On the enigmatic mid-Proterozoic : Single-lid versus plate tectonics

Roberts, Nick M.W.

2022-09-15

Roberts , N M W , Salminen , J , Johansson , Å , Mitchell , R N , Palin , R M , Condie , K C &
Spencer , C J 2022 , ' On the enigmatic mid-Proterozoic : Single-lid versus plate tectonics ' ,
Earth and Planetary Science Letters , vol. 594 , 117749 . https://doi.org/10.1016/j.epsl.2022.117749

http://hdl.handle.net/10138/347188
https://doi.org/10.1016/j.epsl.2022.117749

Earth and Planetary Science Letters 594 (2022) 117749

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

On the enigmatic mid-Proterozoic: Single-lid versus plate tectonics

Nick M.W. Roberts [a,*], Johanna Salminen [b,c], Åke Johansson [d], Ross N. Mitchell [e], Richard M. Palin [f], Kent C. Condie [g], Christopher J. Spencer [h]

[a] Geochronology and Tracers Facility, British Geological Survey, Nottingham, NG12 5GG, UK
[b] Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland
[c] Geological Survey of Finland, P.O. Box 96, FI-02151 Espoo, Finland
[d] Department of Geosciences, Swedish Museum of Natural History, Box 50 007, SE-104 05 Stockholm, Sweden
[e] Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[f] Department of Earth Sciences, University of Oxford, Oxford OX1 3AN, UK
[g] Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, USA
[h] Department of Geological Sciences and Geological Engineering, Queen's University, 13 Kingston, Ontario, Canada

ARTICLE INFO

Article history:
Received 7 April 2022
Received in revised form 9 July 2022
Accepted 22 July 2022
Available online xxxx
Editor: R. Hickey-Vargas

Keywords:
mid-Proterozoic
Plate tectonics
single-lid tectonics
secular mantle cooling
Earth evolution
metamorphic record

ABSTRACT

The mid-Proterozoic (ca. 1850–850 Ma) is a peculiar period of Earth history in many respects: ophiolites and passive margins of this age are rare, whereas anorthosite and A-type granite suites are abundant; metamorphic rocks typically record high thermobaric (temperature/pressure) ratios, whereas ultrahigh pressure (UHP) rocks are rare; and the abundance of economic mineral deposits features rare porphyry Cu-Au and abundant Ni-Cu and Fe-oxide Cu-Ag (IOCG) deposit types. These collective observations have been used to propose that a stagnant-lid, or single-lid, tectonic regime operated at this time, between periods of plate tectonics in the Paleoproterozoic and Neoproterozoic. In our reappraisal of the mid-Proterozoic geological record, we not only assess the viability of the single-lid hypothesis for each line of evidence, but also that of the plate tectonic alternative. We find that evidence for the single-lid hypothesis is equivocal in all cases, whereas for plate tectonics the evidence is equivocal or supporting. We therefore find no reason to abandon a plate tectonic model for the mid-Proterozoic time period. Instead, we propose that the peculiarities of this enigmatic interval can be reconciled through the combination of two processes working in tandem: secular mantle cooling and the exceptionally long tenure and incomplete breakup of Earth's first supercontinent, where both of these phenomena had a dramatic effect on lithospheric behaviour and its resulting imprint in the geological record.

1. Introduction

The modern Earth exhibits plate tectonics, but this may not have always been the case. There continues to be great debate over the age of onset of plate tectonics, and whether it has operated continuously since formation of the first crust, or was presaged by some other type of tectonic behaviour. In the modern "mobile lid" or plate tectonic geodynamic mode, plate movements at the Earth's surface are strongly coupled to mantle convection. Other modes of mantle convection suggested to occur on other planets and moons, however, do not involve the surface layer and are thus termed "stagnant-lid" or "sluggish-lid" (Stern et al., 2018). Whether Earth had such a geodynamic regime soon after its formation, or if it experienced a return to such a state after plate tectonics had been initiated, remains an open and much-debated question.

Perceived to be characterized by a "boring billion" years of climatic stasis (Holland, 2006), the mid-Proterozoic (ca. 1.85–0.85 Ga) is an interval of geological time that is clearly peculiar, and thus presents a likely candidate for a potential respite from plate tectonics in Earth history. The Earth's tectonic mode during the Mesoproterozoic (the era from 1.6 to 1.0 Ga that comprises most of the informal mid-Proterozoic time interval) has been questioned recently, with hypotheses including "orogenic quiescence" (Tang et al., 2021; Zhu et al., 2022) and "single-lid tectonics" (Piper, 2013; Stern, 2020). Other researchers recognize mild tectonic reorganization between the supercontinents Columbia (a.k.a. Nuna) and Rodinia (Roberts, 2013; Ernst et al., 2016), and a different style of hot and thin orogenesis (Spencer et al., 2021), but do not question the vitality of orogenesis nor the plate tectonic regime during this time. Thus, the most basic and pressing question is to assess

---

[*] Corresponding author.
E-mail address: nirob@bgs.ac.uk (N.M.W. Roberts).

https://doi.org/10.1016/j.epsl.2022.117749
0012-821X/

whether the most extreme of these hypotheses – a temporary return to single-lid (or 'stagnant-lid') tectonics – can be refuted or not. Then, and only then, can arguably more elaborate hypotheses regarding the mid-Proterozoic be postulated.

Here, based on the backdrop of recent studies, we take an iterative approach to hypothesis testing to explain the mid-Proterozoic geological record. As we define them, we test two hypotheses – the first, that plate tectonics existed throughout the mid-Proterozoic, and the second, a single-lid model. The appeal of the plate tectonic hypothesis is its consistency with subsequent geologic history and known, uniformitarian processes. The appeal of the single-lid hypothesis is both its mechanistic simplicity and its potentially unique ability to explain the aberrations of the mid-Proterozoic geological record. Ultimately, after assessing different lines of evidence from the extant geological record, we offer a synoptic view, that in our opinion offers the best explanation for the style of mid-Proterozoic tectonics.

2. Methods

Each mid-Proterozoic dataset will be examined within the context of both hypotheses. It is debatable which should be regarded as a "null" hypothesis: on the one hand, the null hypothesis may be the simplest single-lid hypothesis as recently proposed for mid-Proterozoic time (Stern, 2020); on the other hand, as most geologists would agree that plate tectonics has been operational since at least late Neoproterozoic time (Hamilton, 1998; Stern, 2005; Cawood et al., 2006), it may also be regarded as the null hypothesis on the grounds of uniformitarianism. We therefore entertain both hypotheses and assess which explanation is most compelling. After doing so for each individual dataset, we finally synthesize the individual assessments to produce a coherent collective tectonic interpretation.

3. Results

3.1. Paleomagnetism and continental drift

Paleomagnetism offers a quantitative test of plate tectonics. The paleomagnetic database of robust mid-Proterozoic poles is constantly growing (Evans et al., 2021), with some cratons such as Baltica and Laurentia having several robust poles, while others such as Kalahari still have few poles constraining their position. The current dataset for the mid-Proterozoic interval allows for broad paleogeographic reconstructions of the assembly and breakup of the Columbia (e.g., Elming et al., 2021) and Rodinia supercontinents (e.g., Evans, 2021). However, because several cratons are lacking robust poles, it is not possible to reconstruct the complete configuration of Columbia, and several cratons have debated positions (e.g., Evans, 2021; Elming et al., 2021). Despite this, there is some consensus as to the relative configuration of the core cratons of Laurentia, Baltica, Siberia and those of proto-Australia through the Columbia to Rodinia supercontinent cycle. Other cratons such as Amazonia are debated, with some models having it located within the core of Columbia adjacent to Baltica – the South AMerica - BAltica (SAMBA) connection (Johansson, 2009; Zhang et al., 2012; Bispo-Santos et al., 2020); whereas alternative models have it excluded from Columbia (Pisarevsky et al., 2014; Elming et al., 2021).

We reconstruct the Columbia supercontinent and its transition to Rodinia in Fig. 1a. The broad timing of the different phases of the Columbia–Rodinia supercontinent transition are taken as such: Columbia assembly lasted from 1.9 to 1.6 Ga, ending with the suturing of Australia to western Laurentia (present-day coordinates) at around 1.6 Ga (e.g., Pourteau et al., 2018; Volante et al., 2020); Columbia breakup initiated after 1.35 to 1.3 Ga, with proto-Australian cratons drifting northward from Laurentia (Pisarevsky et al., 2014; Elming et al., 2021; Kirscher et al., 2021); and Rodinia assembly initiated by 1.2 Ga (Spencer et al., 2017). This was followed by the 1.1–0.95 Ga final transition from Columbia to Rodinia, that was at least in part accomplished by the ~90° clockwise rotation of Baltica (± Amazonia and West Africa) relative to Laurentia, and their subsequent collision in a new configuration along the Grenville-Sveconorwegian-Putamayo-Sunsas belt (Johansson, 2009; Cawood et al., 2010; Evans, 2013; Martin et al., 2020). The exact timing of the rotation of Baltica with respect to Laurentia is poorly constrained (e.g., Cawood et al., 2010), but paleomagnetic data limit it between 1.12 Ga and 0.99 Ga (Salminen et al., 2009; Swanson-Hysell et al., 2019). Although the use of low quality paleomagnetic data with a loose age criterion (± 200 Ma) has led to the proposal of a single long-lived supercontinent that lasted from the Archean until the Neoproterozoic (Piper, 2013, 2018), high-quality paleomagnetic data contradicts this model (Li et al., 2009).

By comparing coeval pairs of magnetic poles from distinct cratons, the independent or common drift of two or more cratons during a specified time interval can be tested (Buchan et al., 2016). Using great-circle distances and age differences between successive poles, minimum speeds of cratonic motion can be calculated. The calculated rates represent the net sum of motion due to both plate tectonics and true polar wander (TPW; Evans, 2003). During the mid-Proterozoic, only one large-amplitude (>30°) true polar wander event has been proposed at 1.1 Ga (Mitchell, 2014).

By comparing the highest quality coeval paleomagnetic poles, differential motion of the Superior and Slave cratons (Buchan et al., 2016) and Fennoscandia and Sarmatia cratons (Elming et al., 2021) at 1.88–1.75 Ga is documented, providing evidence for plate tectonics operating during the amalgamation of Laurentia and Baltica at the onset of Columbia assembly. Using updated reliable paleomagnetic poles, Elming et al. (2021) showed differential motion of the core of Columbia and other cratons such as those of proto-Australia and North China until the final amalgamation of Columbia at 1.6 Ga, as well as after the onset of breakup at 1.35 Ga, with these motions supporting plate tectonics. In addition, the core cratons of Columbia show divergent paleomagnetic poles through Rodinia assembly at 1.1 Ga to 0.9 Ga (Evans, 2021), indicating differential motion of these cratons. Calculated mid-Proterozoic minimum speeds of cratonic motions (Fig. 1b) are typical for present-day continental plates (Zahirovic et al., 2015), contradicting the single-lid hypothesis and the proposed slow speeds of Piper (2013). Variable and fast drift speeds are recorded during the amalgamation of Columbia, whereas during the tenure of Columbia, unimodal drift speeds of 6–11 cm yr^{-1} are recorded until 1.3 Ga. Drift speeds both increase and become more variable again during the amalgamation of Rodinia, with data for Laurentia showing rates of 20–50 cm yr^{-1} during the main phase of the Grenvillian orogeny at ca. 1.1 Ga, and data for Baltica recording similar speeds during the late stage of the Sveconorwegian orogeny at ca. 0.93 Ga. These obtained speeds exceed the expected limits for plate speeds (Zahirovic et al., 2015) and have been explained by a combination of fast plate motion (Salminen et al., 2009; Swanson-Hysell et al., 2019) and TPW for some periods (Mitchell, 2014). The overall variation in drift speeds during the mid-Proterozoic between separate cratons, comparable drift rates to present day, and faster rates correlating with orogenic activity, strongly supports the plate tectonic hypothesis, and is incompatible with a single-lid mode.

3.2. I-type magmatism and circum-Columbian accretionary belts

Worldwide 2.0–1.6 Ga orogenic events spanning the assembly of the Columbia supercontinent indicate that plate tectonic

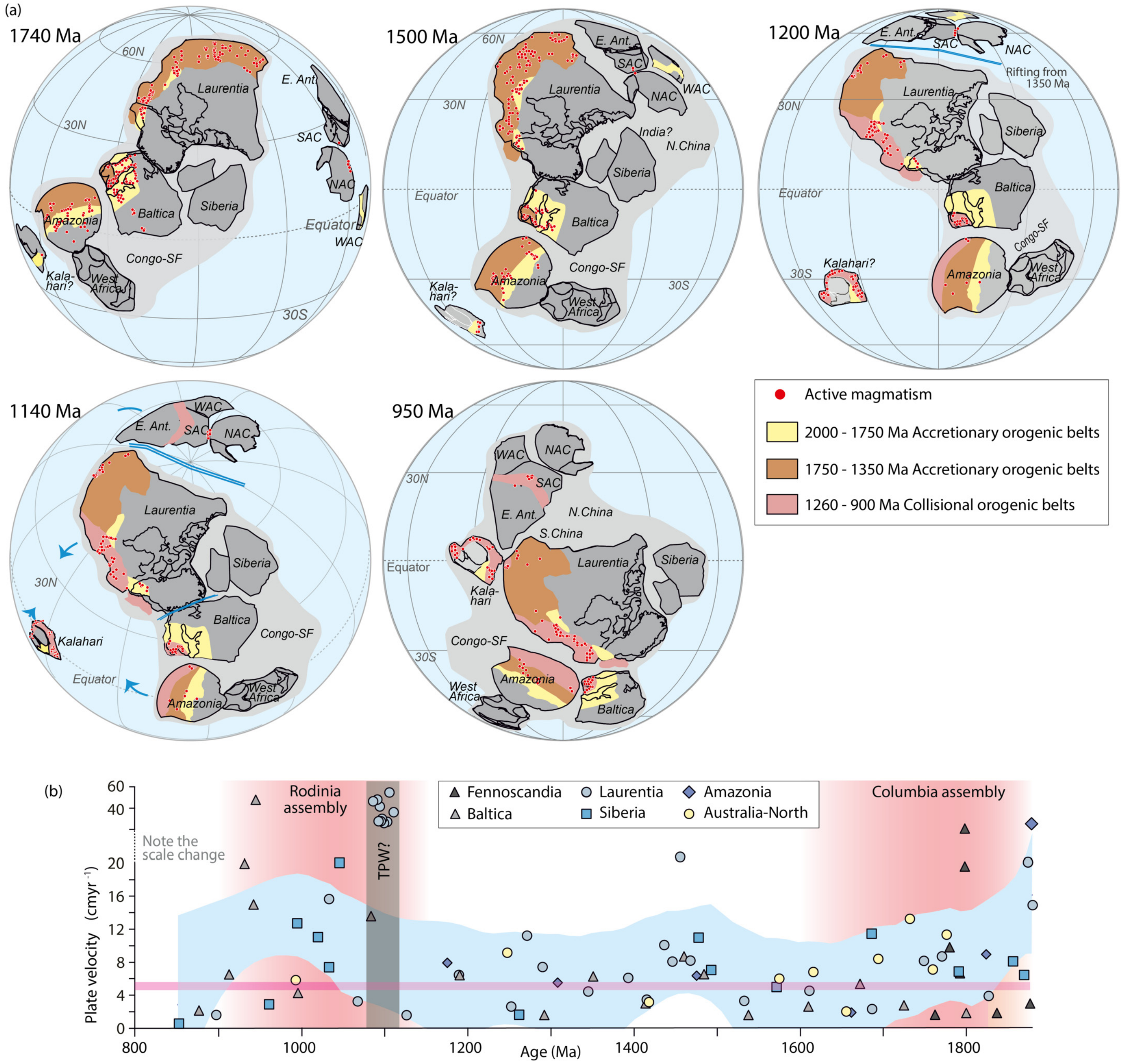

Fig. 1. (a) Paleogeographic reconstructions based on paleomagnetic data, see supplementary files for data and methods. Active magmatism is shown for the following periods in each time frame: 1820–1600 Ma (1740 Ma), 1600–1260 Ma (1500 Ma), 1260–1100 Ma (1200 and 1140 Ma) and 1100–900 Ma (950 Ma), and is limited to magmatism within the accretionary belts. The location of magmatism and accretionary/collisional belts is based on Johansson et al. (2022). SAC = South Australian Cratons, NAC = North Australian Cratons, WAC = West Australian Cratons, SF – Sao Francisco, E. Ant = East Antarctica. (b) Minimum speeds of cratonic motion as calculated from the compiled paleomagnetic data (see Supplementary Files.). Blue curve and band are a lowess smoothing trend through the paleomagnetic record. The pink horizontal bar represents average modern plate speed (Parsons, 1981). (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

movements operated during this time period. Whilst collisional orogenesis was occurring in what became the interior of the supercontinent during its assembly phase, subduction-related accretionary orogenesis began or continued along the exterior margins. This process is akin to the formation of the Terra Australia orogen along the margins of Gondwana (Cawood and Buchan, 2007). This temporally and spatially extensive accretionary belt, the Great Proterozoic Accretionary Orogen (Fig. 3) (GPAO; Condie, 2013; Roberts, 2013), produced calc-alkaline I-type magmatism and significant crustal growth along the margins of SE Laurentia, SW Baltica and SW Amazonia (Whitmeyer and Karlstrom, 2007; Roberts and Slagstad, 2015; Johansson, 2009; Johansson et al., 2022). The extent of the GPAO around the entirety of the Columbia supercontinent is not well constrained, but likely included other continents where magmatism of this timeframe is known (e.g., Kalahari, North China Craton, Siberia, India; Li et al., 2021; Wang et al., 2022; Roberts, 2013; Elming et al., 2021). The poorly constrained paleogeography for many continents in the 1.7–1.1 Ga interval also permits the possibility that the GPAO may have been divided into more than one long-lived circum-continental orogen. The GPAO featured magmatism and orogenic activity (Figs. 1a and 2), including deformation and metamorphism, forming elongated belts that become progressively younger outboard from the Archean continental nuclei. This pattern is strongly suggestive of semi-continuous subduction and

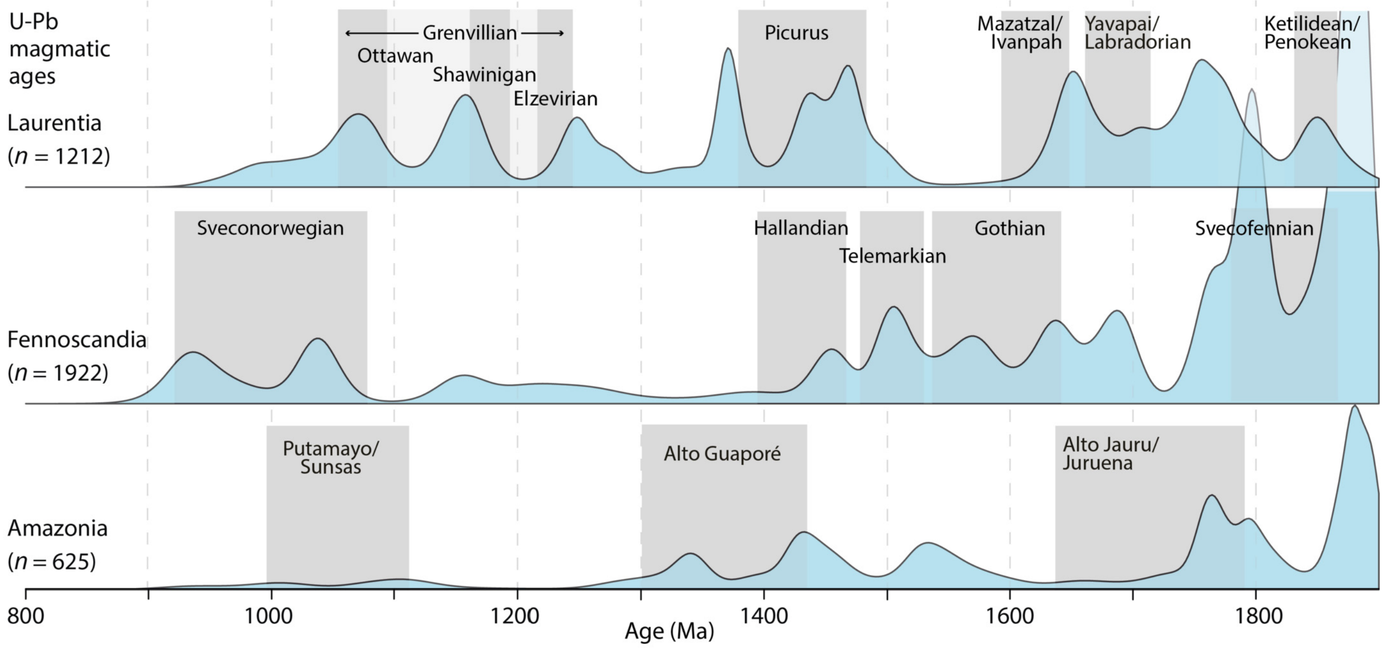

Fig. 2. Compilation of U-Pb ages from the best-known regions of the Great Proterozoic Accretionary Orogen that formed on the margins of the Columbia supercontinent, plotted as KDEs (data compilation from Johansson et al., 2022). Bars show known orogenic periods (from Johansson et al., 2022).

crustal accretion, and hence plate tectonics, occurring along the external margin of Columbia throughout mid-Proterozoic time, but is very difficult to reconcile with a single-lid or stagnant-lid scenario.

3.3. Absence of blueschists and UHP metamorphism

Blueschists form during low-temperature (T) and high-pressure (P) metamorphism, which is characteristic of subduction zones. Thus, their occurrence has been used as an indicator of plate tectonics (e.g., Stern, 2005), although there are non-tectonic explanations for their absence from the early Earth geological record (Palin and White, 2016). The oldest non-equivocal well-dated blueschists on Earth formed at ca. 0.77 Ga (Xia et al., 2019), and they only become abundant after 0.5 Ga (Figs. 3a and 4a), although it is noteworthy that several other occurrences of low T/high P metamorphic rocks are found back to 2.1 Ga (e.g., Ganne et al., 2012). The Neoproterozoic is now typically interpreted as recording a transition in subduction style from previously 'hot and shallow' to 'cold and steep' (e.g., Hawkesworth et al., 2016; Palin et al., 2020). The oldest ultra-high pressure (UHP) eclogite on Earth is dated at ca. 620 Ma and is located in the Brasiliano orogenic belt, southwestern Brazil (Ganade de Araujo et al., 2014), although the oldest high-pressure (HP) eclogite is dated at ca. 2.09 Ga and is located in the Eburnean orogenic belt, Cameroon (Loose and Schenk, 2018). Indeed, there is a curious abundance of HP eclogite at ca. 2.1–1.8 Ga, followed by a gap of around 800 Myr, coinciding with much of the mid-Proterozoic, before they become pervasive again in the geological record after ca. 0.6 Ga (Fig. 1). These Paleoproterozoic occurrences have been used to argue that modern-style continental collisions requiring plate tectonics occurred at ca. 2 Ga (Weller and St-Onge, 2017). The gap in occurrences between ca. 1.8 and 1.0 Ga has been explained by a transition to a warmer mantle at 2 Ga (Tamblyn et al., 2022). This premise of a warmer mid-Proterozoic mantle, originally hypothesized to have been associated with Earth's first supercontinent (Hoffman, 1989), is in accord with numerical modelling of mantle temperatures during supercontinent formation (e.g., Gurnis, 1988; Coltice et al., 2009); however, this model is still speculative given the unknown length- and time-scales of mantle warming relative to the slowly aggregating Columbia supercontinent.

The lack of blueschists and rarity of UHP terranes before the Neoproterozoic is conspicuous, but the meaning of these temporal patterns is equivocal. Using their absence to indicate a lack of plate tectonics didactically infers that plate tectonic processes have not changed through time, which is in stark contrast to other well documented secular changes within the geosphere. For example, the temperature of the mantle impacts the angle and depth of penetration of crustal material subducted into it; it impacts the efficacy of mantle melting, which in turn alters the composition (and buoyancy) of the newly formed oceanic and continental crust; and it impacts the strength of the lithosphere, such that oceanic lithosphere subducted into a hotter mantle on the early Earth would have been less likely to remain coherent, and would have suffered more frequent breakoff (van Hunen and van den Berg, 2008; Sizova et al., 2010, 2014; Fischer and Gerya, 2016). Integrated geodynamic, geochemical, and petrological modelling has shown that: 1) continental crust subducted to UHP depths is unlikely to be exhumed from a hotter mantle (van Hunen and van den Berg, 2008; Sizova et al., 2014); 2) more Mg-rich oceanic crust that would have formed on the Archean Earth from a hotter upper mantle is unable to form archetypal blueschist-facies assemblages, even when metamorphosed to low-T/high-P conditions (Palin and White, 2016); and 3) secular change in the composition of continental crust through time would have rendered exhumation of subducted, more mafic Precambrian continents more difficult (Palin et al., 2021), promoting a bias towards blueschists or eclogites being formed or exhumed mainly in young orogens.

Given that accepted thermal models indicate that the ambient potential mantle temperature was at least 80°C hotter during the Mesoproterozoic than the present-day temperature (Herzberg et al., 2010; Ganne and Feng, 2017), it is expected that UHP eclogites and blueschists would be notably rarer in the Mesoproterozoic rock record than in the Phanerozoic. We thus consider blueschists and UHP rocks circumstantial indicators of ancient plate tectonics, which do not need to be present in a geological terrane to conclude its operation. They are of most immediate use in confirming the prevalence of cool metamorphic geotherms during the

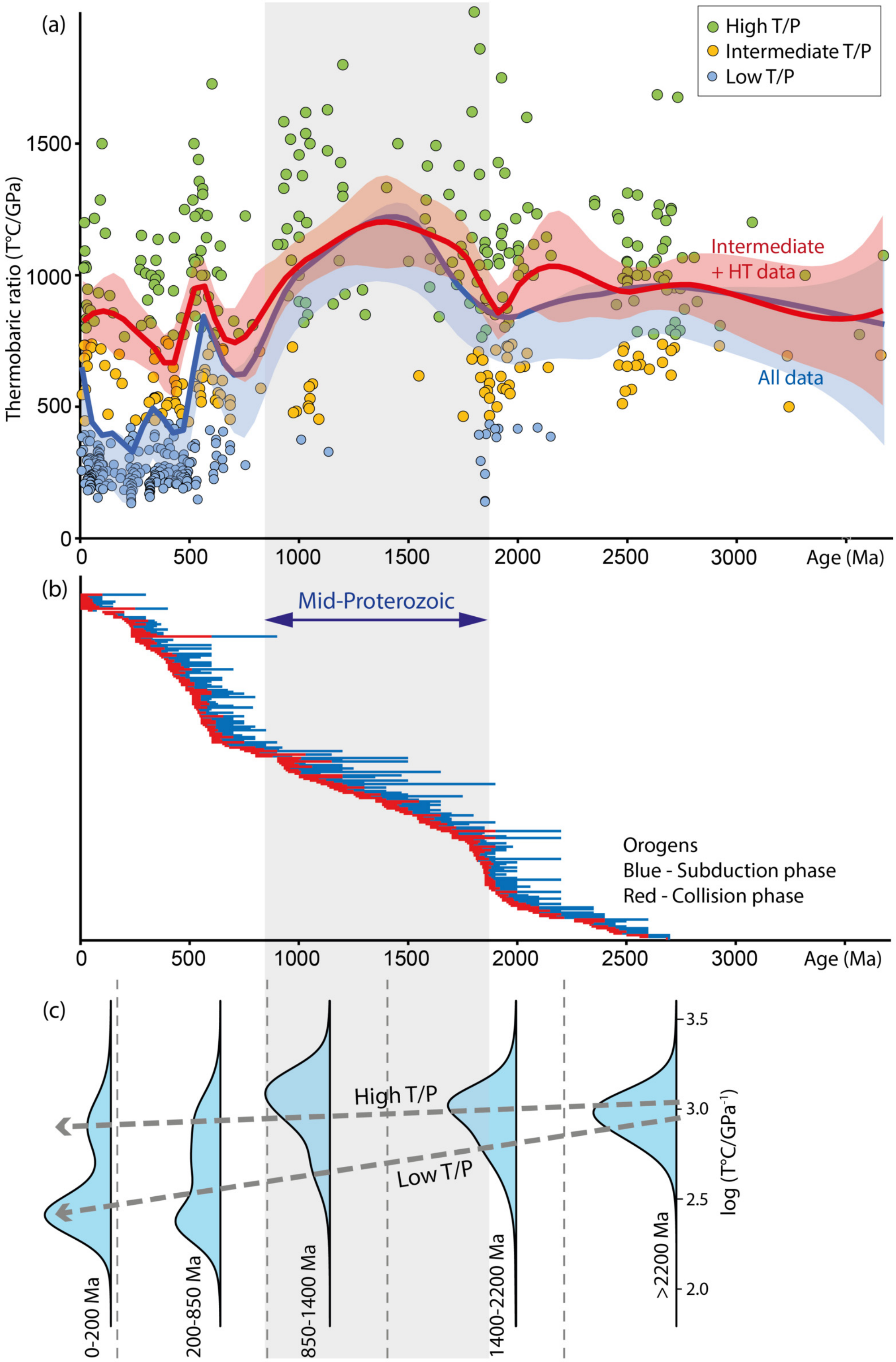

Fig. 3. (a) Global metamorphic record (Brown and Johnson, 2019) plotted as thermobaric ratio (temperature/pressure) through time. Metamorphic types are colour-coded: blue, low-T/P (<440°C/GPa); yellow, intermediate T/P (<750, >440°C/GPa); and green, high T/P (>750°C/GPa). The blue curve and uncertainty band is a lowess curve through all the data, and the red curve and band is a lowess curve through the data omitting the low T/P values. (b) Compilation of orogenic timing from Condie et al. (2021), with blue as the subduction phase and red as the collision phase. (c) The global metamorphic record is binned according to the density of the data through time, and plotted as kernel density estimates (KDEs) using log transformation of the T/P values. The two arrows broadly match the peaks in the KDEs, indicating increasing diversity through time (Holder et al., 2019).

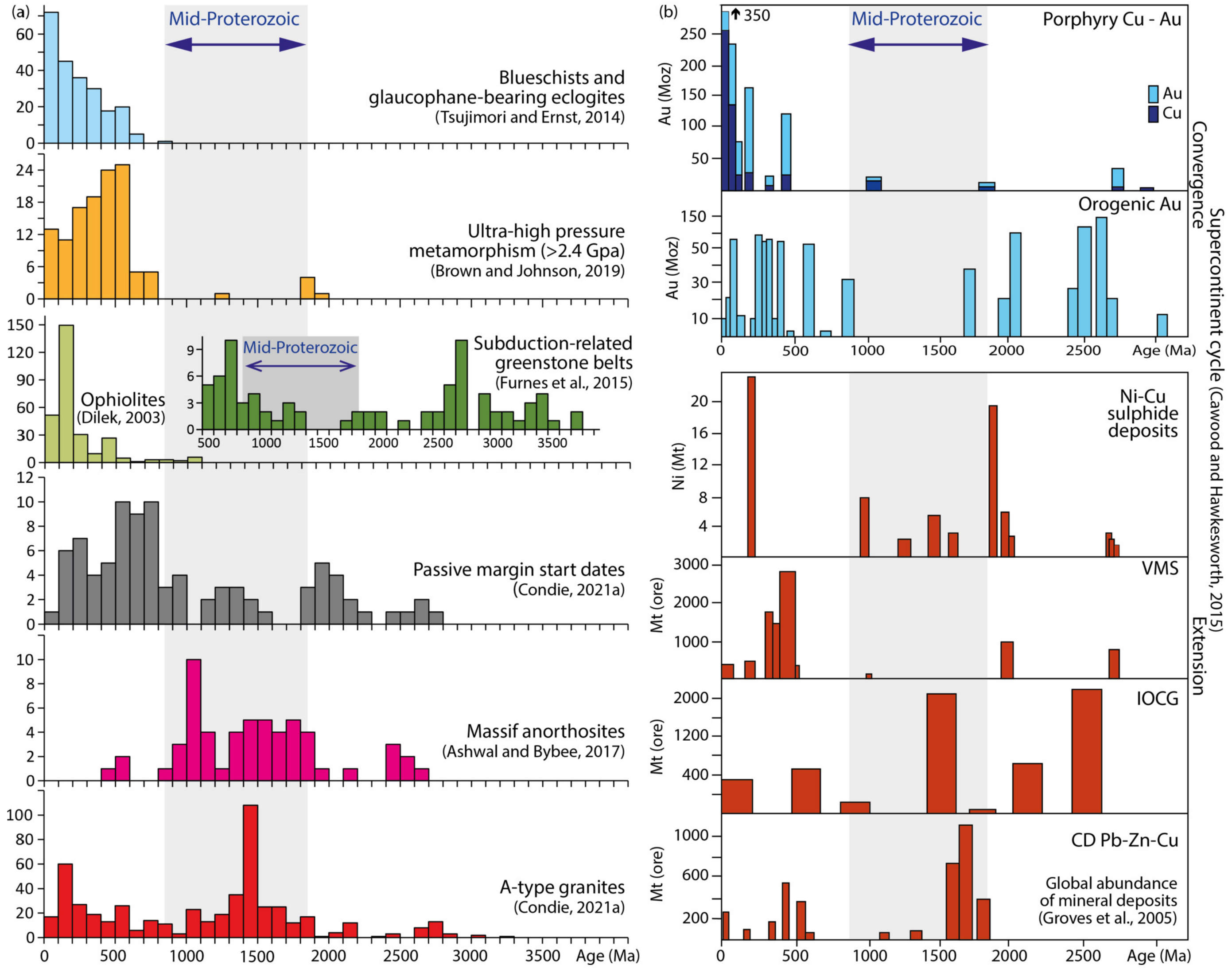

Fig. 4. (a) Various compilations of the preserved geological record as abundance through time. Data sources: Tsujimori and Ernst (2014); Brown and Johnson (2019); Dilek (2003); Furnes et al. (2015); Condie (2021a) and Ashwal and Bybee (2017). (b) Global compilation of mineral deposit abundance, based upon Groves et al., (2005), and split into convergence and extension periods of the supercontinent cycle (Cawood and Hawkesworth, 2015).

Phanerozoic. Given these lines of reasoning, we consider the evidence equivocal in regard to either hypothesis.

3.4. Abundant high temperature metamorphism

In contrast to the "orogenic quiescence" postulated by Tang et al. (2021), the Mesoproterozoic was host to numerous tectonothermal events (Fig. 3b). Collisional orogens were abundant during the formation of the Columbia supercontinent (Zhao et al., 2002; Condie et al., 2021). This amalgamation continued until ca. 1.6 Ga, with accretion of Australia to Laurentia at this time (Pourteau et al., 2018). The preserved record of collisional orogenesis was then subdued, although notably still present (Fig. 1c), until the formation of Rodinia from ca. 1.2 to 0.85 Ga (Li et al., 2008). Across the entire Columbia and Rodinia cycles, the metamorphic record is dominated by medium-*T* to high-*T*/low-*P* thermobaric ratios, when compared to the preceding and subsequent time periods (Fig. 3a), with an apparent maximum in thermobaric ratio in the Mesoproterozoic (Brown and Johnson, 2018). These authors linked the apparent ca. 1.5 Ga peak in thermobaric ratios to mantle insulation under the Columbia supercontinent. Stern (2020) subsequently took this argument as evidence of a single lid existent in the Mesoproterozoic. However, we refer to this peak as apparent for two reasons: first, the metamorphic record in this timeframe is sparse, meaning that small numbers of data points are less likely to be representative for any given period of time, and second because thermal gradients in collisional orogens are continually evolving. Thus, reducing the metamorphic conditions within a terrane to a single *P-T* point at a certain time is potentially misleading in portraying the complex tectonic processes that operate in both plate tectonic and non-plate tectonic regimes.

Here, we outline three observations of the metamorphic record at hand, which are evident (Fig. 3): (i) the metamorphic record shows a broad increase to more variable *P-T* conditions through time; (ii) both the early Proterozoic orogenic periods (2.2–1.8 Ga) and late Proterozoic orogenic periods (1.2–1.0 Ga) record HT as well as HP metamorphism; and (iii) the Mesoproterozoic is characterized by a lower abundance of collisional orogens compared to bounding eras. The first observation is compatible with an increasing bimodality and variability in metamorphic gradients through time (Fig. 3c), as befits a gradual change in geodynamics resulting from secular cooling of the mantle (Holder et al., 2019). The second observation indicates that a prevalence of high-temperature metamorphism was not restricted to the tenure of supercontinent

Columbia, but occurred during both Columbia assembly and its breakup/transition to Rodinia, as well as during the Phanerozoic and the Neoarchean. This implies that the high thermobaric ratios cannot be solely attributed to mantle insulation from a supercontinent. Regarding the third observation, infrequent orogenesis is recorded during other periods of supercontinent breakup, e.g., at 0.8–0.7 Ga, and thus simply reflects the rift-to-drift stage of the continents, prior to collision during the next supercontinent cycle. The low abundance of collisional orogenesis from 1.6 to 1.2 Ga is compatible with the stable tenure and subsequent partial breakup of Columbia before the formation of Rodinia (Roberts, 2013). In the sense of the single-lid model, orogenic events in this timeframe such as the ca. 1.4 Ga Hallandian in Baltica and the Picuris in Laurentia require explanation; it is not clear how events like these would originate in a single lid tectonic regime.

In summary, does the metamorphic record of apparently high geothermal gradients, support a single lid hypothesis? We argue that the evidence for mantle heating from a single-lid is equivocal, and the lack of low thermobaric ratios or high-pressure metamorphism through the middle part of mid-Proterozoic (1.6–1.2 Ga) can be explained by the lack of collisional orogenies during the tenure and breakup of supercontinent Columbia.

3.5. *Paucity of ophiolites and passive margins*

Both ophiolites and the formation of new passive margins are reliable and independent indicators of plate tectonics. The obduction of oceanic lithosphere onto a continent is evidence for compressional tectonics thought only to accompany subduction. By contrast, passive margins form where space is generated along a continental margin that is not experiencing subduction, and this is generally, if not exclusively, achieved by tectonic subsidence following continental rifting. The geological record suggests that passive margins and ophiolites are both relatively rare during the mid-Proterozoic (Bradley, 2008; Fig. 4). A single-lid regime can feasibly explain the paucity of both of these plate tectonic indicators during the mid-Proterozoic (Stern, 2020). However, the question remains whether 'the absence of evidence is evidence of absence', or in this case, whether the relatively small number of passive margins and ophiolites compared to the Paleoproterozoic and the Neoproterozoic can be explained if plate tectonics was operational.

Continental reconstructions may be used to assess passive margin initiation and preservation through time, and such treatment suggests that 11 passive margins formed in the Mesoproterozoic (Fig. 4a; Condie, 2021a). The extent to which the Columbia supercontinent broke up will impact the number of passive margins created. At present, most paleogeographic reconstructions only support partial breakup. This, along with long-lived active margins along many continental blocks, is compatible with a low abundance compared to younger periods of Earth history.

Ophiolites are a problematic form of evidence for identifying convergent margin processes through time, as their preservation is more of an exception than the rule. As oceanic lithosphere is preferentially subducted rather than exhumed, their paucity or absence at any point in Earth history is weak and circumstantial evidence of a single-lid environment operating at that time. The abundance of ophiolites partially correlates with that of low-T/high-P metamorphism (Figs. 3 and 4), indicating that formation or preservation of collisional belts has controlled the abundance of ancient ophiolites. Therefore, although the mid-Proterozoic rarity of both ophiolites and passive margins are conspicuous, the records are in accord with: few and large continental landmasses during this time, a protracted and incomplete breakup of the Columbia supercontinent, and continental margins that featured active rather than passive margins. In summary, the evidence is somewhat marginal; we argue that continued formation of passive margins in the Mesoproterozoic supports a plate tectonic hypothesis, whereas the rarity of ophiolites certainly does not negate plate tectonics.

3.6. *Abundances of anorthosites and A-type granites*

Voluminous anorthosite intrusive complexes are found throughout the Proterozoic, but are particularly common in the mid-Proterozoic (Ashwal and Bybee, 2017; Fig. 4a); they are commonly associated with A-type granitoids. A-type granitoids are found throughout the geological record since the late Archean (Fig. 4a). There has been a view that A-type granitoids are a feature particular to the mid-Proterozoic (Stern, 2020); however, as pointed out by Condie (2021a), we believe this to be biased by North American sampling, where much work has been conducted on the widespread Mesoproterozoic A-type granite suites. We also point out that it is a misconception that anorthosites and A-type granitoids are restricted to anorogenic settings. Voluminous massif anorthosites are indicative of several specific conditions that allowed their formation, namely, a persistent heat source at the base of the Moho, and a stable geodynamic environment that allows for protracted (≥10 Myr) melting, polybaric ascent and crystallization. Ashwal and Bybee (2017) suggest that continental arcs provide the most suitable location for these conditions, and highlight the spatial occurrence of many anorthosite intrusions along known convergent plate boundaries. We posit that continental arcs are likely not the sole location, as many large bodies are known from collisional orogens, such as the Grenville Province (Emslie and Hunt, 1990). These examples likely formed from extensive mantle heating during extensional phases of this long-lived hot orogen (Indares, 2020).

A-type granites were first described from the Lachlan fold belt in SE Australia (Loiselle and Wones, 1979; Collins et al., 1982), where they are known to occur in back-arc settings (Kemp et al., 2009; Collins et al., 2020). Other well studied examples occur in post-collisional settings (Eby, 1990), and notably are now even recognised in the ongoing Himalayan-Tibetan orogen (Hao et al., 2019). Thus, both accretionary and collisional plate boundaries are common settings for A-type granitoids. Taking the well-known and spatially widespread 1.5–1.3 Ga A-types as examples (e.g., the Granite-Rhyolite Province of Laurentia), these were long considered to be devoid of convergent margin processes (Anderson and Bender, 1989); however, there is a growing body of work pointing to compressional tectonics across the region that hosts these suites (e.g., Gordon Medaris Jr et al., 2021), meaning they can now be potentially linked to orogenic rather than anorogenic formation. In summary, two lines of evidence do not support the single-lid hypothesis: (i) A-type granites and anorthosites are prevalent before and during amalgamation of the Columbia supercontinent, as well as younger periods in Earth history, indicating that they do not require heat generated from mantle insulation via a supercontinental lid; and (ii) these magma types are not necessarily indicative of anorogenic geodynamics, but are known to commonly form in convergent settings, either within distal back-arcs or regions of post-collisional lithospheric removal where mantle heat flow is elevated. Both lines of evidence are compatible and supporting of the plate tectonics hypothesis, respectively. In contrast, the single-lid hypothesis requires a mechanism of forming these granitoids in a position peripheral rather than central to the Columbia supercontinent.

3.7. *Mineralization distinction*

Mineral deposits show a heterogeneous distribution in time that has been discussed in many previous reviews (see Cawood and Hawkesworth, 2015 and references therein; Fig. 4b). We consider this distribution and its implications to primarily result from the interplay of four factors: (1) the supercontinent cycle imparts a strong preservation bias on mineral deposits based upon their tectonic setting; (2) preservation in the geological record depends on erosion level; (3) formation of different types of mineral deposits is linked to long-term secular trends in Earth-system conditions, such as mantle cooling and seawater composition; and (4) the record is dominated by exceptionally large mineral deposits that likely require special sets of conditions for formation (the Goldilocks effect), and thus are potentially not indicative of widespread global processes at that time. With reference to the mid-Proterozoic, there is a notable absence of orogenic Au, volcanic massive sulphide (VMS) and porphyry Cu, and a notable presence of Ni-Cu-sulphide, Fe-oxide Cu-Ag (IOCG), and uranium and clastic-dominated (CD)-Pb-Zn deposit types (Fig. 2b). Regarding the preservation of tectonic settings, the lack of orogenic Au and porphyry Cu deposits has been related to the deep erosional level of Precambrian rocks (Goldfarb et al., 2001; Kesler and Wilkinson, 2008). Richards and Mumin (2013) on the other hand, question the importance of erosional bias for the lack of porphyry systems in the Precambrian. They postulate that porphyry Cu ± Au and IOCG form in similar subduction-related environments, but that the Phanerozoic vs. Proterozoic prevalence, respectively, is due to higher geothermal gradients and lower seawater sulfate concentrations in the Precambrian oceans. Liu et al. (2019) postulate that the distribution during the Rodinia timeframe indicates a preservation bias whereby non-arc settings are preserved over arc settings in comparison to other supercontinents. Based on mineral occurrence distribution, notably the presence of HFSE enrichments, these authors also speculate the prevalence of lithosphere-asthenosphere interaction during the Mesoproterozoic, and a bias toward intraplate magmatism.

Does this unusual mineral deposit distribution support the single-lid hypothesis? Bias in the geological record and the unique nature of some mineral systems inhibits our ability to directly relate the temporal record with geodynamic processes. That being said, a potential link exists between the preserved magmatic and metallogenic record, whereby for the mid-Proterozoic, fore-arc related (I-type) magmas and minerals are apparently low in abundance relative to A-type magmas and mineral systems interpreted as 'intraplate' (Liu et al., 2019). If we accept that plate tectonics was in existence, this preservation would have to be explained by a process that destroyed fore-arc terranes, and preserved back-arc and inboard terranes. CD-Pb-Zn deposits can form in intracratonic rift basins, which is compatible with either single-lid or plate tectonic modes (i.e., as continental back-arcs; Ross and Villeneuve, 2003), but does require a mechanism for tectonic subsidence. Regarding the lack of 1.3–0.7 Ga CD-Pb-Zn deposits, this could relate to the style of orogenesis during Rodinia formation (Leach et al., 2010), whereby opposing subduction zones collided, rather than passive margins that can host such mineral deposits. In summary, there is evidence that arc-related ore deposits are low in abundance during the mid-Proterozoic, especially the Mesoproterozoic, which Stern (2020) cites as evidence for a single-lid regime. However, the existence of other deposit types would then also require special circumstances, since these form in post-collisional, intracratonic rift or back-arc extensional settings, all of which require a geodynamic driver for extension. Objectively, we therefore find the metallogenic record compatible with the hypothesis of plate tectonics, and in poor support of the single-lid hypothesis.

4. Discussion

Several lines of evidence commonly used to argue for and against the operation of plate tectonics at any point in Earth history are equivocal, and are contingent on formational and preservational biases; these are the presence (or absence) of passive margins, ophiolites, blueschists, and UHP metamorphic rocks. Other lines of evidence are still ambiguous, in that some lithologies can form in a variety of geodynamic settings, but in our view, can be used in support of a plate tectonic model; these are the abundances of anorthosites, A-type granites, and various mineral deposit types. Finally, there are lines of evidence that entirely support plate tectonics and are incompatible with a single-lid model; these are: (i) accretionary orogenic belts, associated I-type magmatism and deformation; and (ii) plate motions recorded by paleomagnetic data. The weight of evidence falls in favour of a plate tectonic setting throughout the mid-Proterozoic, and the argument for a single lid is equivocal at best, and is ultimately incompatible with the geological record. We acknowledge that we have omitted discussion on the records of igneous geochemistry and radiogenic isotopes (e.g., Hf and Nd); however, as demonstrated by long-lived and ongoing debate over Archean geodynamics, these are far from trivial (e.g. Johnson et al., 2016; Rollinson, 2022), and, given that the geochemical record resulting from a stagnant-lid regime has no modern analogues and would be difficult to reconstruct, is unlikely to provide any definitive answers.

Although evidence from the geological record falls in favour of plate tectonics since at least the Paleoproterozoic, the record of the mid-Proterozoic, and in particular the early to mid-Mesoproterozoic, is markedly different to the bounding time periods, and as such, demands explanation. Although this time period clearly warrants further detailed investigation, our solution is to advocate changes in lithosphere behaviour that are brought about by elevated mantle temperatures compared to today.

Three key features of the Mesoproterozoic geological record that require explanation are an abundance of high-temperature magmatism, an abundance of higher thermobaric ratios of metamorphic rocks, and a lack of certified indicators of subduction (ophiolites, blueschists, and UHP metamorphic rocks). We assume the following: (i) between 1.85 and 0.85 Ga, the potential mantle temperature was on average 80–120°C hotter than today (Fig. 5a), which leads to distinctly different styles of geodynamics at convergent plate boundaries; and (ii) a global network of plate tectonic boundaries had been initiated before the mid-Proterozoic, possibly as late as ca. 2 Ga (Condie, 2021b), or as early as ca. 3 Ga (Cawood et al., 2018). Following the geodynamic modelling of Sizova and others (e.g., Sizova et al., 2010, 2014; Chowdhury et al., 2020), the mid-Proterozoic is predicted to be a transitional period falling between orogenic styles of the Archean and those that characterise the Phanerozoic (Roberts et al., 2015; Sizova et al., 2010, 2014; Chowdhury et al., 2021; Figs. 5b-5c). Although the scope of this paper is not to postulate any of the much-debated Archean tectonic styles, combined geodynamic and petrological modelling predict that convergent margins in the mid to late Archean would have comprised: episodic slab subduction with rapid breaking and drop-off of the slab, peeling back of the lithosphere exposing the upper plate to hot mantle, and no deep subduction of continental material (e.g., Sizova et al., 2010, 2014; Fischer and Gerya, 2016; Chowdhury et al., 2017, 2020). During the Archean, these 'horizontal' tectonic styles likely became more dominant through time, with 'vertical' tectonic processes not associated with convergent margins, i.e. sagduction, becoming less prevalent. Capitanio et al. (2019) summarise this change from stagnant lid, to 'lid and plate', to plate tectonics reminiscent of modern Earth. In contrast to the mid-Proterozoic and older eons, Phanerozoic mantle temperatures allow for sustained slab subduction of oceanic crust, and deep subduction of continental crust (Sizova et al., 2014; van Hunen and van den Berg, 2008). Condie (2021b) argues that 2.5–2.0 and 1.0–0.5 Ga are key timeframes bounding this transitional period, marking the onset and establishment of global subduction, and the onset of continental lithospheric subduction, respectively.

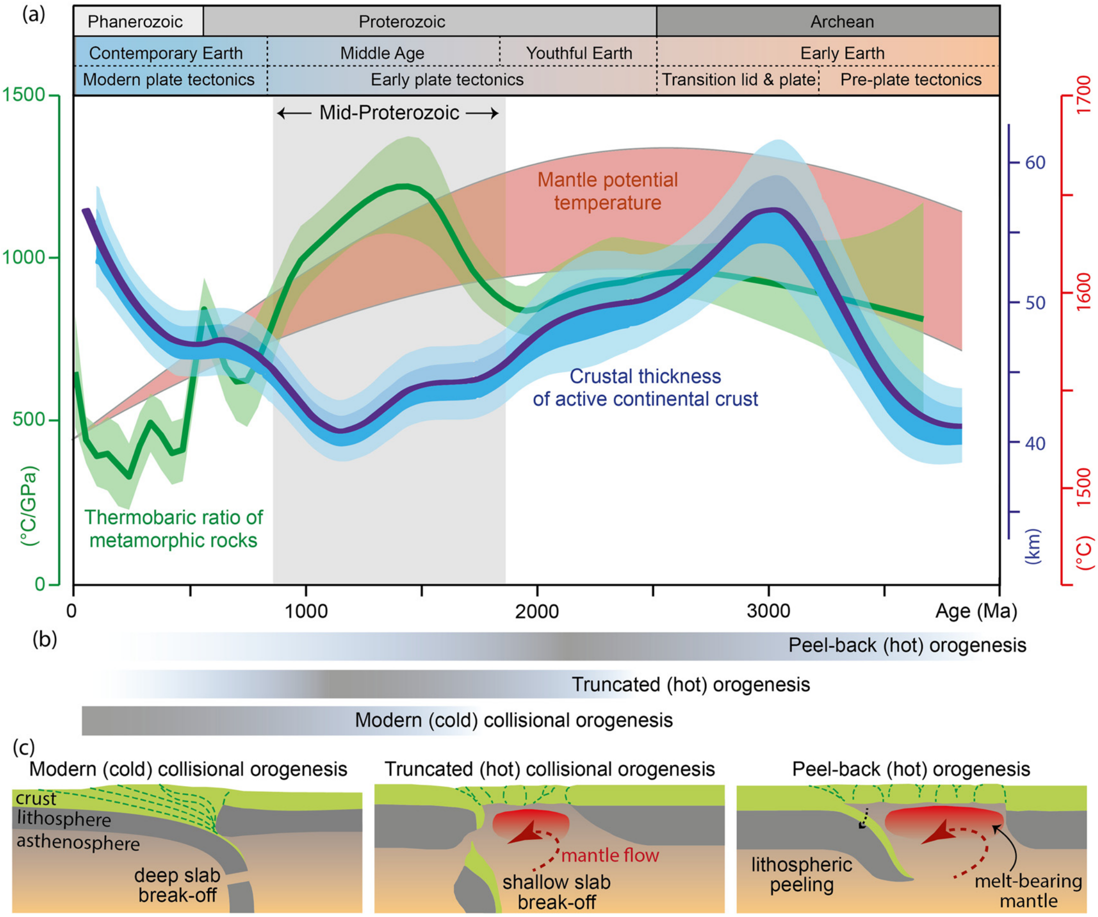

Fig. 5. (a) Top panels show geological eons and divisions of Earth history based on our current understanding of changing geodynamic regimes, from Cawood (2020). Red band shows the average potential mantle temperature (Herzberg et al., 2010). Blue uncertainty bands and curve are an estimate of crustal thickness using the zircon Eu anomaly proxy (Tang et al., 2021). Green band and curve are a lowess smoothing trend through the global metamorphic record (Brown and Johnson, 2019). (b) Estimates of changing geodynamic regimes at convergent plate margins, based on Sizova et al. (2014) and Chowdhury et al. (2021); the potential geodynamic regimes of the Hadean and Paleoarchean are controversial and omitted for clarity. (c) Simplified cartoon cross sections of the evolving geodynamic regimes shown in b, modified from Chowdhury et al. (2020, 2021).

Sizova et al. (2014) demonstrated that a transitional phase at Δ80–100°C (i.e., in the mid to late-Proterozoic) would lead to formation of 'truncated hot orogens' and 'two-sided hot collisional orogens'. Truncated hot orogens are characterised by no deep continental subduction, shallow slab breakoff, low (or even negative) topography, and abundant melt-bearing mantle between the continental plates. Two-sided collisional orogens have similarities, but with lower degrees of extension due to reduced slab-pull, and melt-bearing mantle underlying the downgoing 'lower' plate. Aspects of these hot orogens are found within the Proterozoic orogenic record, for example, those involved in Rodinia formation such as the ca. 1.1–0.9 Ga Grenville and Sveconorwegian orogens (Turlin et al., 2018; Indares, 2020; Bingen et al., 2021). Although continental subduction is precluded in the 'hot orogen' geodynamic models, it is noteworthy that ca. 0.98 Ga continental subduction is recorded in the Sveconorwegian hinterland (Möller et al., 2015), implying an overlap between the 'modern' and 'transitional' regimes (Sizova et al., 2014) of collisional orogenesis in the late Mesoproterozoic to Neoproterozoic. Also notable in the geological record is the potentially thin crust in 'active' (i.e., zircon-forming) regions (Tang et al., 2021; Fig. 5a); however, the robustness of the Eu anomaly proxy for crustal thickness applied to the Precambrian is not yet quantified. Thin and weak lithosphere in the mid-Proterozoic is in accord with the metamorphic record of higher thermobaric ratios during orogenesis (Spencer et al., 2021). The geodynamics of ocean-facing convergent margins have a similar fate under increased mantle temperatures to those of continental collision zones (Sizova et al., 2010). Decompression melting in the mantle would have been greater in volume under mid-Proterozoic mantle temperatures, as would the amount of extension in the over-riding plate (Sizova et al., 2010). Therefore, we suggest that the differences in geodynamics between the mid-Proterozoic and the Phanerozoic, although much smaller compared to the differences between the modern and the Mesoarchean, would lead to significant differences in the abundances of magmatic rock associations, mineral systems and metamorphic field gradients.

All of the geodynamic changes described above were imposed on a time period when the continents were likely amassed into a single supercontinent or only a few continental fragments. Although it is not exactly known how numerous and dispersed continental fragments were during the Columbia to Rodinia supercontinent transition, Columbia appears to have fragmented only partially, and over a long time period. The fact that the Mesoproterozoic comprised a single or a few 'supercontinental plates', added to the enigmatic nature of this time, lends itself to low abundances in plate tectonic indicators such as passive margin onsets. Thus, the combined effects of secular cooling of the mantle and of the long-lived Columbia supercontinent, can adequately explain the geological record of the mid-Proterozoic within a plate tectonic framework, and do not require alternatives such as single-lid tectonics. During the tenure of the Columbia supercontinent, the world's oceans were most likely divided into several separate oceanic plates with intervening mid-ocean ridges and oceanic island arcs, much like the present-day Pacific Ocean; however, this part of the geological record would have poor preservation potential (Spencer et al., 2017) and has been totally lost.

Plate tectonics is a geodynamic regime whereby the plates are coupled to convection in the mantle; in single- or stagnant-lid regimes convection is decoupled. Although the mid-Proterozoic, particularly the Mesoproterozoic, likely comprised few continental landmasses in a framework close to a single lid, the record of ongoing continental drift, orogenesis and convergent margin magmatism, implies an ongoing coupling of convection between the mantle and crust – i.e., plate tectonics was active on Earth since at least 2 Ga, as has also been documented paleomagnetically (Mitchell et al., 2014).

Our study highlights several areas that require further detailed investigation and modelling, and we pose the following questions: (i) Was continental subduction possible in the Paleoproterozoic, but restricted in the Mesoproterozoic due to sub-continental mantle heating (Tamblyn et al., 2022), or is the metamorphic record biased by preservation rather than formation?; (ii) Is mantle heating from supercontinent insulation a requirement for any of the features of the mid-Proterozoic geological record?; (iii) Does preservation bias, such as a deeper erosion levels, explain the lack of preserved ophiolites and/or the dearth of some high-level ore deposit types, such as porphyry copper? If not, what controls the formation and preservation of these deposit types through different eons?; (iv) Given that the ratio of fluid-fluxed to decompression melting at convergent margins will change as a result of mantle temperature (Sizova et al., 2010), how does this balance impact the generation and preservation of magmatic and metallogenic suites? We suggest that an improved geodynamic context of the mid-Proterozoic should help better understand the enigmatic relative biologic and climate stasis of the contemporaneous ‘Boring Billion’ and the links between tectonics and Earth’s surface processes.

5. Conclusions

The mid-Proterozoic, and the Mesoproterozoic in particular, was neither orogenically quiescent, nor tectonically stagnant; it was merely host to geodynamics that differ from the modern Earth as a result of two processes working in tandem: secular cooling of the mantle and a long-lived supercontinent whose breakup was slow and incomplete. The 1.6–1.1 Ga period was dominated by geologic activity occurring along the margins of either a single supercontinental plate (Columbia), or a few plates. We acknowledge that this scenario may give the false impression that the whole Earth consisted of one single plate, and therefore single-lid tectonics might have operated; however, long-lived subduction-related magmatism along the active margin of Columbia, and the plate motions and deformation associated with the transformation from Columbia to Rodinia, collectively attest to the operation of plate tectonics throughout this period, and both lines of evidence are incompatible with single-lid tectonics. Since seafloor spreading and subduction on Earth today are fastest in the oceanic plates of the Pacific Ocean, one should clearly not interpret such long-lived supercontinentality as a single lid. The predicted behaviour of the mid-Proterozoic continental lithosphere with a hotter subcontinental mantle (80–120°C above present) accord with the geological record, but further work should interrogate how the various peculiarities of the mid-Proterozoic can be placed within this geodynamic framework, and how each facet of the geological record is affected by both formation and preservation biases.

CRediT authorship contribution statement

Nick M.W. Roberts: Conceptualization, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Johanna Salminen:** Formal analysis, Visualization, Writing – original draft. **Åke Johansson:** Writing – review & editing. **Ross N. Mitchell:** Conceptualization, Writing – original draft, Writing – review & editing. **Richard M. Palin:** Conceptualization, Writing – original draft, Writing – review & editing. **Kent C. Condie:** Writing – review & editing. **Christopher J. Spencer:** Conceptualization, 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

NR publishes with the permission of the Director of the British Geological Survey. This work forms part of NR’s role in the National Environmental Isotope Facility, funded by the UK Natural Environment Research Council (NE/S011587/1). RM acknowledges funding from the National Science Foundation of China (41888101). This is a contribution to International Geoscience Programme (IGCP) 648 (Supercontinent Cycles and Global Geodynamics) and Deep-time Digital Earth (DDE). The authors thank two anonymous reviewers for comments that improved the paper.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2022.117749.

References

Anderson, J.L., Bender, E.E., 1989. Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States of America. Lithos 23 (1–2), 19–52.
Ashwal, L.D., Bybee, G.M., 2017. Crustal evolution and the temporality of anorthosites. Earth-Sci. Rev. 173, 307–330.
Bingen, B., Viola, G., Möller, C., Vander Auwera, J., Laurent, A., Yi, K., 2021. The Sveconorwegian orogeny. Gondwana Res. 90, 273–313.
Bispo-Santos, F., D'Agrella-Filho, M.S., Pesonen, L.J., Salminen, J.M., Reis, N.J., Silva, J.M., 2020. The long life of SAMBA connection in Columbia: a paleomagnetic study of the 1535 Ma Mucajaí Complex, northern Amazonian Craton, Brazil. Gondwana Res. 80, 285–302.
Bradley, D.C., 2008. Passive margins through earth history. Earth-Sci. Rev. 91 (1–4), 1–26.
Brown, M., Johnson, T., 2018. Secular change in metamorphism and the onset of global plate tectonics. Am. Mineral.: J. Earth Planet. Mater. 103 (2), 181–196.
Brown, M., Johnson, T., 2019. Time’s arrow, time’s cycle: granulite metamorphism and geodynamics. Mineral. Mag. 83 (3), 323–338.
Buchan, K.L., Mitchell, R.N., Bleeker, W., Hamilton, M.A., LeCheminant, A.N., 2016. Paleomagnetism of ca. 2.13–2.11 Ga Indin and ca. 1.885 Ga Ghost dyke swarms of the Slave craton: implications for the Slave craton APW path and relative drift of Slave, Superior and Siberian cratons in the Paleoproterozoic. Precambrian Res. 275, 151–175.
Capitanio, F.A., Nebel, O., Cawood, P.A., Weinberg, R.F., Clos, F., 2019. Lithosphere differentiation in the early Earth controls Archean tectonics. Earth Planet. Sci. Lett. 525, 115755.
Cawood, P.A., 2020. Earth Matters: A tempo to our planet’s evolution. Geology 48 (5), 525–526.
Cawood, P.A., Buchan, C., 2007. Linking accretionary orogenesis with supercontinent assembly. Earth-Sci. Rev. 82 (3–4), 217–256.
Cawood, P.A., Hawkesworth, C.J., 2015. Temporal relations between mineral deposits and global tectonic cycles. Geol. Soc. (Lond.) Spec. Publ. 393 (1), 9–21.
Cawood, P.A., Hawkesworth, C.J., Pisarevsky, S.A., Dhuime, B., Capitanio, F.A., Nebel, O., 2018. Geological archive of the onset of plate tectonics. Philos. Trans. R. Soc. A, Math. Phys. Eng. Sci. 376 (2132), 20170405.
Cawood, P.A., Kroner, A., Pisarevsky, S., 2006. Precambrian plate tectonics: criteria and evidence. GSA Today 16 (7), 4.

Cawood, P.A., Strachan, R., Cutts, K., Kinny, P.D., Hand, M., Pisarevsky, S., 2010. Neoproterozoic orogeny along the margin of Rodinia: Valhalla orogen, North Atlantic. Geology 38 (2), 99–102.

Chowdhury, P., Chakraborty, S., Gerya, T.V., 2021. Time will tell: secular change in metamorphic timescales and the tectonic implications. Gondwana Res. 93, 291–310.

Chowdhury, P., Chakraborty, S., Gerya, T.V., Cawood, P.A., Capitanio, F.A., 2020. Peel-back controlled lithospheric convergence explains the secular transitions in Archean metamorphism and magmatism. Earth Planet. Sci. Lett. 538, 116224.

Chowdhury, P., Gerya, T., Chakraborty, S., 2017. Emergence of silicic continents as the lower crust peels off on a hot plate-tectonic Earth. Nat. Geosci. 10 (9), 698–703.

Collins, W.J., Beams, S.D., White, A.J.R., Chappell, B.W., 1982. Nature and origin of A-type granites with particular reference to southeastern Australia. Contrib. Mineral. Petrol. 80 (2), 189–200.

Collins, W.J., Huang, H.Q., Bowden, P., Kemp, A.I.S., 2020. Repeated S–I–A-type granite trilogy in the Lachlan Orogen and geochemical contrasts with A-type granites in Nigeria: implications for petrogenesis and tectonic discrimination. Geol. Soc. (Lond.) Spec. Publ. 491 (1), 53–76.

Coltice, N., Bertrand, H., Rey, P., Jourdan, F., Phillips, B.R., Ricard, Y., 2009. Global warming of the mantle beneath continents back to the Archaean. Gondwana Res. 15 (3–4), 254–266.

Condie, K.C., 2013. Preservation and recycling of crust during accretionary and collisional phases of Proterozoic orogens: a bumpy road from Columbia to Rodinia. Geosciences 3 (2), 240–261.

Condie, K.C., 2021a. Revisiting the mesoproterozoic. Gondwana Res. 100, 44–52.

Condie, K.C., 2021b. Two major transitions in Earth history: evidence of two lithospheric strength thresholds. J. Geol. 129 (5), 455–473.

Condie, K.C., Pisarevsky, S.A., Puetz, S.J., 2021. LIPs, orogens and supercontinents: the ongoing saga. Gondwana Res. 96, 105–121.

Dilek, Y., 2003. Ophiolite pulses, mantle plumes and orogeny. Geol. Soc. (Lond.) Spec. Publ. 218 (1), 9–19.

Eby, G.N., 1990. The A-type granitoids: a review of their occurrence and chemical characteristics and speculations on their petrogenesis. Lithos 26 (1–2), 115–134.

Elming, S.Å, Salminen, J., Pesonen, L.J., 2021. Paleo-Mesoproterozoic Columbia supercycle. In: Ancient Supercontinents and the Paleogeography of Earth. Elsevier, pp. 499–548.

Emslie, R.F., Hunt, P.A., 1990. Ages and petrogenetic significance of igneous mangerite-charnockite suites associated with massif anorthosites, Grenville Province. J. Geol. 98 (2), 213–231.

Ernst, W.G., Sleep, N.H., Tsujimori, T., 2016. Plate-tectonic evolution of the Earth: bottom-up and top-down mantle circulation. Can. J. Earth Sci. 53 (11), 1103–1120.

Evans, D.A., 2003. True polar wander and supercontinents. Tectonophysics 362 (1–4), 303–320.

Evans, D.A., 2013. Reconstructing pre-Pangean supercontinents. Bulletin 125 (11–12), 1735–1751.

Evans, D.A., 2021. Meso-Neoproterozoic Rodinia supercycle. In: Ancient Supercontinents and the Paleogeography of Earth. Elsevier, pp. 549–576.

Evans, D.A., Pesonen, L.J., Eglington, B.M., Elming, S.Å, Gong, Z., Li, Z.X., McCausland, P.J., Meert, J.G., Mertanen, S., Pisarevsky, S.A., Pivarunas, A.F., 2021. An expanding list of reliable paleomagnetic poles for Precambrian tectonic reconstructions. In: Ancient Supercontinents and the Paleogeography of Earth. Elsevier, pp. 605–639.

Fischer, R., Gerya, T., 2016. Regimes of subduction and lithospheric dynamics in the Precambrian: 3D thermomechanical modelling. Gondwana Res. 37, 53–70.

Furnes, H., Dilek, Y.D., De Wit, M., 2015. Precambrian greenstone sequences represent different ophiolite types. Gondwana Res. 27 (2), 649–685.

Ganade de Araujo, C.E., Cordani, U.G., Weinberg, R.F., Basei, M.A., Armstrong, R., Sato, K., 2014. Tracing Neoproterozoic subduction in the Borborema Province (NE-Brazil): clues from U-Pb geochronology and Sr-Nd-Hf-O isotopes on granitoids and migmatites. Lithos 202, 167–189.

Ganne, J., De Andrade, V., Weinberg, R.F., Vidal, O., Dubacq, B., Kagambega, N., Naba, S., Baratoux, L., Jessell, M., Allibon, J., 2012. Modern-style plate subduction preserved in the Palaeoproterozoic West African craton. Nat. Geosci. 5 (1), 60–65.

Ganne, J., Feng, X., 2017. Primary magmas and mantle temperatures through time. Geochem. Geophys. Geosyst. 18 (3), 872–888.

Goldfarb, R.J., Groves, D.I., Gardoll, S., 2001. Rotund versus skinny orogens: well-nourished or malnourished gold? Geology 29 (6), 539–542.

Gordon Medaris Jr, L., Singer, B.S., Jicha, B.R., Malone, D.H., Schwartz, J.J., Stewart, E.K., Van Lankvelt, A., Williams, M.L., Reiners, P.W., 2021. Early Mesoproterozoic evolution of midcontinental Laurentia: defining the geon 14 Baraboo orogeny. Geosci. Front. 12 (5), 101174.

Gurnis, M., 1988. Large-scale mantle convection and the aggregation and dispersal of supercontinents. Nature 332 (6166), 695–699.

Hamilton, W.B., 1998. Archean magmatism and deformation were not products of plate tectonics. Precambrian Res. 91 (1–2), 143–179.

Hao, L.L., Wang, Q., Wyman, D.A., Ma, L., Wang, J., Xia, X.P., Ou, Q., 2019. First identification of postcollisional A-type magmatism in the Himalayan-Tibetan orogen. Geology 47 (2), 187–190.

Hawkesworth, C.J., Cawood, P.A., Dhuime, B., 2016. Tectonics and crustal evolution. GSA Today. https://doi.org/10.1130/GSATG272A.1.

Herzberg, C., Condie, K., Korenaga, J., 2010. Thermal history of the Earth and its petrological expression. Earth Planet. Sci. Lett. 292 (1–2), 79–88.

Hoffman, P.F., 1989. Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga). Geology 17 (2), 135–138.

Holder, R.M., Viete, D.R., Brown, M., Johnson, T.E., 2019. Metamorphism and the evolution of plate tectonics. Nature 572 (7769), 378–381.

Holland, H.D., 2006. The oxygenation of the atmosphere and oceans. Philos. Trans. R. Soc. B, Biol. Sci. 361 (1470), 903–915.

Indares, A., 2020. Deciphering the metamorphic architecture and magmatic patterns of large hot orogens: insights from the central Grenville Province. Gondwana Res. 80, 385–409.

Johansson, Å., 2009. Baltica, Amazonia and the SAMBA connection—1000 million years of neighbourhood during the Proterozoic? Precambrian Res. 175 (1–4), 221–234.

Johansson, Å., Bingen, B., Huhma, H., Waight, T., Vestergaard, R., Soesoo, A., Skridlaite, G., Krzeminska, E., Shumlyanskyy, L., Holland, M.E., Holm-Denoma, C., Teixeira, W., Faleiros, F.M., Ribeiro, B.V., Jacobs, J., Wang, C.-C., Thomas, R.B., Macey, P.M., Kirkland, C.L., Hartnady, M.I.H., Eglington, B.M., Puetz, S.J., Condie, K.C., 2022. A geochronological review of magmatism along the external margin of Columbia and in the Grenville-age orogens forming the core of Rodinia. Precambrian Res. 371, 106463. https://doi.org/10.1016/j.precamres.2021.106463. 43 pp.

Johnson, T.E., Brown, M., Goodenough, K.M., Clark, C., Kinny, P.D., White, R.W., 2016. Subduction or sagduction? Ambiguity in constraining the origin of ultramafic–mafic bodies in the Archean crust of NW Scotland. Precambrian Res. 283, 89–105.

Kemp, A.I.S., Hawkesworth, C.J., Collins, W.J., Gray, C.M., Blevin, P.L., 2009. Isotopic evidence for rapid continental growth in an extensional accretionary orogen: the Tasmanides, eastern Australia. Earth Planet. Sci. Lett. 284 (3–4), 455–466.

Kesler, S.E., Wilkinson, B.H., 2008. Earth's copper resources estimated from tectonic diffusion of porphyry copper deposits. Geology 36 (3), 255–258.

Kirscher, U., Mitchell, R.N., Liu, Y., Nordsvan, A.R., Cox, G.M., Pisarevsky, S.A., Wang, C., Wu, L., Murphy, J.B., Li, Z.X., 2021. Paleomagnetic constraints on the duration of the Australia-Laurentia connection in the core of the Nuna supercontinent. Geology 49 (2), 174–179.

Leach, D.L., Bradley, D.C., Huston, D., Pisarevsky, S.A., Taylor, R.D., Gardoll, S.J., 2010. Sediment-hosted lead-zinc deposits in Earth history. Econ. Geol. 105 (3), 593–625.

Li, C., Liu, Z., Dong, X., Xu, Z., Wen, K., Wang, S., Wang, C., Gao, Y., 2021. Mesoproterozoic ($\sim$1.4 Ga) magmatism in the Liaoyuan Accretionary Belt, NE China: new implications for tectonic affinity and crustal evolution of microcontinents along the southern Central Asian Orogenic Belt. Precambrian Res. 365, 106389.

Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2008. Assembly, configuration, and break-up history of Rodinia: a synthesis. Precambrian Res. 160, 179–210.

Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Evans, D.A.D., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., 2009. How not to build a supercontinent: a reply to JDA Piper. Precambrian Res. 174 (1–2), 208–214.

Liu, C., Runyon, S.E., Knoll, A.H., Hazen, R.M., 2019. The same and not the same: Ore geology, mineralogy and geochemistry of Rodinia assembly versus other supercontinents. Earth-Sci. Rev. 196, 102860.

Loiselle, M.C., Wones, D.R., 1979. Characteristics and origin of anorogenic granites. Abstr. Program – Geol. Soc. Am. 12 (7), 468.

Loose, D., Schenk, V., 2018. 2.09 Ga old eclogites in the Eburnian-Transamazonian orogen of southern Cameroon: significance for Palaeoproterozoic plate tectonics. Precambrian Res. 304, 1–11.

Martin, E.L., Spencer, C.J., Collins, W.J., Thomas, R.J., Macey, P.H., Roberts, N.M.W., 2020. The core of Rodinia formed by the juxtaposition of opposed retreating and advancing accretionary orogens. Earth-Sci. Rev. 211, 103413.

Mitchell, R.N., 2014. True polar wander and supercontinent cycles: implications for lithospheric elasticity and the triaxial Earth. Am. J. Sci. 314 (5), 966–979.

Mitchell, R.N., Bleeker, W., Van Breemen, O., Lecheminant, T.N., Peng, P., Nilsson, M.K., Evans, D.A., 2014. Plate tectonics before 2.0 Ga: evidence from paleomagnetism of cratons within supercontinent Nuna. Am. J. Sci. 314 (4), 878–894.

Möller, C., Andersson, J., Dyck, B., Lundin, I.A., 2015. Exhumation of an eclogite terrane as a hot migmatitic nappe, Sveconorwegian orogen. Lithos 226, 147–168.

Palin, R.M., Moore, J.D., Zhang, Z., Huang, G., Wade, J., Dyck, B., 2021. Mafic Archean continental crust prohibited exhumation of orogenic UHP eclogite. Geosci. Front. 12 (5), 101225.

Palin, R.M., Santosh, M., Cao, W., Li, S.S., Hernández-Uribe, D., Parsons, A., 2020. Secular change and the onset of plate tectonics on Earth. Earth-Sci. Rev. 207, 103172.

Palin, R.M., White, R.W., 2016. Emergence of blueschists on Earth linked to secular changes in oceanic crust composition. Nat. Geosci. 9 (1), 60–64.

Parsons, B., 1981. The rates of plate creation and consumption. Geophys. J. Int. 67 (2), 437–448.

Piper, J.D., 2013. A planetary perspective on Earth evolution: lid tectonics before plate tectonics. Tectonophysics 589, 44–56.

Piper, J.D.A., 2018. Dominant Lid Tectonics behaviour of continental lithosphere in Precambrian times: Palaeomagnetism confirms prolonged quasi-integrity and absence of supercontinent cycles. Geosci. Front. 9 (1), 61–89.

Pisarevsky, S.A., Elming, S.Å, Pesonen, L.J., Li, Z.X., 2014. Mesoproterozoic paleogeography: supercontinent and beyond. Precambrian Res. 244, 207–225.

Pourteau, A., Smit, M.A., Li, Z.X., Collins, W.J., Nordsvan, A.R., Volante, S., Li, J., 2018. 1.6 Ga crustal thickening along the final Columbia suture. Geology 46 (11), 959–962.

Richards, J.P., Mumin, A.H., 2013. Magmatic-hydrothermal processes within an evolving Earth: Iron oxide-copper-gold and porphyry Cu±Mo±Au deposits. Geology 41 (7), 767–770.

Roberts, N.M.W., 2013. The boring billion?–Lid tectonics, continental growth and environmental change associated with the Columbia supercontinent. Geosci. Front. 4 (6), 681–691.

Roberts, N.M.W., Slagstad, T., 2015. Continental growth and reworking on the edge of the Columbia and Rodinia supercontinents; 1.86–0.9 Ga accretionary orogeny in southwest Fennoscandia. Int. Geol. Rev. 57 (11–12), 1582–1606.

Roberts, N.M.W., Slagstad, T., Viola, G., 2015. The structural, metamorphic and magmatic evolution of Mesoproterozoic orogens. Precambrian Res. 265, 1–9.

Rollinson, H., 2022. No plate tectonics necessary to explain Eoarchean rocks at Isua (Greenland). Geology 50, 147–151.

Ross, G.M., Villeneuve, M., 2003. Provenance of the Mesoproterozoic (1.45 Ga) Belt basin (western North America): another piece in the pre-Rodinia paleogeographic puzzle. Geol. Soc. Am. Bull. 115 (10), 1191–1217.

Salminen, J., Pesonen, L.J., Mertanen, S., Vuollo, J., Airo, M.L., 2009. Palaeomagnetism of the Salla Diabase Dyke, northeastern Finland, and its implication for the Baltica-Laurentia entity during the Mesoproterozoic. Geol. Soc. (Lond.) Spec. Publ. 323 (1), 199–217.

Sizova, E., Gerya, T., Brown, M., 2014. Contrasting styles of Phanerozoic and Precambrian continental collision. Gondwana Res. 25 (2), 522–545.

Sizova, E., Gerya, T., Brown, M., Perchuk, L.L., 2010. Subduction styles in the Precambrian: insight from numerical experiments. Lithos 116 (3–4), 209–229.

Spencer, C.J., Mitchell, R.N., Brown, M., 2021. Enigmatic Mid-Proterozoic Orogens: hot, thin, and low. Geophys. Res. Lett. 48 (16), e2021GL093312.

Spencer, C.J., Roberts, N.M.W., Santosh, M., 2017. Growth, destruction, and preservation of Earth's continental crust. Earth-Sci. Rev. 172, 87–106.

Stern, R.J., 2005. Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time. Geology 33 (7), 557–560.

Stern, R.J., 2020. The mesoproterozoic single-lid tectonic episode: prelude to modern plate tectonics. GSA Today 30 (12), 4–10.

Stern, R.J., Gerya, T., Tackley, P.J., 2018. Stagnant lid tectonics: perspectives from silicate planets, dwarf planets, large moons, and large asteroids. Geosci. Front. 9 (1), 103–119.

Swanson-Hysell, N.L., Ramezani, J., Fairchild, L.M., Rose, I.R., 2019. Failed rifting and fast drifting: Midcontinent Rift development, Laurentia's rapid motion and the driver of Grenvillian orogenesis. GSA Bull. 131 (5–6), 913–940.

Tamblyn, R., Hasterok, D., Hand, M., Gard, M., 2022. Mantle heating at ca. 2 Ga by continental insulation: evidence from granites and eclogites. Geology 50 (1), 91–95.

Tang, M., Chu, X., Hao, J., Shen, B., 2021. Orogenic quiescence in Earth's middle age. Science 371 (6530), 728–731.

Tsujimori, T., Ernst, W.G., 2014. Lawsonite blueschists and lawsonite eclogites as proxies for palaeo-subduction zone processes: a review. J. Metamorph. Geol. 32 (5), 437–454.

Turlin, F., Deruy, C., Eglinger, A., Vanderhaeghe, O., André-Mayer, A.S., Poujol, M., Moukhsil, A., Solgadi, F., 2018. A 70 Ma record of suprasolidus conditions in the large, hot, long-duration Grenville Orogen. Terra Nova 30 (3), 233–243.

van Hunen, J., van den Berg, A.P., 2008. Plate tectonics on the early Earth: limitations imposed by strength and buoyancy of subducted lithosphere. Lithos 103 (1–2), 217–235.

Volante, S., Pourteau, A., Collins, W.J., Blereau, E., Li, Z.X., Smit, M., Evans, N.J., Nordsvan, A.R., Spencer, C.J., McDonald, B.J., Li, J., 2020. Multiple P–T–d–t paths reveal the evolution of the final Columbia assembly in northeast Australia. J. Metamorph. Geol. 38 (6), 593–627.

Wang, Z., Wang, Z., Zhang, Y., Xu, B., Li, Y., Tian, Y., Wang, Y., Peng, J., 2022. Linking∼1.4–0.8 Ga volcano-sedimentary records in eastern Central Asian orogenic belt with southern Laurentia in supercontinent cycles. Gondwana Res. 105, 416–431.

Weller, O.M., St-Onge, M.R., 2017. Record of modern-style plate tectonics in the Palaeoproterozoic Trans-Hudson orogen. Nat. Geosci. 10 (4), 305–311.

Whitmeyer, S.J., Karlstrom, K.E., 2007. Tectonic model for the Proterozoic growth of North America. Geosphere 3 (4), 220–259.

Xia, B., Zhang, L., Du, Z., Xu, B., 2019. Petrology and age of Precambrian Aksu blueschist, NW China. Precambrian Res. 326, 295–311.

Zahirovic, S., Müller, R.D., Seton, M., Flament, N., 2015. Tectonic speed limits from plate kinematic reconstructions. Earth Planet. Sci. Lett. 418, 40–52.

Zhang, S., Li, Z.X., Evans, D.A., Wu, H., Li, H., Dong, J., 2012. Pre-Rodinia supercontinent Nuna shaping up: a global synthesis with new paleomagnetic results from North China. Earth Planet. Sci. Lett. 353, 145–155.

Zhao, G., Cawood, P.A., Wilde, S.A., Sun, M., 2002. Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. Earth-Sci. Rev. 59 (1–4), 125–162.

Zhu, Z., Campbell, I.H., Allen, C.M., Brocks, J.J., Chen, B., 2022. The temporal distribution of Earth's supermountains and their potential link to the rise of atmospheric oxygen and biological evolution. Earth Planet. Sci. Lett. 580, 117391.

Further reading

Stern, R.J., 2018. The evolution of plate tectonics. Philos. Trans. R. Soc. A, Math. Phys. Eng. Sci. 376, 20170406.