

Did the transition to plate tectonics cause Neoproterozoic Snowball Earth?

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Abstract

When Earth's tectonic style transitioned from stagnant lid (single plate) to the modern episode of plate tectonics is important but unresolved, and all lines of evidence should be considered, including the climate record. The transition should have disturbed the oceans and atmosphere by redistributing continents, increasing explosive arc volcanism, stimulating mantle plumes and disrupting climate equilibrium established by the previous balance of silicate-weathering greenhouse gas feedbacks. Formation of subduction zones would redistribute mass sufficiently to cause true polar wander if the subducted slabs were added in the upper mantle at intermediate to high latitudes. The Neoproterozoic Snowball Earth climate crisis may reflect this transition. The transition to plate tectonics is compatible with nearly all proposed geodynamic and oceanographic triggers for Neoproterozoic Snowball Earth events, and could also have contributed to biological triggers. Only extraterrestrial triggers cannot be reconciled with the hypothesis that the Neoproterozoic climate crisis was caused by a prolonged (200–250 m.y.) transition to plate tectonics.

1 | INTRODUCTION

It is important to understand when and how plate tectonics began and what Earth's tectonic style before this was. In the following essay, we follow the modern redefinition of plate tectonics by Stern and Gerya (in press): "A theory of global tectonics powered by subduction in which the lithosphere is divided into a mosaic of strong lithospheric plates, which move on and sink into weaker ductile asthenosphere. Three types of localized plate boundaries form the interconnected global network: new oceanic plate material is created by seafloor spreading at *mid-ocean ridges*, old oceanic lithosphere sinks at *subduction zones*, and two plates slide past each other along *transform faults*. The negative buoyancy of old dense oceanic lithosphere, which sinks in subduction zones, provides major power for plate movements." When Earth began to behave this way and how we can use the climate record to shed light on the transition to plate tectonics, as defined above, is the crux of this paper.

Understanding the evolution of plate tectonics on Earth is key to understanding how our planet became habitable. We know that Earth formed hot and has since been cooling. Geodynamic modelling

indicates that Earth's interior had to cool by a few hundred degrees in order for sustainable subduction and thus plate tectonics to happen. Cooling caused greater strength and density of oceanic lithosphere, which promoted long-lasting subduction (Gerya, Stern, Baes, Sobolev, & Whattam, 2015). The geodynamic transition from a single-plate (stagnant lid) tectonic style with plume-induced short-lived lithospheric drips and embryonic subduction zones to global modern-style plate tectonics, with deep and long-lived subduction, reflected the thickening, strengthening and densification of oceanic lithosphere due to mantle cooling. It is uncertain when this transition occurred and how long it took to generate the modern plate mosaic.

Most geoscientists think that plate tectonics began early in Earth history, particularly in Archaean time (Cawood, Kroner, & Pisarevsky, 2006; Korenaga, 2013). Nevertheless, it is increasingly clear that Earth went through major tectonic changes in Neoproterozoic time (e.g. Brown, 2010; Ernst, Sleep, & Tsujimori, 2016; Hawkesworth, Cawood, & Dhuime, 2016). It is worth further considering whether this was when plate tectonics as defined above began. Geological evidence is critical (Figure 1), including the observations that most ophiolites — direct indicators of seafloor spreading and thus plate

tectonics — are Neoproterozoic and younger (Figure 1b) and that all blueschists and ultra-high pressure (UHP) metamorphic terranes — direct evidence of deep subduction and thus plate tectonics — are Neoproterozoic and younger. Perspectives from other geoscientific disciplines are useful in this inquiry, for example studies of gemstones and kimberlites. Rubies only form in continental collision zones and jadeitite only forms in subduction zones, and both of these “plate tectonic gemstones” are limited to Neoproterozoic and younger time (Figure 1c,d).

Kimberlites — the water- and carbon dioxide-charged eruptions that carry diamonds from deep in the lithosphere to the surface — are concentrated in Neoproterozoic and younger time (Figure 1a), perhaps because large volumes of these volatiles were not delivered to great depth in the mantle before subduction and plate tectonics began at this time (Stern, Leybourne, & Tsujimori, 2016).

Below, we build on the well-founded assumption that the transition to plate tectonics would have resulted in major changes in the solid Earth system — possibly including the spin axis, volcanism and topographic relief — and that these changes would have profound effects on Earth's climate and related systems. Specifically, we use the work of other geoscientists to explore the possibility that the major shifts in climate and the C isotopic record known as “Neoproterozoic Snowball Earth” (NSE) were caused by a prolonged (~250 Ma) transition from stagnant lid tectonics > ~800 Ma to a global plate tectonic regime by ~550 Ma. We first state our assumptions and outline what is known about Earth's tectonic regime before the NSE. We then summarize our present understanding of the timing and causes of NSE and show how NSE could have been the response of Earth's climate and hydrosphere to the transition to plate tectonics. We acknowledge that such an exploration of links between fundamental changes in Earth's tectonic and climate systems cannot yet be definitive, but we do think that it is novel and useful.

2 | PREMISES

We can informally define the moment that something changes in an important way as a singularity. Some singularities are obvious: they start with a bang and leave clear evidence. As an example of a “loud and clear” singularity, consider the beginning of thermonuclear fusion in the core of the Sun ~4.5 Ga. This may have resulted in an explosion, powerful enough to blow away the atmospheres of the inner planets. Other singularities leave little evidence when they occur and take many millions of years to affect their surroundings. The origin of life — the first self-replicating cell — may have been such a cryptic singularity, with clear evidence for life appearing much later in fossil stromatolites and C isotopic compositions of carbon-bearing sediments. The beginning of plate tectonics may not have occurred as a singularity, but instead over an extended period of time. We do not know the duration of the transition from a stagnant lid one-plate regime to a two-plate embryonic plate tectonic regime to the modern 12-big plate tectonic regime (Gerya et al., 2015). Did the transition require 10, 100 or 1000 million years to accomplish? Was it

smooth and continuous once underway, or was it episodic, with stops and starts? We have only begun to consider these questions.

We assume that the transition to plate tectonics (hereafter, “the transition”) disturbed the oceans and atmosphere enough to leave evidence in the sediment record. This is expected because as the number of plates grew, so did the global distribution of important plate-margin processes (e.g. increased H₂O and silica content and thus explosivity of magmas, increased CO₂ due to volcanic degassing, increased crustal thickening and relief above sea level and associated precipitation and weathering). This transition would have shifted the distribution of masses, resulted in albedo changes associated with ocean/land distribution, changed silicate weathering intensity and nutrient supply to oceans and associated CO₂ sinks. The transition is likely to have redistributed planetary mass by forming new subduction zones at intermediate-high latitudes to sufficiently change Earth's moment of inertia and cause true polar wander. Any combination of these likely responses to the transition is likely to have catastrophically disturbed the regulation of Earth's surface temperature — namely the greenhouse-weathering thermostat. These expected linkages provide central assumptions of and motivations for this paper.

We acknowledge that many Neoproterozoic sediments are poorly dated and lack fossils for correlation; however, Earth's surface was dominated then as now by continuous sedimentary accumulations. The sedimentary record for the time periods of interest is sufficiently complete that it is usefully interrogated to see if it preserves evidence of the transition. If the climate record can be linked to the start of plate tectonics, then the higher resolution available from the associated sedimentary record may allow us to better understand the pace and timing of the transition than any of the direct proxies for plate tectonics: ophiolites, blueschists, etc.

In this exploration, we make no effort to evaluate the many proposed explanations for NSE. Instead, we build on our understanding that the transition from stagnant lid to plate tectonics should have strongly affected climate, show that such effects are in most cases consistent with inferred causes of NSE, note that such effects are not known from other times inferred for the start of plate tectonics (Note: the Huronian snowball Earth episode shown on Figure 1 occurs at a time that has not been advocated for when plate tectonics started), and comment on whether or not the duration of NSE is consistent with that expected for the transition to plate tectonics. We start by showing that the preceding tectonic regime in Mesoproterozoic time appears to have been a protracted stagnant lid episode.

3 | THE BORING BILLION: A MESOPROTEROZOIC STAGNANT LID EPISODE?

Before we consider how the transition might have caused NSE, we must consider Earth's tectonic and climatic regime before NSE. This was a protracted episode known as “The Boring Billion” (aka Dullest Time on Earth, Barren Billion, Earth's Middle Age) between 1.8 and 0.8 Ga that was characterized by remarkable environmental,

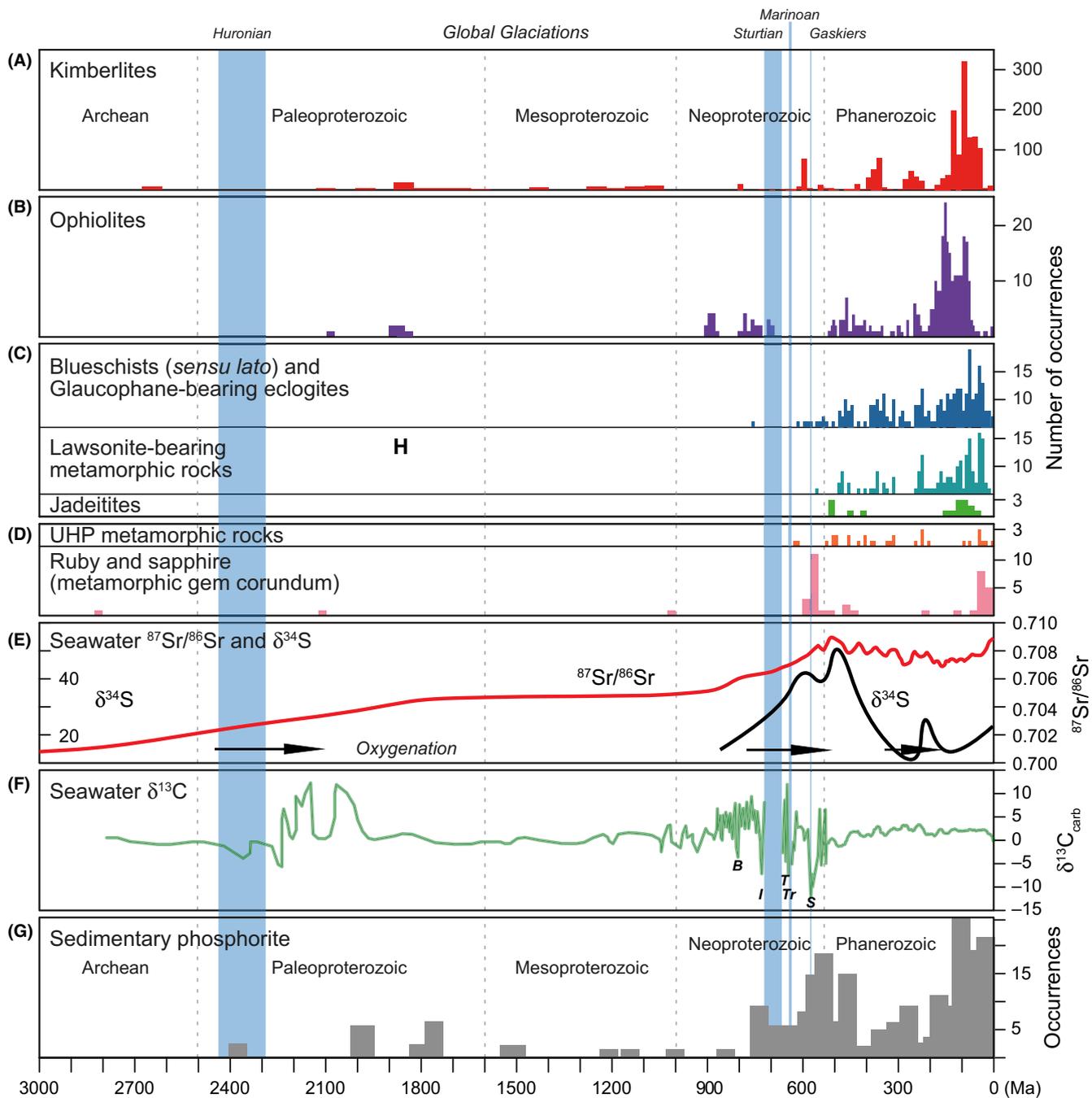


FIGURE 1 Comparisons of key petrotextonic indicators for plate tectonics and timings of major glacial episodes (vertical blue regions, after Cox et al., 2016) spanning the last 3 byrs. a) Kimberlites provide evidence of mantle ingassing due to subduction (Stern et al., 2016). b) Ophiolites provide evidence of seafloor spreading and horizontal motions consistent with plate tectonics (Stern, Leybourne, & Tsujimori, 2017; modified by Palaeoproterozoic ophiolites from Condie, in press). c) Indicators of subduction zone metamorphism — blueschists, glaucophane-bearing eclogites, lawsonite-bearing metamorphic rocks and jadetites — form only in the cool, fluid-rich environments in and above subduction zones (Stern, Tsujimori, Harlow, & Groat, 2013). d) Ultra-high pressure metamorphic rocks and the gemstone ruby proxy continental collision and deep subduction of continental crust (Stern et al., 2017). e) Seawater $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{34}\text{S}$ of carbonate rocks, and timing of giant P sedimentary deposits (after Shields, 2007). Note the rapid rise in $^{87}\text{Sr}/^{86}\text{Sr}$ during Neoproterozoic time, from ~ 0.705 to ~ 0.709 , indicating enhanced continental input. f) Seawater $\delta^{13}\text{C}$ curve. Curve > 900 Ma digitized from Young (2013, Figure 1), the 2600–1600 Ma portion follows Melezhik, Roberts, Fallick, Gorokhov, and Kuznetsov (2005); the 1600–920 Ma portion follows Kah (2004). The 540–920 Ma portion follows Cox et al. (2016), including LIPs; Neoproterozoic C-isotope excursions B, I, T, Tr and S denote Bitter Springs, Islay, Tayshir, Trezona and Shuram anomalies, respectively. The Phanerozoic portion follows Shields and Mills (2017); note this is a smooth of the composite curve. g) Sedimentary phosphorite abundance as represented by deposits (Planavsky, 2014) [Colour figure can be viewed at wileyonlinelibrary.com]

evolutionary and lithospheric stability (Brasier, 2012; Buick, Des Marais, & Knoll, 1995; Cawood & Hawkesworth, 2014; Holland, 2006; Young, 2013), although the formation of the Rodinia supercontinent occurred near the end of this interval. Cawood and Hawkesworth (2014) list seven characteristics of the Boring Billion: paucity of passive margins; absence of glacial deposits and iron formations; lack of significant seawater Sr-isotope spikes; lack of phosphate deposits (Figure 1g); high ocean salinity; abundant anorthosites and alkali granites; and limited orogenic gold deposits. Sr and C isotopic compositions of seawater-proxy carbonates change little during this time (Figure 1e, f). The Boring Billion was also a long time when deep oceans were substantially ferruginous/anoxic/euxinic and the complexity of life increased very slowly, possibly because high levels of plume activity and hydrothermal Fe input restricted oxygen to low levels while limiting the availability of important micronutrients (Lyons, Reinhard, & Planavsky, 2014 and

references therein); biological evolution is likely to be slower during stagnant lid episodes than during plate tectonic episodes, as discussed by Stern (2016). These characteristics are very like that expected from a stagnant lid episode, although we stress that we have much to learn about likely variations in stagnant lid behaviour (Stern et al., in press; Wyman, 2017).

4 | COULD THE TRANSITION TO PLATE TECTONICS HAVE CAUSED NEOPROTEROZOIC SNOWBALL EARTH?

Many explanations have been offered for what caused NSE. Table 1 parses these into 22 possible causative mechanisms placed into four groups: extraterrestrial, geodynamic, oceanographic and biotic. These four groups of mechanisms are differently susceptible to forcing by

TABLE 1 Possible causes of Neoproterozoic Snowball Earth and links to the transition to plate tectonics (TPT)

Class — Proposed events promoting cooling	Main cooling mechanism(s)	References	Caused by TPT?
Extraterrestrial			
1.1. Fainter Neoproterozoic sun	Lower (ed) insolation	H64	No
1.2. Collapse of orbiting ice rings into Earth's atmosphere	Lower (ed) insolation	S84	No
1.3. Variation in cosmic ray flux	Lower (ed) insolation	MM04	No
1.4. Variation in interstellar dust	Lower (ed) insolation	P05	No
1.5. Impact ejecta	Lower (ed) insolation	BB02	No
Geodynamic			
2.1. Colder, more seasonal, tropics due to high obliquity	High obliquity	W00	Yes
2.2. Low-latitude Rodinia after ~800 Ma true polar wander episode	Enhanced albedo & C sequestration	Li04	Yes
2.3. Low-latitude Rodinia (unspecified)	Enhanced albedo & C sequestration	HS02	Yes
2.4. Rodinia break-up	Enhanced C sequestration	D04	Yes
2.5. Rodinia break-up (elevated, diachronous rifting)	Tectonic uplift, active rift margins	EJ04	Yes
2.6. Rodinia break-up + basalt weathering	Enhanced C sequestration	G03	Yes
2.7. Rodinia break-up + basalt weathering + ocean fertilization	Enhanced C sequestration	H15, G16	Yes
2.8. Clathrate reservoir (tectonic?) exhumation and depletion	Loss of atmospheric methane	H02	Yes
2.9. Atmospheric sulphur aerosols — explosive volcanism	Lower (ed) insolation	S08	Yes
2.10. Atmospheric sulphur aerosols — LIP emplacement within S evaporite	Lower (ed) insolation	MW17	Yes
2.11. Reduced continent-volcanic arc activity	Lull in volcanic CO ₂ outgassing	M17	No
Oceanographic			
3.1. Ocean stagnation and enhanced organic burial	Enhanced C sequestration	K93	Yes
3.2. Carbonate burial depletes PCO ₂	Enhanced C sequestration	R76	Yes
3.3. Hypsometric effect — deeper CCD depletes PCO ₂	Enhanced C sequestration	R03	Yes
Biotic			
4.1. Methane destroyed by a Neoproterozoic oxidation event	Loss of atmospheric methane	P03	Yes
4.2. Biocatalysed weathering enhances PCO ₂ drawdown	Enhanced C sequestration	K06	Yes
4.3. Enhanced organic export production and anaerobic mineralization	Enhanced C sequestration	T11	Yes

References are intended to be representative, not exhaustive: H64, Harland, 1964a; S84, Sheldon, 1984; MM04, Marcos & Marcos, 2004; P05, Pavlov, Toon, Pavlov, Bally, & Pollard, 2005; BB02, Bendtsen & Bjerrum, 2002; W02, Williams, 2000, 2008; HS02, Hoffman & Schrag, 2002; D04, Donnadieu, Godd ris, Ramstein, N d lec, & Meert, 2004; EJ03, Eyles & Januszczak, 2004; G03, Godd ris et al., 2003; H15, Horton, 2015; G16, Gernon, Hinc, Tyrrell, Rohling, & Palmer, 2016; H02, Halverson, Hoffman, Schrag, & Kaufman, 2002; S08, Stern et al., 2008; MW17, Macdonald & Wordsworth, 2017; M17, McKenzie et al., 2016; K93, Kaufman, Jacobsen, & Knoll, 1993; R76, Roberts, 1976; R03, Ridgwell, Kennedy, & Caldeira, 2003; P03, Pavlov, Hurtgen, Kasting, & Arthur, 2003; K06, Kennedy, Droser, Mayer, Pevear, & Mrofka, 2006; T11, Tziperman, Halevy, Johnston, Knoll, & Schrag, 2011.

environmental changes resulting from the transition. Nearly, all of the 11 proposed geodynamic mechanisms could have been directly caused by the start of plate tectonics whereas the five extraterrestrial mechanisms cannot be related to the transition. The three oceanographic mechanisms and three biotic mechanisms could have been related to the proposed geodynamic factors (e.g. disruption of a stratified ocean, increasing nutrient delivery to oceans) and so are not addressed here. Below, we briefly consider how the 11 geodynamic mechanisms listed in Table 1 (numbers listed in parentheses) could have been caused by the transition from the Boring Billion stagnant lid episode to plate tectonics in Neoproterozoic time.

Earth's seasons are today controlled by modest obliquity of 23.5°; greater obliquity would make stronger seasonality. Unusually high obliquity (>54°) of Earth's spin axis to the ecliptic is suggested for pre-Edicaran glaciations (2.1). This is the HOLIST (High Obliquity, Low-latitude Ice, STRong seasonality) hypothesis (Williams, 2008). This could have been caused by mass redistribution such as may have occurred during the transition to plate tectonics. Ultimately, high obliquity may have transitioned to the more moderate obliquity of today by mass redistributions as a result of plate tectonics.

True Polar Wander (2.2; TPW) is a dramatic reorientation of Earth's rotation axis due to mass redistribution. Planets rotate such that the largest moment of inertia axis is aligned with the spin axis. When this is not the case because mass is redistributed, the spin axis realigns with that of the largest moment of inertia axis. When the first subduction zone formed during initiation of plate tectonics, the sinking lithosphere of the subducting plate beneath lithosphere of the overriding plate effectively increased the proportion of dense lithosphere where the first subduction zone formed, at the same time thinning lithosphere elsewhere on the planet, where the first spreading axis formed in response. The mass redistribution associated with the transition is thus very likely to have caused TPW. An episode of Neoproterozoic TPW would have greatly changed the distribution of planetary insolation, directly affecting climate. In addition, TPW may have concentrated landmasses within weathering intensive tropical latitudes, leading to NSE by enhanced global albedo and carbon sequestration in carbonate and organic-rich sediments.

Several workers previously proposed Neoproterozoic TPW. For example, Li, Evans, and Zhang (2004) used geochronological and palaeomagnetic data from 802 ± 10 Ma dykes in S. China and existing data to propose that Earth's spin axis underwent rapid $\sim 90^\circ$ rotation at ~ 750 Ma. They further suggested this TPW episode was triggered by initiation of a mantle superplume beneath the polar end of Rodinia. Similarly, Maloof et al. (2006) suggested two episodes of TPW, linked to Rodinian break-up and bracketing the ca. 820–790 Ma Bitter Springs negative $\delta^{13}\text{C}$ excursion, may have driven global changes in the flux of organic carbon relative to total carbon burial.

Another explanation for NSE is that supercontinent Rodinia moved to or amalgamated within low latitudes, thereby increasing planetary albedo and leading to cooling (2.3). Such a scenario is proposed by Meredith et al. (2017) on the basis of geological and

palaeomagnetic synthesis. Rodinia moving to low latitude is easily explained as caused by the transition.

Rodinia break-up (2.4) in association with various other processes is invoked as a cause for NSE. Ancillary contributions include uplift and weathering (2.5), basalt weathering (both subaerial and submarine; 2.6) and ocean fertilization (2.7). Break-up of the supercontinent Rodinia would have led to rift margin uplift and increased moisture delivery to continental interiors, increased runoff, increasing weathering and drawdown of atmospheric CO_2 , weakening the greenhouse and causing cooling. Large igneous provinces (LIPs) were more common in Neoproterozoic relative to Mesoproterozoic time (Ernst, Bleeker, Soerland, & Kerr, 2013), perhaps in association with increased rifting caused by the transition. There is abundant evidence for LIPs, erupted between 825 and 750 Ma in association with Rodinia break-up (Godd ris et al., 2003; Li et al., 2003). Pulses of 825–755 Ma tholeiitic magmatism are documented in Australia, NW Laurentia, South China and Congo cratons (Key et al., 2001; Li, Li, Kinny, & Wang, 1999; Park, Buchan, & Harlan, 1995; Wingate, Campbell, Compston, & Gibson, 1998; Wingate & Giddings, 2000). These underlie formations containing Sturtian/Rapitan glacial deposits. The length of dyke swarms, thickness of associated volcanics, and geochemistry indicate that the 825 and 780 Ma events are plume-related large continental basalt provinces, and all events may constitute a “plume time-cluster” (Ernst & Buchan, 2002; Godd ris et al., 2003).

As previously suggested by Godd ris et al. (2003), break-up volcanism is likely to have affected Neoproterozoic climate. This would at first lead to increased atmospheric CO_2 by magmatic degassing, increasing the greenhouse effect, and subsequently to consumption of carbon dioxide through terrestrial and submarine weathering that may have greatly decreased atmospheric carbon dioxide concentrations and weakened the pre-existing greenhouse. These possibilities indicate that tectonic changes could have triggered a progressive transition from a greenhouse to an icehouse climate during the Neoproterozoic era. All of these scenarios — Rodinia rifting, increased lengths of rifts and areas of rift flank uplift, and LIP volcanism — are expected in association with the transition. They are also consistent with increases in limestone $^{87}\text{Sr}/^{86}\text{Sr}$, sulphate $\delta^{34}\text{S}$, and marine P from chemical weathering of LIPs (e.g. Horton, 2015; Reinhard et al., 2017) (Figure 1E,G).

The huge swings in C isotopic composition observed in Neoproterozoic sediments, featuring distinct negative $\delta^{13}\text{C}$ excursions (Figure 1f. Bitter Springs, Islay, Tayshir, Trezona, Shurham events), imply correspondingly large variations in release and burial of organic carbon. Schrag, Berner, Hoffman, and Halverson (2002) (2.8) suggested that clathrate formation and exposure and depletion of clathrates might explain the $\delta^{13}\text{C}$ variations and that associated collapse of transient methane greenhouse states might trigger global glaciations. Clathrate formation and destruction could readily be accomplished by rapid burial of organic-rich sediments in new rift basins and exhumation by uplifts (Schrag et al., 2002). This conclusion is consistent with that of Shields and Mills (2017), who argued that tectonic controls were “underlying drivers” of C-isotope variations in

Neoproterozoic marine carbonates that were previously ascribed to organic carbon burial or to the changing isotopic composition of carbon sources. Tremendous changes in carbon sequestration and release are likely signatures of the transition.

Explosive volcanic eruptions — especially those associated with convergent margins and magmatic arcs — inject sulphur aerosols into the stratosphere; these aerosols reflect incoming solar radiation and cool the atmosphere and surface. Cooling as a result of increased explosive volcanism (2.9) may have caused NSE (Stern, Avigad, Miller, & Beyth, 2008). A similar effect was recently ascribed to LIP volcanism (2.10; Macdonald & Wordsworth, 2017). A transition to plate tectonics is very likely to have greatly increased explosive arc volcanism.

The last proposed geodynamic mechanism for NSE is that reduced continental arc igneous activity prior to the Cryogenian glaciation was responsible (2.11; McKenzie et al., 2016). We think that this conclusion is misleading. About 20% of the continental crust formed in Neoproterozoic time (Stern, 2008), so that if abundant Cryogenian arc sequences in especially the Arabian-Nubian Shield and elsewhere in Africa (Stern, 1994) were better captured in the McKenzie et al. (2016) compilation of U-Pb zircon ages that the significance of Cryogenian arc volcanism would be more truly represented. If future efforts confirm decreased arc volcanism during Cryogenian time, this would be a significant argument against a Neoproterozoic start for plate tectonics.

In summary, 10 of the 11 proposed geodynamic mechanisms for Neoproterozoic Snowball Earth are readily explained if the transition from stagnant lid to plate tectonics occurred during this time.

5 | DISCUSSION

The preceding presentation is based on the inference that the transition from stagnant lid to plate tectonics should disturb climatic and oceanographic stability, and that such disturbances are likely to have continued as the plate mosaic grew from one plate to two plates to the present 7+ plate system. We have shown that there are several ways that this transition could have disturbed the surface systems. We do not attempt to distinguish which of these actually happened or which were most important. The fact that strong climate and oceanographic effects are observed in Neoproterozoic time is a powerful supporting argument that this is indeed the time of the transition, and is an argument that — to our knowledge — has not heretofore been considered. The fact that other proposed times for the transition — for example at 3.0 Ga or 2.5 Ga — are not associated with comparable oceanographic or climatic disturbances weakens these as candidate times, although the available sedimentary record is admittedly sparse. The only time earlier in Earth history when a comparable climate disturbance is observed is the ~2.3 Ga (Huronian or Makganyene) glaciation, and this is not a time interval proposed for the transition to plate tectonics.

The other interesting point resulting from this discussion is that we now have a potential independent constraint for how long of a time it took for the transition from stagnant lid to formation of the first subduction zone to the development of a global plate tectonic network and when important episodes in this transition might have occurred. In this interpretation, each climatic and oceanographic episode might indicate formation of new subduction zones and associated rifts and spreading ridges that broke up the remaining stagnant lid, beginning with the Bitter Springs event ~0.8 Ga and ending with the mid-to-late Ediacaran glaciation (Etemad-Saeed et al., 2016). If this interpretation is correct, the transition took 200–250 Ma to accomplish. It may also be noteworthy that the duration of Late Neoproterozoic glaciations also decrease through time (Sturtian ca 720–660 Ma, Marinoan ca 650–630 Ma, Gaskiers ca 580 ± 1 Ma), potentially consistent with a progressively changing balance of silicate-weathering greenhouse feedbacks as the increasingly plate tectonic behaviour of the planet approached a new (Phanerozoic) equilibrium.

6 | CONCLUSIONS

Geological evidence constraining the timing of signature plate tectonic processes (e.g. ophiolites/sea floor spreading; UHPM/cold subduction) supports the hypothesis that the Neoproterozoic marked a prolonged transition from stagnant lid to modern-style plate tectonics. During this time, associated marine sedimentary proxies indicate extreme perturbations of the global carbon cycle (e.g. $\delta^{13}\text{C}_{\text{CO}_3, \text{OM}}$), an overall increase in silicate weathering (e.g. $\delta^{87}\text{Sr}/^{86}\text{Sr}_{\text{CO}_3}$ and $\delta^{34}\text{S}_{\text{SO}_4}$) and that Earth's climate regulating (greenhouse-silicate weathering) thermostat repeatedly failed leading to global scale glaciations (subtropical glacial deposits) for only the second time in Earth history. We posit that late Neoproterozoic climate oscillations inevitably followed from this tectonic transition, by disrupting the spatial distribution of continental landmasses, the nature of plate-margin processes, and the previous billion-year-long balance of silicate weathering greenhouse gas feedbacks. Environmental changes expected to accompany the transition to plate tectonics are consistent with nearly all postulated geodynamic triggers for late Neoproterozoic icehouse events and are not known to have accompanied other proposed times for the transition to plate tectonics. The possible linkage between the transition to plate tectonics, the pattern and severity of ensuing glaciations, and changing habitability on Earth is worth further consideration.

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