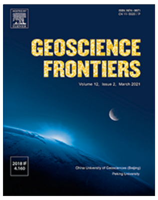
Geoscience Frontiers 14 (2023) 101553

Contents lists available at ScienceDirect

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf



Focus Paper

The Orosirian (1800–2050 Ma) plate tectonic episode: Key for reconstructing the Proterozoic tectonic record

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ARTICLE INFO

Article history:
Received 27 December 2022
Revised 11 January 2023
Accepted 17 January 2023
Available online 31 January 2023
Handling Editor: M. Santosh

Keywords:
Plate tectonics
Single lid tectonics
Urey ratio
Paleoproterozoic

ABSTRACT

Eight lines of evidence indicate that the Orosirian Period in mid-Paleoproterozoic time was characterized by plate tectonics: ophiolites, low T/P metamorphism including eclogites, passive margin formation, tall mountains, paleomagnetic constraints, ore deposits, abundant S-type granites, and seismic images of paleo-subduction zones. This plate tectonic episode occurred about 1 billion years earlier than the present plate tectonic episode began in Neoproterozoic time. The two plate tectonic episodes bracket the 'Boring Billion', which may have been a protracted single lid tectonic episode that began when the supercontinent Nuna or Columbia formed. Recognition of multiple lines of evidence for Orosirian plate tectonics demonstrates that Earth's tectonic style can be reconstructed with some confidence back to at least Early Paleoproterozoic time, and thus the absence of compelling evidence for Mesoproterozoic plate tectonics is not obvious due to poor preservation. A tectono-magmatic lull ~2.3 Ga suggests an earlier episode of single lid tectonics. Evidence for two episodes of plate tectonics and two episodes of single lid tectonics indicates that Earth switched between single lid and plate tectonics multiple times during the last 2.4 Ga.

1. Introduction

The controversy about when Plate Tectonics began and what came before continues to interest geoscientists (Palin et al., 2020; Roberts et al., 2022). Much of the controversy stems from disagreement about how far back in time the geologic record is well-enough preserved to be used to confidently interpret Earth's tectonic history. The continental crust preserves most of the geologic record, and this record becomes increasingly poorly preserved the farther back in time we look (Cawood et al., 2013). Preservation bias reflects the fact that erosion, burial, metamorphism, and crustal recycling combine to progressively remove evidence preserved in the crust, so that preservation is some function of age. Then there is the question of how to recognize evidence for a non-plate tectonic regime. Harrison and Lenardic (in press) implicitly highlighted these problems in articulating what they call Burke's Law: *If there's unambiguous evidence that global geodynamics is today dominated by plate tectonics, then we should assume it was operating since global silicate differentiation until we have evidence that it was not*. Burke's Law requires that the search for unambiguous evidence must first demonstrate that the evidence for or against ancient plate tectonics is sufficiently well-preserved to be useful for the period of interest. Burke's Law also places the burden of proof on demonstrating the existence of a non-plate tectonic regime. This is an imposing challenge because, in order to satisfy Burke's Law, we must answer three questions: (1) What might a non-plate tectonic regime be? (2) How can we recognize evidence for this in the rock record? And (3) How can we know that such evidence is preserved for the time of interest? Each of these questions is addressed in the following paragraphs.

Addressing the first question is both easy and difficult. It is easy because if an actively convecting silicate body like Earth does not have plate tectonics, it must have some kind of single lid tectonics. Plate tectonics is a global mosaic of independently moving plates, which move on and sink into weaker ductile asthenosphere as a result of subduction. Plates move relative to each other across three types of boundaries: divergent, convergent, and transform (Bird, 2003). The negative buoyancy of old dense oceanic lithosphere sinking in subduction zones mostly powers plate movements (Forsyth and Uyeda, 1975). Single lid tectonics contrasts with plate tectonics by having a single, unfragmented, all-encompassing lithosphere (Stern et al., 2018). However, answering the first question is difficult because there are many variants of single lid tectonics and we do not yet know the full range of these.

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https://doi.org/10.1016/j.gsf.2023.101553
1674-9871/

We know that the three other tectonically active silicate bodies in the Solar System – Venus, Mars, and Io – have single lid tectonics. Each shows a distinct single lid tectonic style (Stern et al., 2018). We are only beginning to explore the range of active silicate body single lid behaviors and terminology is still confusing. O'Neill and Roberts (2018) refer to stagnant, sluggish, plutonic squishy, and heat pipe variants whereas Fischer and Gerya (2016) refer to plume-lid tectonics. 'Sagduction' — the vertical sinking of weak lithosphere — is another vigorous non-plate tectonic style (Nédélec et al., 2017), as is catalytic delamination-driven tectonomagmatism (Bédard, 2006). Some workers call this basket of tectonic styles "stagnant lid" but this term is best reserved for convectively dead bodies like Mercury and our Moon, with surfaces that are mostly shaped by impacts. It needs emphasizing that single lid tectonic episodes are not necessarily times of no or even reduced magmatism and deformation, these can be just as intense and pervasive as plate tectonic episodes. This contrasts with stagnant lid, which have no igneous or tectonic activity.

Answering the second question — How can we recognize evidence for non-plate tectonic behavior in the rock record? — is also difficult, largely because we don't know the full range of single lid tectonic styles and thus our predictions of diagnostic indicators are handicapped. Because we are only beginning to explore the full range of single lid tectonic styles, we are at an even earlier stage of thinking about what in the rock record might be diagnostic for these. This contrasts with our excellent understanding of the diagnostic rock assemblages produced by plate tectonics. Stern (2018) identified three groups of rocks and minerals that only form by plate tectonics, called plate tectonic indicators (PTIs). These are: (1) ophiolites, indicators of subduction initiation and seafloor spreading; (2) blueschists, lawsonite-bearing metamorphic rocks, and jadeitite, indicators of subduction; and (3) ultra-high pressure (UHP) metamorphic rocks along with ruby and sapphire, indicators of continent–continent collision. Paleomagnetic measurements demonstrating major independent movements of multiple crustal blocks are also useful but showing that only a few blocks moved independently does not demonstrate a global plate mosaic.

What might single lid indicators (SLIs) be? Stern (2020) identified 3 groups for an inferred Mesoproterozoic (1600–1000 Ma) single lid episode: (1) dry magma indicators; (2) thermal insulation indicator; and (3) evidence of no passive margin formation. The first of these SLIs is based on the expectation that single lid tectonics would be much less effective in delivering water to the mantle than are plate tectonics and subduction zones and thus magmas should differ from especially modern arc magmas in being less hydrous. In fact, A-type granites and anorthosites — which formed from dry magmas — are unusually abundant among Mesoproterozoic igneous rocks. The second SLI is based on the inference that a single lid regime would insulate the mantle and retard cooling or even allow the body to heat up. This is consistent with calculated P/T thermobarometric ratios for metamorphic rocks through time, which show that the Mesoproterozoic was a time when the lithosphere stopped cooling and heated up (Brown and Johnson, 2019). The third line of evidence is the paucity of new passive continental margins that formed in Mesoproterozoic time (Bradley, 2008). Passive continental margins form when continents rift and drift apart as part of the Wilson Cycle. They form frequently in a plate tectonic regime but not in a single lid tectonic regime. Similar sets of SLIs will need to be developed for other single lid tectonic styles.

Making a strong argument that a particular interval in Earth history was a time of single lid tectonics and not plate tectonics requires demonstrating two things: (1) the presence of SLIs; and (2) the absence of PTIs. Transitions between single lid and plate tectonics are likely to take tens to hundreds of millions of years and these are likely to produce and preserve both PTIs and SLIs.

This gets us to the third question, that of preservation. Earth's tectonic history cannot be reconstructed back to the beginning, but it can be reconstructed with some confidence as far back as critical evidence is preserved. Given that we are only beginning to think about SLIs, it is better to focus on PTIs, about which there is much agreement. If PTIs are missing from some episode in Earth history — say, the Mesoproterozoic — this might reflect the absence of plate tectonics or it might be a preservation problem. In order to follow Burke's Law and make progress reconstructing Earth's tectonic history as far back in time as possible, we must address the preservation problem — question 3 — first. That is the main purpose of this paper: to show that the mid-Paleoproterozoic (2.1–1.8 Ga) rock record preserves multiple PTIs, indicating that the geologic record is adequate to allow reconstruction of Earth's tectonic style back at least this far and probably at least to the beginning of the Proterozoic.

This essay summarizes eight independent lines of evidence for a plate tectonic-like regime ~2.1–1.8 Ga, an interval that encompasses the Orosirian Period (2050–1800 Ma) in the Paleoproterozoic Era. Because Paleoproterozoic periods were established arbitrarily (Robb et al., 2004), it is not surprising that PTIs also occur a bit before and after the Orosirian. This was a distinct episode of plate tectonics that occurred prior to the modern episode, which began in Neoproterozoic time (Stern, 2018). The purpose of this paper is threefold. First is to demonstrate that evidence for Earth's tectonic history is adequately preserved for Paleoproterozoic time in order that its tectonic regime can be unambiguously identified as plate tectonics. Second is to use this assessment to argue that preservation should also be adequate to characterize the tectonic regime of the younger (1.6–1.0 Ga) Mesoproterozoic Era; specifically, that the paucity of Mesoproterozoic PTIs is not due to poor preservation. Third is to provide some context for the 2.3–2.2 Ga tectono-magmatic lull, which may have been an earlier single lid episode. Below we first summarize Paleoproterozoic tectonic history and then briefly summarize Orosirian PTIs before discussing the implications of these observations.

2. The Paleoproterozoic solid Earth system

The earliest global-scale orogenic belts developed during the Paleoproterozoic era (2500–1600 Ma; Fig. 1). Associated orogenic events include the 2.1–2.0 Ga trans-Amazonian and Eburnean orogens in South America and West Africa; the ~2.0 Ga Limpopo Belt in southern Africa; the 1.9–1.8 Ga trans-Hudson, Penokean, Taltson-Thelon, Wopmay, Ungava and Tornqat orogens in North America, the 1.9–1.8 Ga Nagssugtoqidian Orogen in Greenland; the 1.9–1.8 Ga Kola–Karelia, Svecofenian, Volhyn-Central Russian, and Pachema orogens in Baltica; the 1.9–1.8 Ga Akitkan Orogen in Siberia; the ~1.95 Ga Khondalite Belt and the ~1.85 Ga Trans-North China Orogen in North China, and the 1.8–1.6 Ga Yavapai and Mazatzal orogens in southern North America. This transcontinental and temporally restricted pattern of orogenic belts supports the formation of a Proterozoic supercontinent named Columbia or Nuna (De Olivera Chaves, 2021). One of the two most important peaks in continental crust production in Earth history as indicated by U-Pb zircon age histograms occurred at 1.8 Ga to 2.1 Ga (Puetz, 2018). There is no question that the mid-Paleoproterozoic witnessed a major tectonic episode of continental crust formation and deformation. The next section summarizes eight lines of evidence that the 1.8–2.1 Ga interval marks an important early episode of plate tectonics.

In contrast to strong tectonic and magmatic activity in mid-Paleoproterozoic time, the Early Paleoproterozoic witnessed the Tectono-Magmatic Lull (TML, 2365–2235 Ma). This was a time with less abundant granitic rocks and deformation, but no recognized age gap (Spencer et al., 2018; Condie et al., 2022). This was also a time when few basalts were erupted (Liu et al., 2020).

3. Orosirian plate tectonic indicators

Below we consider eight PTIs: ophiolites, eclogites, passive continental margins, tall collisional mountains, paleomagnetic constraints, hydrous fluid-sensitive ore deposits, S-type granites, and deep crustal geophysical imaging. These are distributed on all continents, as expected for a global plate tectonic mosaic.

Ophiolites are fragments of oceanic lithosphere thrust up on land and are key plate tectonic indicators (Stern, 2018). Ophiolites are missing from the Mesoproterozoic but Orosirian and slightly older examples are well known from North America, Europe, Asia, and Africa. Condie (2022) reported 7 ophiolites that range in age from 2150 Ma to 1850 Ma: two each from Canada and Scandanavia, one each from India, Greenland, and West Africa (Fig. 1). The preservation of these ophiolites on 4 continents is strong indication that a global plate tectonic mosaic existed 2.15–1.85 Ga.

Eclogites are a second PTI. Low T/P eclogites — produced in subduction zones today — formed at 1.7–2.09 Ga. Brown and Johnson (2019) compiled T, P, thermobaric ratio (T/P), and age (*t*) of metamorphism for 564 localities from the Cenozoic to the Eoarchean, dividing these into high T/P (>750 °C/GPa), Intermediate T/P (750–400 °C/GPa) and Low T/P (<400 °C/GPa) (Fig. 2). Low T/P metamorphic environments occur in subduction zones today. Ultra-low T/P environments capable of producing ultra-low T/P blueschists are restricted to Neoproterozoic and younger times. Although no blueschists are known from the Paleoproterozoic, four of five >1.0 Ga examples of low P/T metamorphism are Orosirian or slightly older, consistent with a proto-plate tectonic episode. These include the oldest known HP–LT eclogite worldwide (2089 ± 13 Ma; 17–23 kbar/500–550 °C), discovered in the Democratic Republic of the Congo (François et al., 2018). Imayama et al. (2017) concluded that the absence of Paleoproterozoic blueschist indicates that Orosirian subduction zones were warmer than younger subduction zones, consistent with the cooling of Earth's mantle over Earth history. Eclogitic rocks have been reported from Paleoproterozoic orogens all over the world with ages mostly of 2.09–1.70 Ga (Fig. 1), including the Trans–Hudson orogen and Snowbird tectonic zone in Canada, Belomorian Mobile Belt in Russia, Nagssugtoqidian Orogen in Greenland, Olekma granite–greenstone region in Siberia, and Nimrod Orogen in Antarctica. These eclogites are mostly hosted in orthogneiss (or Archean TTGs) and indicate geothermal gradients of 11–13 °C/km, representing continental subduction or thickening. Only Trans–Hudson Orogen eclogites show a low geothermal gradient of ∼8 °C/km, comparable with that in Phanerozoic subduction zones (Zhang et al., 2020). Moreover, some HP eclogites recording geothermal gradients of 12–14 °C/km were reported from Ubendian and Usagaran orogens, Tanzania (Boniface and Tsujimori, 2021). The wide distribution of HP eclogite facies rocks in 1.7 Ga to 2.09 Ga orogens suggests that plate tectonics operated during this time.

The creation of new passive continental margins is a third PTI. Passive continental margins are created when continents break up to form new oceans as part of the Wilson/Supercontinent cycle and are intimate aspects of a plate tectonic regime. Bradley (2008) shows a significant increase in passive margins at 1.8–2.1 Ga

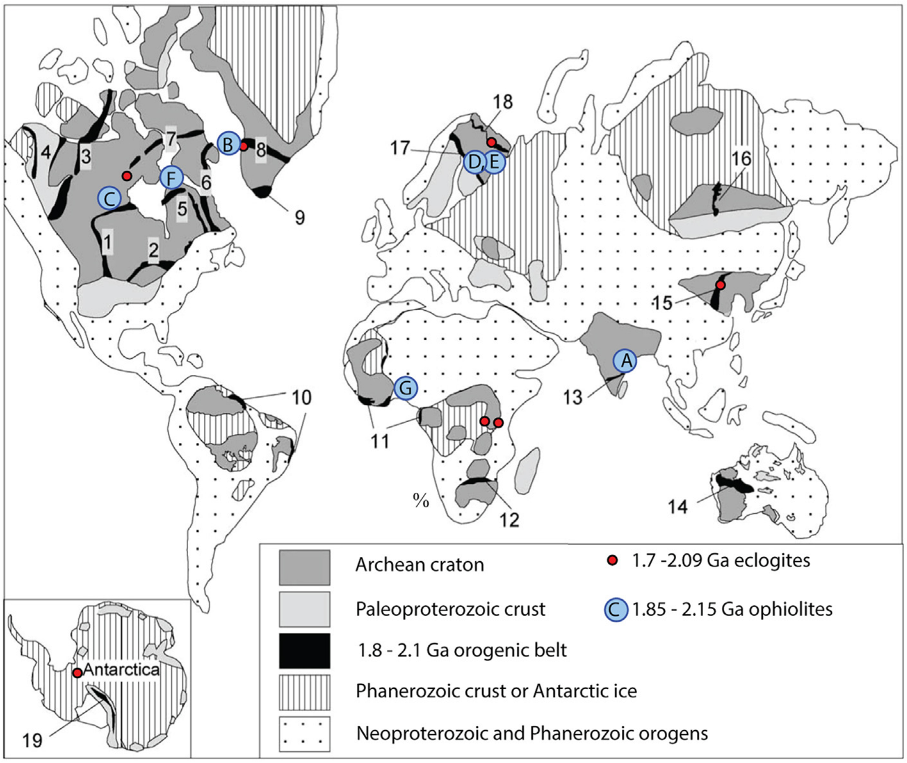

Fig. 1. Spatial distribution of 2.1–1.8 Ga orogens and associated Archean cratons. 1—trans-Hudson Orogen; 2—Penokean Orogen; 3— Taltson – Thelon Orogen; 4—Wopmay Orogen; 5—Cape Smith –New Quebec Orogen; 6—Torngat Orogen; 7—Foxe Orogen; 8— Nagssugtoqidian Orogen; 9—Makkovikian – Ketilidian Orogen; 10—Transamazonian Orogen; 11—Eburnian Orogen; 12—Limpopo Belt; 13—Moyar Belt; 14—Capricorn Orogen; 15—Trans-North China Orogen and Khondalite Belt; 16—Central Aldan Belt; 17—Svecofennian Orogen; 18—Kola– Karelian Orogen; 19—Transantarctic Orogen. Locations of Paleoproterozoic ophiolites shown with letters: A = Kandra (1850 Ma); B = Nagssugtoquidian (1900–1850 Ma); C = Amiski Flin Flon (1900 Ma); D = Jormua (1995 Ma); E = Central Karelia (2100 Ma); F = Purtuniq (1998 Ma); G = Mako Birimian (2150 Ma). Red dots show locations of 1.7–2.09 Ga eclogites and granulitized eclogites, including Belmorian Province, Russia (Li et al., 2023), Snowbird Tectonic Zone, Canada (Baldwin et al., 2004), Ubendian-Usagaran Belt, Tanzania (Boniface and Tsujimori, 2021), Hongqiyingzi Complex, Trans-North China Orogen, North China Craton (Zhang et al., 2020), Nagssugtoqidian Orogen (Müller et al., 2018), and Nimrod Orogen, Transantarctic Mts., Antarctica (Goodge et al., 2001). Modified after Zhao et al. (2002).

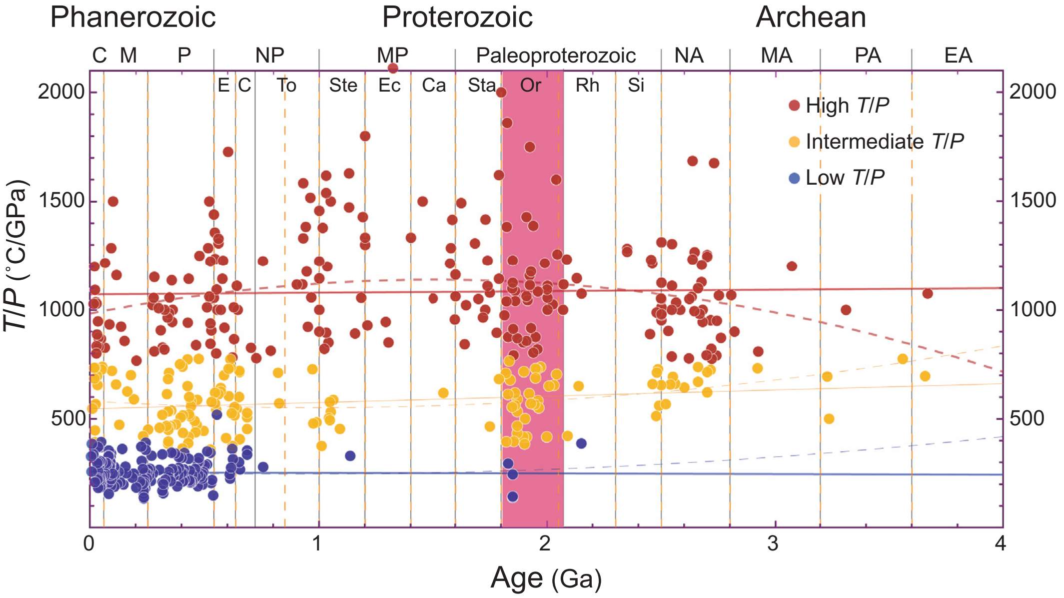

Fig. 2. Metamorphic thermobaric ratios (T/P) for 564 localities grouped by type plotted against age. The three types of metamorphism are high T/P in red, intermediate T/P in orange, and low T/P in blue. The Orosirian period is highlighted. Proterozoic stages: E = Ediacaran, C = Cryogenian, To = Tonian, Ste = Stenian, Ec = Ectasian, Ca = Calymmian, Sta = Statherian, Or = Orosirian, Rh = Rhyacian, Si = Siderian. Modified after Brown and Johnson (2019).

(Fig. 3A). Condie (2022) took a different look at the distribution of passive margins through time (Fig. 3B). There is considerable disagreement between the passive margin histograms of Bradley (2008) and Condie (2022), especially for the Mesoproterozoic, but both agree that the Orosirian was when more passive margins formed than any other time before the Neoproterozoic.

Formation of tall mountains as a result of continental collision is expected for plate tectonics. Zhu et al. (2022) used the distribution of low-Lu and low-Lu/Dy zircons, derived from the eroded roots of mountains, where trace amounts of zircon compete with abundant garnets for heavy rare earth elements, to identify periods of extensive high mountain (supermountain) formation. The data (Fig. 4A) reveals 3 main episodes of supermountain formation, interpreted to be when the average metamorphic pressure of orogenic belts exceeded 1.2 GPa, the pressure at which metamorphic garnet becomes abundant. The first supermountains formed in the Orosirian (~1.8–1.9 Ga), the second at 650–500 Ma during the amalgamation of Gondwana, and the third 300 Ma during Pangea formation.

Paleomagnetic measurements also offer potentially powerful insights into whether or not plate tectonics occurred during the Orosirian. Mitchell et al. (2014) and Swanson-Hysell et al. (2021) demonstrated that the Superior Province had a paleomagnetic pole that was similar to that of the Slave and Rae provinces, establishing the coherence of Laurentia following the ~1.8 Ga trans-Hudson orogenesis. This consistency supports interpretations that older discrepant 2.22–1.87 Ga pole positions between the provinces are the result of differential motion as a result of plate tectonics. A similar conclusion for the ~2.0–1.8 Ga motions of Laurentia and Baltica inferred from paleomagnetics, culminating in collision to form Nuna/Columbia ~1.8 Ga, was reached by Pesonen et al. (2021).

Some ore deposits are sensitive to delivery of fluids from subduction zones, especially porphyry copper and orogenic gold. These types of deposits are abundant in Neoproterozoic and younger time and are missing from the Mesoproterozoic (Santosh and Groves, 2023). Orogenic gold deposits are important in the Orosirian, as expected for this plate tectonic episode. Porphyry copper deposits of Orosirian age are known but are not abundant (Cawood and Hawkesworth, 2015). Modest peaks in carbonatite and kimberlite at this time also indicate somewhat enhanced fluid input to the mantle by subduction zones (Liu et al., 2023).

The inference of modestly enhanced water input in Orosirian subduction zones is consistent with the lack of "less-negative europium anomaly" zircons of this age (Triantafyllou et al., 2022). Such "less negative Eu anomaly" zircons are common in Neoproterozoic and Phanerozoic rocks. Triantafyllou et al. (2022) interpret the 0.9 Ga rise to record increasing hydration of magmagenetic sites due to the development of cold subduction systems, the water from which suppresses the saturation of plagioclase in magmas.

S-type granites may be a useful new PTI, especially for identifying continental collisions that cause supermountains. Granitic rocks are subdivided into three main groups based on the tectonic setting in which these melts normally form. A-type granitic rocks are associated with rifts, intra-plate, and continental backarc settings, I-type granitic rocks form above subduction zones, and S-type granitic rocks are produced by partial melting of pelitic metasediments. Unusual abundances of anhydrous magmas especially A-type granites and massif anorthosites are found for the Mesoproterozoic and are important reasons for identifying that Era as a single lid episode. These rock types are not abundant in the Osirian, as expected for a plate tectonic episode (Stern, 2020). In contrast, S-type granites, defined as strongly peraluminous, with $Al_2O_3/(CaO + Na_2O + K_2O) > 1.1$ (Chappell and White, 2001), are abundant in the Orosirian (Zhu et al., 2020). S-type granitic melts are most readily produced when thick sequences of turbidites — most commonly shed from collisional mountains like the modern Bengal and Indus fans — are squeezed and heated in collision zones as convergence continues (Zhu et al., 2020). Zhu et al. (2020) compiled zircon trace elements and U–Pb ages and used these to reconstruct the distribution of S-type granites through time (Fig. 4B). There is no peak for the most recent supermountains – the Himalaya – because erosion has not yet exposed and eroded these granitic rocks (aka Himalayan leucogranites) sufficiently, but the previous two continental collisions and supermountain-forming episodes — in the Late Paleozoic, to form the Pangean supercontinent and in the Ediacaran, to form Greater Gondwanaland — show clear peaks.

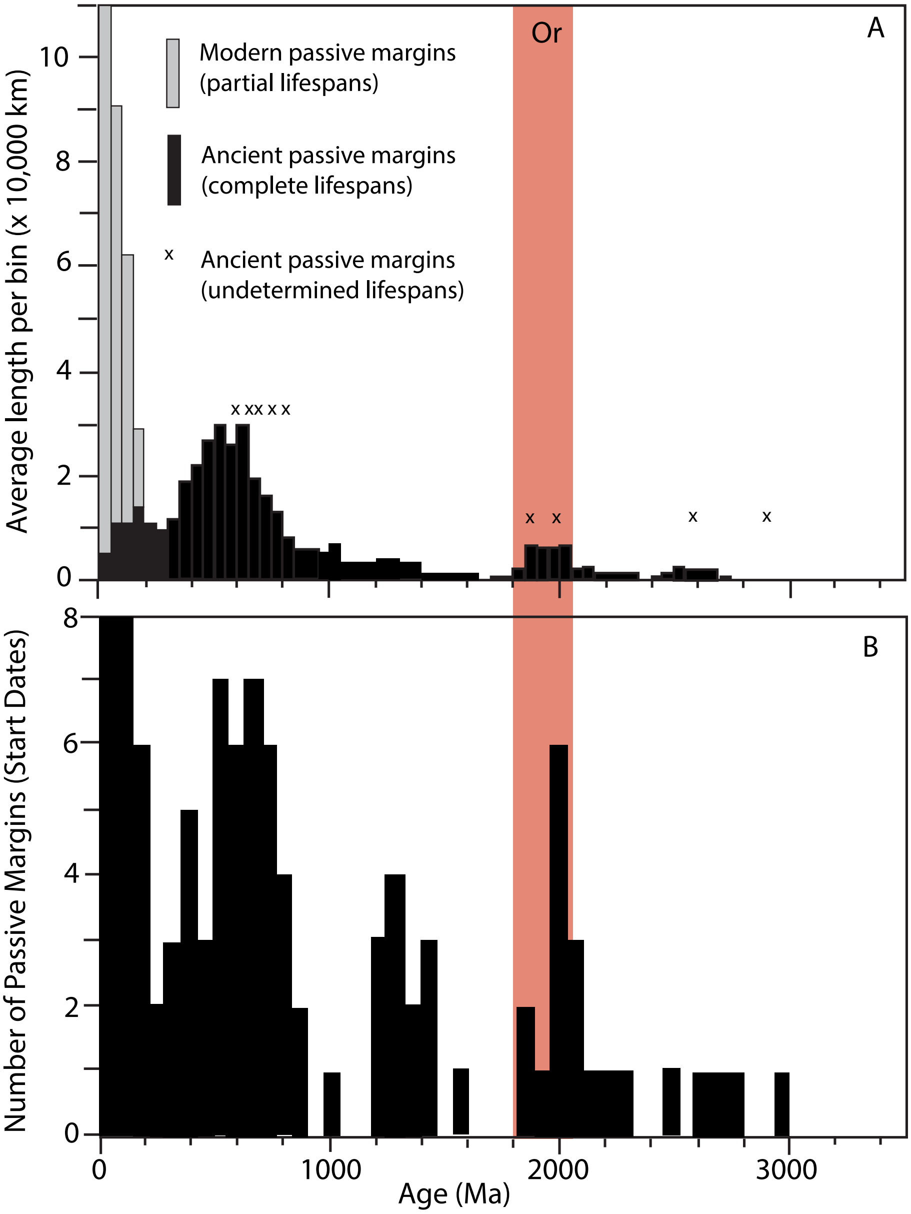

Fig. 3. (A) Histograms showing the age distribution of ancient and modern passive margins (Bradley, 2008). Bins are 50 m.y. in duration and each margin is weighted by length. Thus, a particular 1000-km-long passive margin that existed from 525 Ma to 375 Ma would contribute 1000 km to the height of four consecutive bins. (B) Distribution of passive margin start dates from 3 Ga onwards. Modified after Condie (2022).

Another small peak is seen for the Grenville Orogen ~1 Ga. There is a strong peak in S-type granite zircons ~1.8–1.9 Ga (Fig. 4B), consistent with continental collision, supermountain formation, and plate tectonics in Orosirian time.

Geophysical studies in Canada, Scandanavia, and China image crustal structures beneath 1.8–2.0 Ga that are reminiscent of modern subduction/collision zones (BABEL Working Group, 1990; Lucas et al., 1993; Wan et al., 2020), providing further evidence of Orosirian plate tectonics.

4. Discussion

From the above brief review of ophiolites, low T/P metamorphic rocks, passive continental margins, supermountains, paleomagnetics, ore deposits, granitic rocks, and geophysical imaging there can be little doubt that the Orisirian witnessed a significant episode of plate tectonics. This episode differed somewhat from the modern episode. For example, it was shorter (~300 Ma vs >700 Ma), lacked blueschists, preserved relatively few ophiolites, and seems to have injected less water into the mantle by subduction. Some of the implications of recognizing the Osirian plate tectonic episode are worth exploring.

First, inferring the operation of plate tectonics ~2 Ga from multiple lines of evidence indicates that preservation is sufficient to allow Earth's tectonic history to be reconstructed at least this far back in time. It was noted in the Introduction that satisfying Burke's Law first requires demonstrating that preservation is not a problem. Because so many PTIs are preserved for the Orosirian, we can be reasonably confident that preservation of geologic evidence for tectonic styles is adequate for at least the last half of Earth's history.

Second, while identifying compelling evidence for plate tectonics in the Orosirian is not a new contribution, interpreting this as a distinct early episode of plate tectonics is. Such identification is

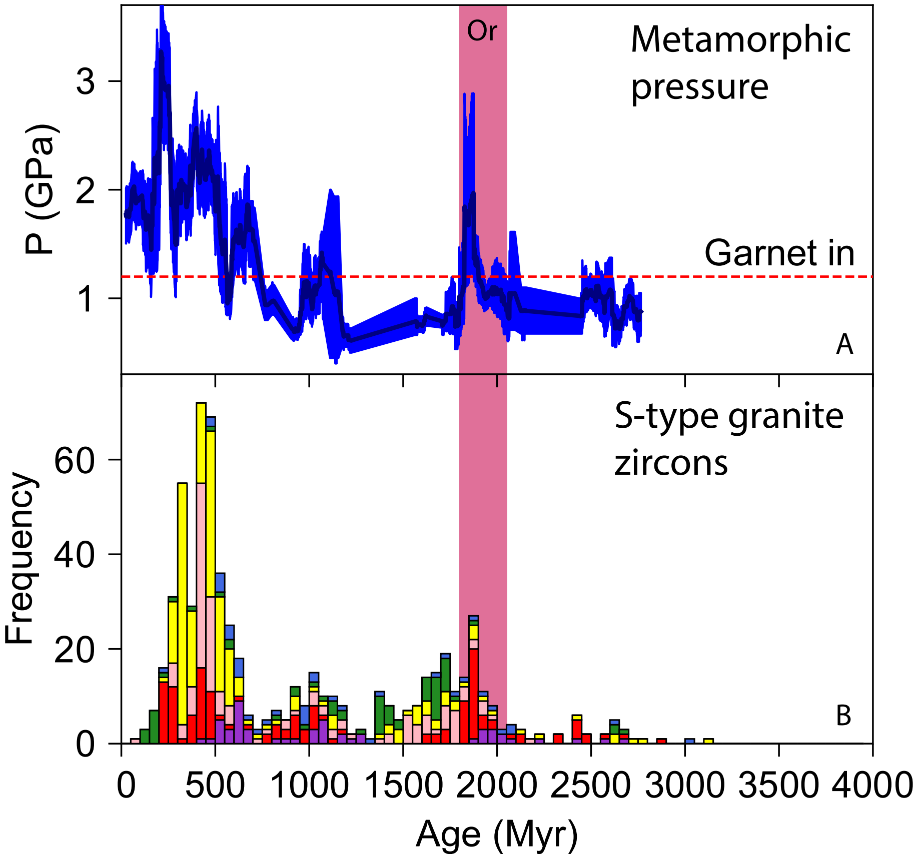

Fig. 4. Peak metamorphic pressures and S-type granite zircons, from Zhu et al. (2022). (A) A 50-Myr-bin moving average of the peak pressure of metamorphic rocks from Zhu et al. (2022). The uncertainty is presented as the 95 % confidence interval as generated by Monte Carlo analysis with bootstrap resampling. (B) S-type zircons (n = 653). Vertical pink band shows Orosirian (Or).

consistent with earlier suggestions for intermittent plate tectonics (Silver and Behn, 2008) and tectonic mode switching (Lenardic, 2018). Distinguishing two distinct plate tectonic episodes also helps clarify the controversy about when the modern episode of plate tectonics began, because now it is possible that the modern episode began in Neoproterozoic time although an earlier episode of plate tectonics also occurred.

A third implication of recognizing the Orosirian plate tectonic episode is that interpreting the Mesoproterozoic as a distinct and unusual tectonic episode is supported. Stern (2020) interpreted the Mesoproterozoic as a protracted single lid tectonic episode, an assessment that is questioned by others (e.g., Roberts et al., 2022). There are two reasons that recognizing the Orosirian plate tectonic episode supports the Mesoproterozoic single lid hypothesis. First, any purported distinct tectonic episode should be readily distinguished from the episode that came before as well as what came after. Identifying a distinct tectonic episode presupposes that something different happened before as well as after the episode in question. PTIs are scarce in the Mesoproterozoic but become increasingly abundant in the Neoproterozoic. The 8 lines of evidence for Osirian plate tectonics outlined above and those for the Mesoproterozoic summarized by Stern (2020) are very different, compelling the conclusion that these two tectonic episodes were fundamentally different. Second, the recognition of multiple lines of evidence for Orosirian plate tectonics and the absence of any of these from the Mesoproterozoic makes it unlikely that preservation is responsible. If the Mesoproterozoic did witness plate tectonics, PTIs should be as well or better preserved than those of the significantly older Orosirian period and they are not.

A fourth result is to provide context for the 2.3–2.2 Ga tectonomagmatic lull (TML; Spencer et al., 2018). The TML is likely to have been an earlier episode of single lid tectonics that was followed by the Orosirian plate tectonic episode. This suggestion is especially intriguing because it helps explain the “Great Oxidation Event” (GOE) ~2.3 Ga as caused by a decrease in O_2 sinks at this time. Evidence for oxygenic photosynthesis appeared much earlier, in the Archean, but the abundance of oxidizable gasses and rocks easily absorbed the O_2 that photosynthetic organisms excreted, with the result that the atmosphere remained anoxic for hundreds of millions (Kadoya et al., 2020). Production of readily oxidized volcanic gasses and rocks was greatly reduced during the TML, allowing O_2 to build up in the atmosphere and hydrosphere and cause the GOE.

Why did the Orosirian plate tectonic episode begin and end when it did? We can only speculate on what started this episode; it could have been a bolide impact (O’Neill et al., 2019) or perhaps the arrival of a large mantle plume head (Gerya et al., 2015). It is easier to infer what ended the Orosirian plate tectonic episode: formation of the supercontinent Nuna/Columbia. Plate tectonics depends on the operation of subduction zones and supercontinent assembly destroys these, especially if they are associated with the closing ocean (Silver and Behn, 2008). This may have been the situation for the Orosirian, with the 7 ophiolites (oceanic remnants) located in interior orogens (Silver and Behn, 2008). Because plate motions are mostly powered by the sinking of oceanic lithosphere in subduction zones (Forsyth and Uyeda, 1975), the destruction of subduction zones can stop plate tectonics, leading to establishment of a single lid tectonic regime. This seems to have been what hap-

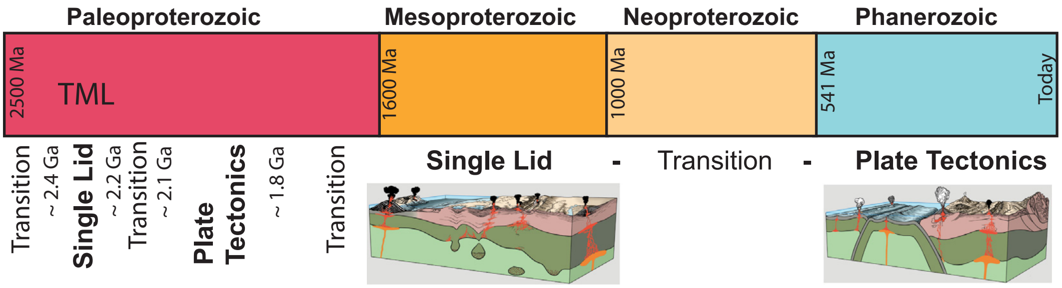

Fig. 5. Reconstruction of Earth's tectonic history for Proterozoic and younger times. See text for further explanation.

pened when the supercontinent Nuna/Columbia formed about 1.8 Ga.

Fig. 5 reconstructs Earth's tectonic history back to almost Archean times. Much more research is needed to test and refine this timeline. Of particular interest is the significance of the 1.8–1.7 Ga Yavapai and 1.7–1.6 Ga Mazatzal terranes in the SW USA (Whitmeyer and Karlstrom, 2007). These orogens have many characteristics of young accretionary orogens (Holland et al., 2020) although significant differences from modern arcs related to plate tectonics have been noted (Bickford and Hill, 2007). What is this broad terrane telling us about the transition from Orosirian plate tectonics to Mesoproterozoic single lid tectonics?

Identifying an earlier episode of plate tectonics separated from the present one by an intervening single lid episode also helps us better understand Earth's thermal history. There is increasing evidence that Earth has lost heat much more slowly than is predicted from a backward extrapolation of its present cooling rate. The ratio of Earth's internal heat production to heat loss is called the Urey Ratio (U_r; Korenaga, 2008). Best estimates of the modern U_r (~0.35) implies rapid cooling and this leads to unacceptably high mantle temperatures for ages >1 Ga [so-called thermal catastrophe] (Fig. 6), which did not occur. There are only two ways to explain this paradox. One is to assume a much higher value of U_r = 0.7 (Fig. 6). This is an unacceptably high value given our understanding of Earth's bulk composition, especially the concentration of heat-producing elements (K, U, Th; Korenaga, 2008). Recent measurements of Earth's neutrino flux are consistent with compositional models for the bulk silicate Earth (the crust plus the mantle) that infer radiogenic heat production resulting in an even lower U_r (~0.13) than the generally accepted value (~0.35), (Abe et al., 2022), making the "thermal catastrophe" paradox even worse. The only reasonable solution to this problem is if Earth's present heat loss regime — plate tectonics — was not operating throughout Earth history. Plate tectonics is an especially efficient way to cool the mantle because it injects cool lithosphere into the mantle while simultaneously exposing hot mantle at spreading ridges; the modern U_r (~0.35) is the plate tectonic U_r. Because single lid tectonic regimes establish unbroken lithosphere which serves as a planetary insulating blanket, U_r for single lid tectonic regimes are likely to be much higher and could in some instances be >1, causing brief episodes of heating. As noted above, there are multiple styles of single-lid tectonics, including squishy lid, sagduction, heat pipe etc., but all of these aforementioned tectonic styles are single lid modes. These will have slightly different Urey ratios but none (with the possible exception of heat pipe tectonics, which was only likely in the early Hadean) will approach the super-efficient mantle cooling mode of plate tectonics. The most straightforward way to solve the paradox of Earth's thermal history is for single lid episodes to represent a significant fraction of Earth's tectonic history, as shown in Fig. 6. Such an interpretation is also consistent with evidence from primitive basalts for Earth's mantle potential temperature (Ganne and Feng, 2017) (red boxes in Fig. 6).

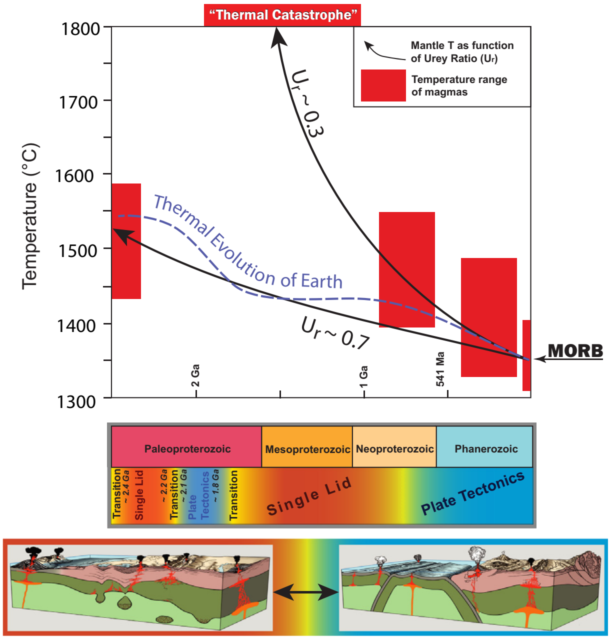

Fig. 6. Earth's thermal history for last 2.5 Ga. Black lines indicate cooling history calculated for ratios of internal heat production to surface heat loss (Urey ratio, U_r). Heat loss today is controlled by plate tectonic processes and is large, so that U_r is estimated to be ~0.3 (Korenaga, 2008). Extrapolating Earth's mantle potential temperature back in time using this value would lead to wholesale melting of the mantle (thermal catastrophe) ~1.5 Ga, which did not happen. Mantle potential temperatures inferred from primitive basalts constrain the cooling to have been much less. Red boxes encompass mantle potential temperatures (T_p) at three times in Earth history by Ganne and Feng (2017): 2.5 Ga, Neoproterozoic, Phanerozoic, and today (MORB). Remarkably, the difference of temperature observed between Tp maxima and minima did not change significantly with time (~170 °C). One solution to the Urey ratio paradox is to argue for a much higher Urey ratio (U_r ~0.7) but this is inconsistent with geochemical models for the Earth and with observed geoneutrino flux, as discussed in the text. A better solution results from alternating tectonic styles, with U_r ~0.3 during plate tectonic episodes and a higher U_r during single lid episodes (dashed blue line). See text for further discussion.

A final implication of identifying an earlier episode of plate tectonics is that this provides a useful test of the uniformitarianist vs emergent systems approach to reconstructing Earth's tectonic history. Uniformitarianism — the philosophy that the processes that are observed today have operated in the past — was a tremendous breakthrough two centuries ago, when Hutton, Lyell, Darwin and other scientists challenged religious orthodoxy, and is still useful in confronting creationists today. Emergence articulates that high energy, far-from-equilibrium systems are likely to reorganize in ways that cannot be predicted, and Earth's convecting interior is likely to show emergent behavior (Stern and Gerya, 2021). Earth is likely to have experienced multiple tectonic transitions, from single lid to plate tectonics and back to single lid, perhaps multiple times.

Uniformitarianism (and its modern equivalent Actualism) is much less useful than Emergence for reconstructing Earth's tectonic evolution because it impedes objective examination of the evidence. Emergence is a better way to reconstruct Earth's history because it allows us to think more clearly about the significance of changes in Earth products over time. Geochemical, isotopic, and mineralogical changes are often interpreted as due to the beginning of plate tectonics (e.g., El Dien et al., 2020; Turner et al., 2020; Ning et al., 2022) partly because only the question of when plate tectonics began is addressed, ignoring the possibility that these changes may reflect other changes in Earth's convective style and lithospheric responses. Such changes may also reflect changing styles of single lid tectonics, for example from a style of more 2D "drips" to more 3D "peels" for returning lithosphere to the deeper mantle. We should also keep in mind that identifying evidence of one subduction zone is not sufficient for identifying a global plate tectonic network.

5. Conclusions

Five important conclusions come from this study.

(1) Eight independent lines of evidence indicate that an episode of plate tectonics lasting about 300 million years occurred in mid-Paleoproterozoic time. The modern episode of plate tectonics may have begun in Neoproterozoic time, but another plate tectonic episode occurred a billion years earlier.
(2) Preservation of rock evidence is not a problem for at least the last 2 Ga of Earth history, which means that the absence of evidence for Mesoproterozoic plate tectonics is evidence of absence of Mesoproterozoic plate tectonics. Ironically, recognizing the Orosirian plate tectonic episode makes us more confident that interpreting the Mesoproterozoic as a single lid episode is a useful hypothesis.
(3) Recognizing the Orosirian plate tectonic episode provides context for the ~2.3–2.4 Ga Tectono-Magmatic Lull. This is most simply interpreted as an earlier episode of single lid tectonics, an interpretation that helps explain the Great Oxygenation Event at this time as result of the greatly diminished supply of oxidizable materials.
(4) The past 2.5 Ga of Earth's thermal evolution is best explained by alternating fast-cooling plate tectonic regimes with slow-cooling (or reheating) single lid regimes.
(5) Recognizing the Orosirian plate tectonic episode, bracketed by younger and older single lid episodes further challenges substantive uniformitarianist interpretations of Earth history. The perspective offered by emergence is more promising.

The door is open to more realistic interpretations of Earth's tectonic history by working backward from the present through increasingly ancient times by refining our understanding of what constitutes reliable indicators of plate tectonics and single lid tectonic regimes. Because we know so much more about PTIs than SLIs, it makes sense to first concentrate on the former, if only to decide whether or not geologic evidence is preserved well enough for a tectonic interpretation to be usefully constructed. Identifying single lid episodes through this approach provides opportunities to identify SLIs and understand the controls on their formation.

CRediT authorship contribution statement

Robert J. Stern: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Thanks to Peter Copeland, Ross Mitchell, Mark Harrison and an anonymous reviewer for constructive reviews of this and an earlier version of this manuscript, and to M. Santosh for speedy editorial handling. Thanks to Mike Brown, Kent Condie, Peter Cawood, David Evans, Tatsuki Tsujimori, and Guochun Zhao for advice and information. Thanks to Clinton Crowley for help with artwork. This is UTD Geosciences contribution # 1700.

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