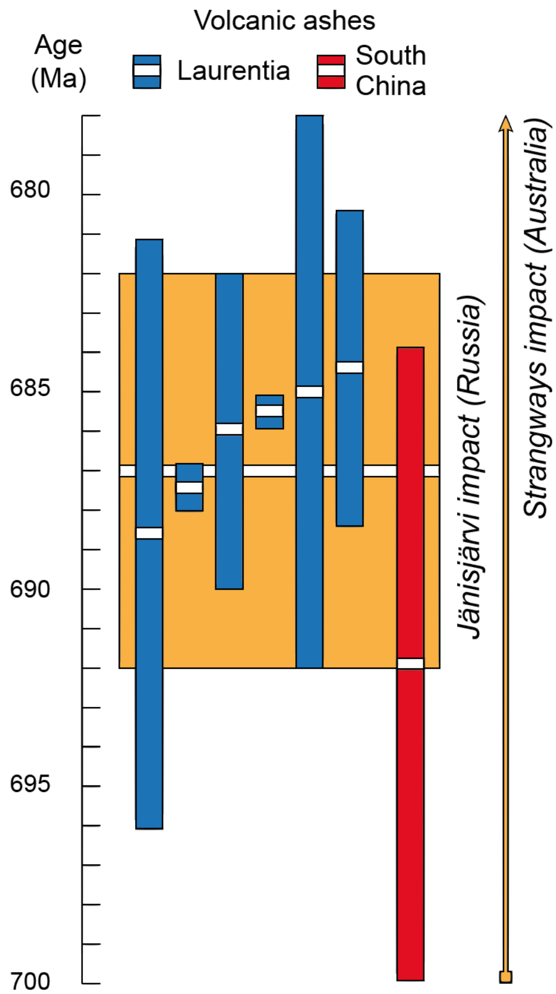

Fig. 2. The relative timing of impacts and ash falls during the Sturtian glaciation. Ages for volcanic ashes as reported for Laurentia (blue) reported by Rooney et al. (2015) and South China (red) by Lan et al. (2015). Ages for the Jänisjärvi impact of Baltica (yellow box) and Strangways impact of Australia (yellow arrow) were both recalculated by Schmieder and Kring (2020); see text for primary references.

The simplest explanation for the preservation of multiple ash falls is a temporary glacial retreat and open ocean conditions at this time allowed volcanic ash emitted in plumes in the atmosphere to settle through the water column. It has been argued that moulins (i.e., vertical shafts in glaciers formed by meltwater percolation) at low-latitudes where sublimation was high could flush ash falls into a snowball ocean (Hoffman et al., 2017). However, it is questionable whether such a process could deposit coherent ash layers because volcanic ash flushed through an ice shelf and reworked until finally deposited beyond the ice grounding line would likely be strongly diluted by abundant terrigenous glacial detritus. Furthermore, the moulin model cannot easily account for the temporal rarity of ash layers as well as the spatiotemporal similarity of the observed tuffs (Figs. 1, 2, and 3), as during the Sturtian low-latitude continents were widespread (Fig. 3A); the moulins should have only been distributed at all continental margins within ~15˚ of the equator (Hoffman et al., 2017).

It could also suggest that the ash layers could be hydrovolcanic; however, the tuffs contain abundant dateable zircon in each of the tuffs (Lan et al., 2015; Rooney et al., 2015), which indicates they were most likely derived from evolved continental volcanic arcs. Furthermore, consistent with our interpretation of ash layers as evidence of open ocean conditions, tuffs also occur both early and late in both the Sturtian and Marinoan glaciations, i.e., during glacial advance and retreat, respectively (Prave et al., 2016; Rooney et al., 2015). Thus, the next question is whether the open ocean model can account for the ash falls being restricted to these two, or at least only a few, continents.

3. Paleogeography and ice dynamics

Sturtian paleogeography indicates that of the five continental margins exhibiting evidence for transient open ocean conditions, three (Laurentia, South China, and Australia) were nearest neighbors surrounding a shared restricted seaway, Namibia (Congo craton) also had a restricted seaway, and Scotland (northeastern Laurentia, facing the Baltica craton) was nearest to the Jänisjärvi impact, one of the two craters known from this time interval (Fig. 3A). The presence of restricted seaways is also supported by an alternative paleogeography, but would imply the existence of a third such seaway (Fig. 4). All three continents experienced mafic magmatism between 830-720 Ma immediately preceding the Sturtian glaciation that has been interpreted as related to plume magmatism facilitating the breakup of supercontinent Rodinia (Li et al., 2008). The restricted seaway(s) between these continents may have just opened up at this time, or already existed as an embayment within Rodinia (Jing et al., 2020).

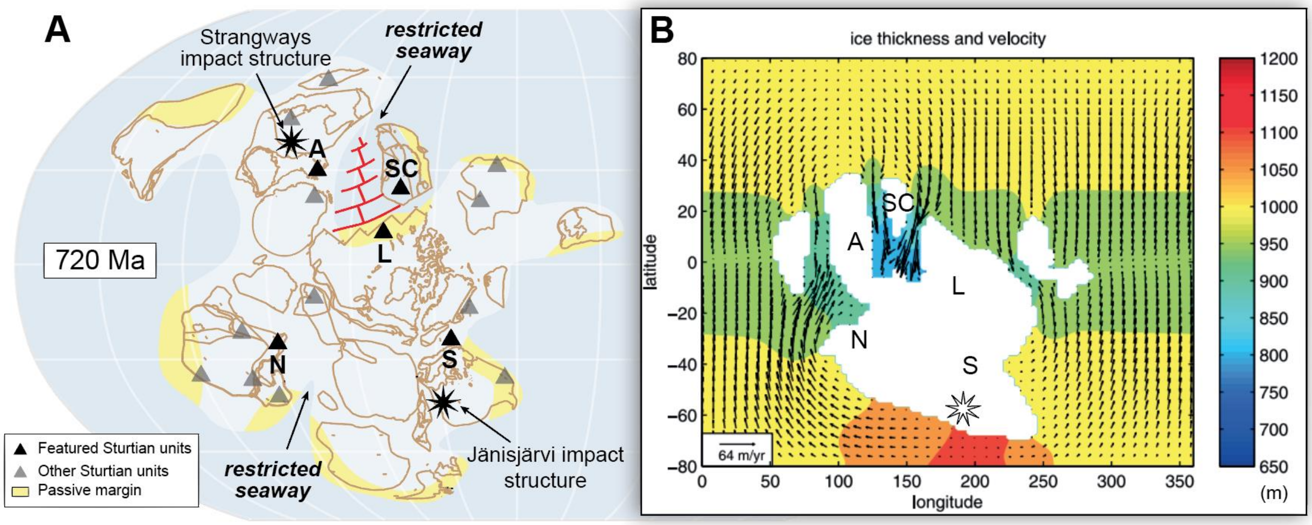

Fig. 3. Continent, ocean, and ice configurations during the Sturtian glaciation. (A) Paleogeography ca. 720 Ma (Li et al., 2013). Note pronounced embayment or restricted seaway due to coeval rifting in between Laurentia (L), Australia (A), and South China (SC), and another east of Namibia (N). An alternative position for South China is also consistent with our hypothesis but involves a third restricted seaway (Fig. 4). (B) Sea-ice flow and thickness modeled according to a similar paleogeographic arrangement at ca. 630 Ma (Li et al., 2008) indicating sea-ice thinning within the embayment due to continental constriction (Tziperman et al., 2012). Locations of each basin in Figure 1 are shown: N, Namibia; A, Australia; SC, South China; L; Laurentia; S, Scotland.

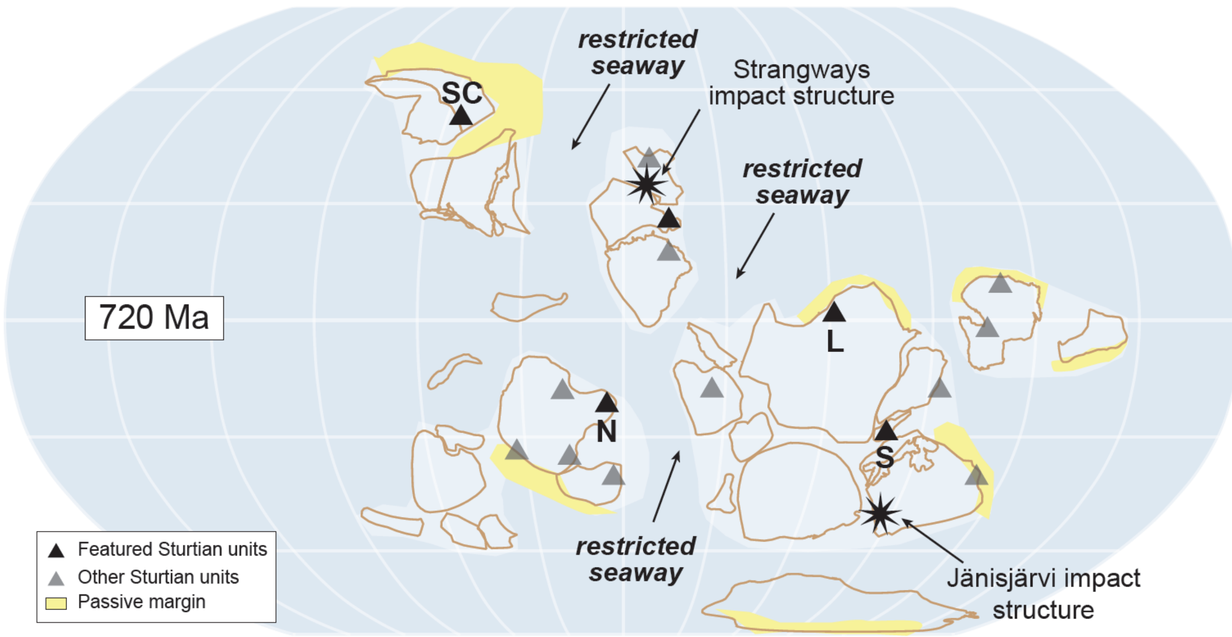

Figure 4. Paleogeography ca. 720 Ma (Merdith et al., 2017). Compare with Figure 3A.

Such seaways would have played a pivotal role in the dynamics and distribution of Sturtian sea ice. When considered only in one dimension (i.e., latitude), snowball sea-ice thickness is essentially uniform, behaving like a "sea glacier" where thicker areas of ice flow gravitationally, thickening initially thinner areas (Hoffman et al., 2017). Two-dimensional sea-ice modeling (i.e., latitude and longitude) accounts for the distribution of Neoproterozoic continents and depicts considerable variation in ice thickness in restricted seaways (Campell et al., 2011; Tziperman et al., 2012) (Fig. 3B). Ice flow through narrow passages is faster since there must be a balance with total ice melting and evaporation; faster ice flow will prevent homogenous sea-ice thickening that occurs throughout the rest of the snowball ocean (Tziperman et al., 2012). Thus, open ocean conditions during a snowball Earth is most likely to occur in restricted seaways where sea-ice is thinnest. Nonetheless, some additional forcing is still needed to explain the observations requiring ice-free ocean.

4. Snowball impact hypothesis

As "waterbelt" climate solutions are plausible but unable to accommodate the geologic evidence for predominantly limited air-sea-gas exchange characteristic of a snowball Earth (Hoffman et al., 2017), we seek an exogenic forcing to explain the temporary glacial retreat of a hard snowball Earth. We note that the ~14 km diameter Jänisjärvi impact crater in Russia (southern Baltica) is well-dated with Ar-Ar on impact melt rock at 687 ± 5 Ma (Jourdan, 2012; Jourdan et al., 2008; Schmieder and Kring, 2020) and coeval with the well-dated volcanic ash falls preserved in Laurentia and South China (Fig. 2). Also overlapping with the Sturtian glaciation, albeit with considerable uncertainty, is the ~25 km diameter Strangways impact crater in north Australia dated with Ar-Ar on impact melt rock at 657 ± 43 Ma (Schmieder and Kring, 2020; Spray et al., 1999). Both ages have been recalculated using the most currently revised K decay constants and monitor ages (Schmieder and Kring, 2020). The Jänisjärvi impact coincides with and occurs around the average age of the ash falls (Fig. 2). The coincidence motivates consideration of a potential cause and effect relationship between the Jänisjärvi impact and the temporary glacial retreat.

It is also likely that other impacts have not yet been discovered, or more likely, not preserved from the time of the Sturtian glaciation. For example, impacts that occurred in the circum-supercontinent Mirovoi Ocean constituting >75% of Earth's surface area would have been lost over time due to subduction. The lunar cratering record has 4 (potentially 6) impacts during the Sturtian glaciation (Mazrouei et al., 2019) (Table 1). Given Earth's substantially larger target size than that of the Moon, at least 21 terrestrial impacts are expected to occur for every lunar impact

(Mazrouei et al., 2019). Based on the lunar cratering record, therefore, as many as 84 terrestrial impacts could feasibly have occurred during the Sturtian glaciation. On this basis, during the interval between 717-661 Ma when 8 craters with diameter (D) >10 km formed on the Moon (Table 1), about 160 diameter (D) >10 km craters would correspondingly have formed on Earth over the same period.

Terada et al. (2020) dated 58 D >20 km lunar craters over the last ~2.5 billion years, and found that 2 D >20 km lunar craters formed during the equivalent interval to the Sturtian glaciation on Earth. Based on the lunar crater size distribution, the ratio of D >20 km craters to D >10 km craters on the Moon from the lunar crater size distribution is approximately a factor of 3.6. Accordingly, 2 D >20 km craters correspond to 7 D >10 km craters on the Moon, which is about the same value as that from Mazourei et al. (2019). Therefore, it is reasonable to conclude that 140-160 D >10 km craters and 40 D >20 km craters formed on Earth during the Sturtian glaciation. Then, using the crater size distribution formed on the Moon since 3 Ga (McEwen et al., 1997; Wilhelms et al., 1978), the likely occurrence of 40 D >20 km craters on Earth implies that the probability of a single D 100 km crater (i.e., Popigai-sized) formed during the same interval is high. This possibility is intriguing because a Popigai-sized crater formation would significantly affect the climate of the planet.

Provided that snowball continental ice sheets were as thick as 6 km (Creveling and Mitrovica, 2014), it is estimated that most impactor sizes would have only excavated ice and not reached bedrock to preserve an impact crater (Kring, 2003). In the case of the Jänisjärvi crater, the Rb and Sr isotopes of its impact melt are notably out of equilibrium with the target sedimentary rock

(Larionova et al., 2006), which is indicative of the short amount of time for equilibration between the impactor and the bedrock, and possibly due to interaction with ice instead of bedrock. Thus, while there is strong evidence for at least one impact during the Sturtian snowball Earth, there are compelling reasons to believe there could have been more, perhaps even an asteroid breakup event at this time as implied by the lunar record. An asteroid shower has recently been identified at ca. 800 Ma (Terada et al., 2020). There is often a substantial delay between asteroid breakup and when the debris impacts Earth that can be, depending on the family in question, millions of years (Zappalà et al., 1998) or even hundreds of millions of years (Vokrouhlický et al., 2017). Therefore, the Jänisjärvi impact may be terrestrial evidence of the pre-Sturtian asteroid breakup event inferred from the lunar record. A final consideration is that if the Jänisjärvi impact actually occurred under kilometers of glacial ice, then the impactor would have to have been much larger than the existing scar in the Karelia implies, which would have effectively made it a rarer event overall. Thus, whether the Jänisjärvi impact acted alone or not is uncertain.

Table 1. Lunar craters of the age of the Sturtian glaciation (ca. 717-661 Ma). From Mazrouei et al. (2019).

Names	Longitude (°E)	Latitude (°N)	Diameter (km)	Age (Ma)
Reimarus H*	62	-49	11	640
No name*	166	36	12	645
Das*	223	-27	36	657
Nicolai A	24	-42	14	669
No name	215	6	13	678
Eichstadt G	279	-22	12	686
No name	200	-45	12	708
Pythagoras K*	284	67	13	732

*Ages outside of Sturtian age, but within uncertainty.

The fact that a well-dated impact is coeval with, and most likely immediately pre-dates, multiple well-dated ash falls that correspond with sedimentological evidence for a glacial retreat during the Sturtian glaciation suggests that the impact may have caused temporary glacial retreat. Previous suggestions have been made concerning the climatic effects of an impact during a snowball Earth (Erickson et al., 2020; Koeberl and Ivanov, 2019; Kring, 2003). With an impact into ice, the most profound effect would be the vaporization of the impacted ice sheet and the injection of a water vapor plume into the stratosphere. Estimates of the magnitude of H_2O released on the order of 10^4 GT (Erickson et al., 2020; Kring, 2003) (varying by impactor size and ice sheet thickness) would represent as much as 8 orders of magnitude more water vapor than resides in the present stratosphere (Kring et al., 1996). Since water vapor is a highly efficient greenhouse gas, it was suggested that impact-induced global warming could even trigger snowball deglaciation (Erickson et al., 2020; Kring, 2003). However, subsequent studies of deglacial facies found no compelling evidence of any geochemical or mineralogical signatures of an impact (e.g., enrichments in siderophile element abundances or the presence of Cr-spinels or shocked minerals) for either the Sturtian or the Marinoan snowball Earths (Gyollai et al., 2014).

Whereas an impact may be insufficient to terminate a snowball Earth, impact modeling (Erickson et al., 2020; Koeberl and Ivanov, 2019) suggests that the large resultant water vapor plume would strongly perturb Earth's atmosphere, and if sufficiently long-lived, might yield sufficient warming to cause sea-ice-free conditions in continental embayments such as those that existed between Laurentia, Australia, and South China, as well as near Namibia, both regions being specifically the only areas where ice flow modeling parameterized by paleogeography (Tziperman et al., 2012) indicates sea ice was already thin (Fig. 3B). After the temporary and localized impact-induced glacial retreat, glacial re-advance would have occurred due to the still substantial albedo effect of a snowball Earth overcoming the transient greenhouse warming. While this hypothesis requires further testing, it does reconcile geologic observations indicating temporary glacial retreat during a largely “hard” and long-lived Sturtian snowball Earth.

5. Pros, cons, and predictions

This hypothesis pointing to a potentially understudied aspect of snowball climatology—localized and temporary meltback due to impact—provides impetus for further testing. The most obvious prediction of the hypothesis would be direct evidence of impact, either geological (e.g., tektites, shocked minerals, Cr-spinels, or siderophile element enrichments) or geochemical (e.g., Ir or ^{3}He anomalies), in the basal facies associated with glacial meltback in the middle of the Sturtian in those basins identified here (Fig. 1). Searches for such evidence of impact have been conducted on the Sturtian glaciation already, with no such evidence being found, but both studies (Bodiselitsch et al., 2005; Gyollai et al., 2014; Peucker-Ehrenbrink et al., 2016) targeted glacial termination facies (i.e., cap carbonates) in an attempt to test whether impact caused deglaciation—in contrast to our hypothesis of temporary meltback during the middle of the Sturtian.

One strength of our hypothesis is that the well-dated tuff layers are synchronous with each other and with the well-dated Jänisjärvi impact crater (Fig. 2). But a weakness is that the intervals of BIF, mudstone, and sandstone purported to signify temporary meltback during the Sturtian glaciation (Fig. 1) are more difficult to date. Nonetheless, such a goal is something to aim for as the most apparent stratigraphic prediction of our hypothesis is that these interlude facies should be globally synchronous and of similar duration in each basin in which they occur. Another pro of the hypothesis is that it is independent of which available paleogeographic reconstruction is preferred (Figs. 3A and 4). But a con is that because Rodinia reconstructions are controversial and still being refined, the predictions for which basins were part of restricted seaways are loosely defined. Integrating realistic ice flow modeling with refined paleogeography could be utilized to test our hypothesis. Lastly, more sophisticated modelling of impact-induced climate perturbations specifically designed for snowball Earth should provide an additional means of testing the hypothesized connection between impact and transient glacial retreat in restricted seaways.

Acknowledgements

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