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Pannotia: To be or not to be?

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ABSTRACT

Following a decade during which its presence was widely accepted, the existence of the putative Ediacaran supercontinent Pannotia has come into question since the turn of the millenium, largely due to the geochronology of Ediacaran-Cambrian orogens, which suggests that the supposed landmass had begun to break up well before it was fully assembled. Paleomagnetic data from this time interval have been used to both support and refute the existence of Pannotia, but are notoriously equivocal. Proxy signals for Ediacaran-Cambrian supercontinent assembly and breakup, although collectively compelling, can be individually challenged, and efforts to detect the mantle legacy expected of supercontinent amalgamation, while promising, are inconclusive. Yet the existence of Pannotia is central to the nature, duration and evolution of the supercontinent cycle, and dictates the cycle's geodynamic pathway from the breakup of Rodinia to the assembly of Pangea. Hence, the question of Pannotia's existence, like that of Hamlet, is one of fundamental importance and demands far more attention than it has hitherto received.

1. Introduction

Over the past two decades, the putative Ediacaran-Cambrian supercontinent Pannotia has introduced an ironic twist in the notion, embodied by the concept of the supercontinent cycle, that a significant proportion of Earth history has been underscored by the episodic assembly and breakup of supercontinents, at which time most of the continents are assembled into a single landmass. Of the various pre-Pangean supercontinents that have gained recognition during this period (e.g., Rodinia, Nuna/Columbia, Kenorland), Pannotia might be expected to be best understood since it was the first to be proposed (Valentine and Moores, 1970) and is geologically the most recent. It was also the candidate for which the case was considered strongest when the supercontinent cycle was first advanced four decades ago (Worsley et al., 1984, 1985; Nance et al., 1986, 1988). But at the very time that the supercontinent cycle has gained popularity, the existence of Pannotia has come into question. Cases have been made both in favor (e.g., Nance and Murphy, 2019; Murphy et al., 2021) and against (e.g., Evans, 2021) the reality of this supercontinent, and in many studies its existence is acknowledged (e.g., Golonka et al., 2006; Scotese, 2009, 2021; Kröner et al., 2021). But in an increasing number of recent studies, Pannotia is either disputed (e.g., Oriolo et al., 2017), discounted (e.g., Merdith et al., 2017; Merdith et al., 2021; Li et al., 2019; Cawood et al., 2021; Condie et al., 2021; Mitchell et al., 2021; Pesonen et al., 2021; Wang et al., 2021), or ignored.

The implications are profound. The existence or non-existence of Pannotia not only dictates the interval over which the supercontinent cycle takes place, but it also determines the geodynamic pathway followed by the cycle from the breakup of its predecessor, Rodinia, to the assembly of its successor, Pangea, more than 500 million years later.

In this article, we briefly outline the origin of Pannotia's fall from grace and review the evidence in favor of its existence and the arguments against it. We then examine the ramifications of either outcome and suggest possible avenues by which the vital issue of its existence might be resolved.

2. Background

The existence of an end-Precambrian supercontinent was first suggested on the basis of faunal diversity by Valentine and Moores (1970, 1972) in a pair of pioneering papers linking such diversity to patterns of continental breakup and assembly, and accompanying changes in sea level (Fig. 1). Recognizing that marine regression and increased seasonality during continental assembly should cause both sea level and

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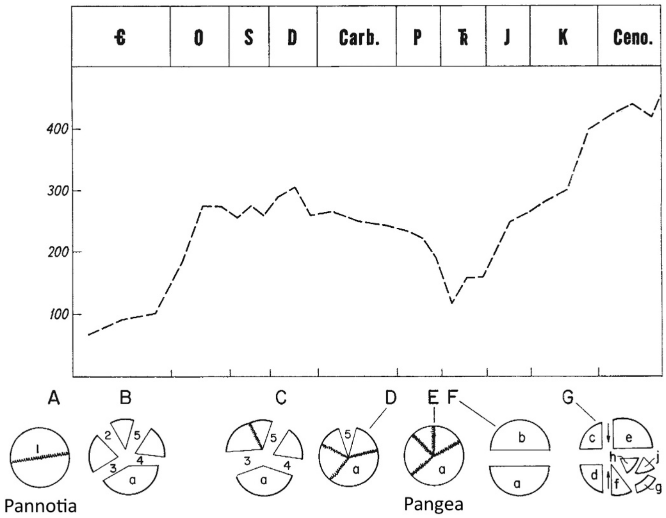

Fig. 1. Phanerozoic correlation of biological diversity and patterns of continental assembly and breakup (modified from Valentine and Moores, 1970). A = Ediacaran suturing of Pan African-Baikalian system (1) and formation of Pannotia (their Pangaea I); B = Cambrian-Ordovician breakup to produce Paleozoic oceans (2 = Iapetus, 3, 4 = Rheic, 5 = paleo-Uralian); C = Silurian-Devonian Caledonian suturing; D = Pennsylvanian-Permian Appalachian-Variscan suturing; E = Permian-Triassic Uralian suturing to form Pangea (their Pangaea II); F = Triassic-Lower Jurassic opening of Tethys; G = Cretaceous-Recent Tethys closure and opening of the Atlantic. a = Gondwana, b = Laurasia, c = North America, d = South America, e = Eurasia, f = Africa, g = Antarctica, h = India, j = Australia.

faunal diversity to be lowest following the assembly of a supercontinent, as evidenced by Pangea (their Pangaea II), they argued that a similar pattern associated with Pan African-Baikalian continental assembly pointed to the existence of an earlier (“Eocambrian”) supercontinent (their Pangaea I).

The existence of a supercontinent in the late Neoproterozoic first found paleomagnetic support in Morel and Irving (1978), although Piper (1976) had previously proposed the existence of a supercontinent throughout much of the Proterozoic (spanning the tenure of both Rodinia and Pannotia), and others had suggested that a supercontinent had assembled in the late Mesoproterozoic and had broken up during the Neoproterozoic (e.g., Stewart, 1976; Sawkins, 1976). The breakup of a late Neoproterozoic supercontinent at 625-555 Ma was subsequently advanced by Bond et al. (1984) based on tectonic subsidence curves for early Paleozoic passive margins in North and South America, Australia and the Middle East. It was also a proposed supercontinent enduring until the Ediacaran-Cambrian transition that McMenamin and McMenamin (1990) called Rodinia (from the Russian *rodit*, to beget) because it incubated the earliest animals and spawned the Phanerozoic continents.

With the moniker Rodinia subsequently appropriated as the name of an earlier, Meso-Neoproterozoic supercontinent (see Evans, 2013, 2021, for brief historical discussions of the nomenclature), the proposed late Neoproterozoic supercontinent, referred to as “Vendia” by Duncan and Turcott (1994) and “Greater Gondwanaland” by Stern (1994), was renamed Pannotia (from the Greek for “all southern”) by Powell (1995). The name was derived from the term “Pannotios” coined by Stump (1987) for a cycle of Neoproterozoic sedimentation and tectonic activity common to the southern (Gondwana) continents that ended with the formation of a supercontinent. A full reconstruction of the configuration of this late Neoproterozoic supercontinent that included Siberia (Fig. 2a) was first provided by Dalziel (1991, 1992) and figured prominently in his subsequent synthesis of Neoproterozoic-Paleozoic geography and tectonics incorporating all available paleomagnetic, geological and faunal data (Dalziel, 1997). Subsequent reconstructions for the Ediacaran are shown in Fig. 2b-g.

2.1. Paleomagnetic and geochronological uncertainties

Pannotia initially enjoyed broad recognition as a potential supercontinent, but since 2000, its authenticity has been brought into question. Paleomagnetism and geochronology, when applied to the global tectonostratigraphic record, are the two principal data sources upon which the existence of past supercontinents usually hinge. An initial paleomagnetic challenge to Pannotia’s existence was raised by an apparently wide separation between near-equatorial Laurentia and the south-polar Amazonian sector of Gondwana at 550 Ma (McCausland and Hodych, 1998), suggesting that the Iapetus oceanic tract long preceded Gondwana assembly and that the Appalachian rift-drift transition merely marked the separation of a ribbon-like terrane into that realm (Cawood et al., 2001). However, the Ediacaran-Cambrian interval is notorious for highly dispersed paleomagnetic datasets that could hint at non-uniformitarian processes such as oscillatory inertial interchange true polar wander (Evans, 1998) or a nonuniformitarian magnetic field (Abrajevitch and Van der Voo, 2010; Halls et al., 2015; Meert et al., 2016; Bono et al., 2019; Thallner et al., 2021), or both of these processes acting in concert. Consequently, whereas some paleomagnetic reconstructions of the past two decades are supportive of the supercontinent (e.g., Dalziel, 1997, 2013; Meert and Lieberman, 2004; Scotese, 2017) (Figs. 2a, c, f), others are equivocal (e.g., Cordani et al., 2003; Rino et al., 2008; Robert et al., 2018) (Figs. 2b, d), and yet others refute its existence (e.g., Li et al., 2008; Merdith et al., 2017, 2021; Zhao et al., 2018; Wen et al., 2020; Robert et al., 2020, 2021; Evans, 2021) (Figs. 2e, g). Given these considerations, it has not been possible to substantiate Pannotia paleomagnetically.

At the same time, increasingly precise absolute age constraints on Ediacaran-Cambrian stratigraphy and tectonics opened the possibility that continental breakup began well before the landmass was fully assembled. As Hoffman (1991) presciently described the emerging geochronological debate, “not surprisingly, some question the reality of a supercontinent that may have disintegrated before it had formed.” The putative assembly of Pannotia is attributed to Pan African-Brasiliano orogenesis and the uniting of Gondwana cratons, to which Laurentia, Baltica and perhaps Siberia should have remained attached (e.g., Dalziel, 1997; Meert and Van Der Voo, 1997; Blakey, 2008; Scotese, 2009). Late Neoproterozoic continental breakup, on the other hand, took place with the separation of Laurentia, Baltica and Siberia from the West Gondwana cratons, reflecting the opening of the Iapetus and Tornquist oceans (e.g., Cawood et al., 2001). The timing of the collisional orogenesis of assembly spans the broad interval ca. 700-500 Ma, with peaks at ca. 650-600 Ma and 570-530 Ma, based on the ages of associated magmatism and metamorphism (e.g., Meert, 2003; Kröner and Stern, 2004; Oriolo et al., 2017; Schmitt et al., 2018), and inferred from the age spectra of detrital zircon and monazite in modern river systems (e.g., Rino et al., 2008; Itano et al., 2016).

The breakup interval of ca. 625-555 Ma documented by Bond et al. (1984) corrects to ca. 605-520 Ma in accordance with the revised geological timescale of Gradstein et al. (2020). Precise radiometric ages for rift-related magmatic rocks broadly concur with this estimate. On the eastern margin of Laurentia, magmatic activity spanning the interval ca. 615-550 Ma is traditionally linked to Iapetus Ocean opening (Kamo et al., 1989), although there remains the possibility that only a ribbon-like continental fragment dispersed at that time into an already-wide proto-Iapetan oceanic tract developed earlier, in mid-Neoproterozoic time (Cawood et al., 2001; Waldron and van Staal, 2001; Chew et al., 2008; Escayola et al., 2011; Casquet et al., 2012; Rapela et al., 2016; Robert et al., 2020, 2021). Such a scenario would seem to preclude a conjoined landmass containing Laurentia and a united Gondwana, but even the traditional model, in which the passive margin succession along eastern margin of Laurentia is related to Iapetus opening, merits scrutiny of the geochronological data for testing possible Pannotia connections. Evidence of rifting in eastern Laurentia, southwestern Baltica, and Oaxaquia in the form of mafic dikes is as old as 620-615 Ma

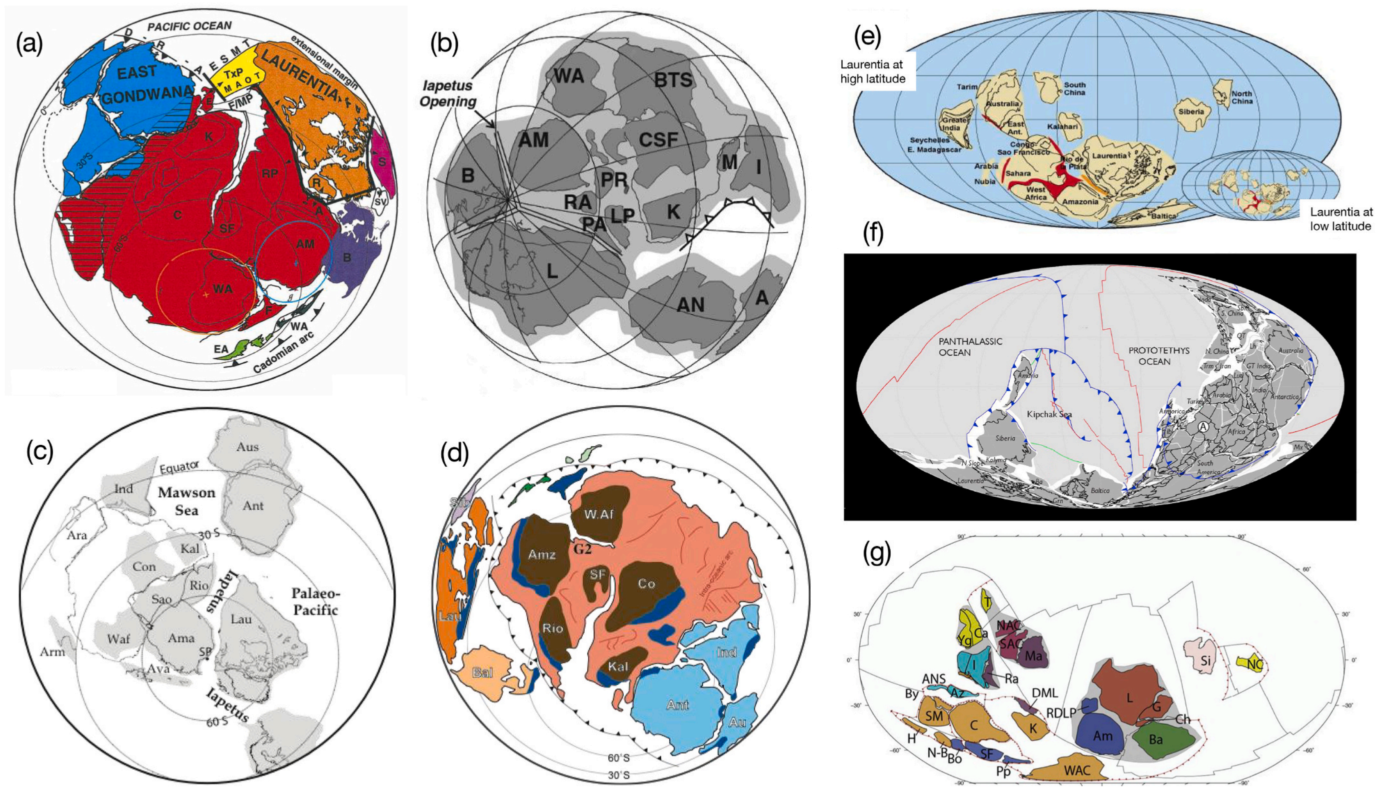

Fig. 2. Continental reconstructions for the Ediacaran at: (a) ca. 545 Ma (Dalziel (1997), (b) ca. 600–580 Ma (Cordani et al., 2003), (c) ca. 580 Ma (Meert and Lieberman, 2004), (d) ca. 540 Ma (Rino et al., 2008), (e) ca. 600 Ma (Li et al., 2008), (f) ca. 600 Ma (Scotese, 2017), and (g) ca. 600 Ma (Merdith et al., 2017). (a) Horizontal shading = East African collisional orogen involving East and West Gondwana; thick lines = incipient mid-Iapetus ridges, crosses with 95% confidence circles = paleomagnetic poles; AM = Amazonia, B = Baltica, C = Congo, D-R-A = Delamarian–Ross arc, E = Ellsworth-Whitmore, ESMT = hypothetical Ellsworth–Sonora–Mojave transform, F = Florida, F/MP = Falkland–Malvinas Plateau, K = Kalahari, MAOT = hypothetical Malvinas–Alabama–Oklahoma transform, R = Rockall, RP = Rio de la Plata, S = Siberia; SF = São Francisco, SV = Svalbard, TxP = hypothetical Texas plateau, WA = West African Craton, EA = East Avalonia, WA = West Avalonia. (b) A = Australia, AM = Amazonia, AN = Antarctica, B = Baltica, BTS = Borborema–Trans-Sahara, CSF = Congo–São Francisco, I = India, K = Kalahari, L = Laurentia, LP = Rio de la Plata, M = Madagascar, PA = Pampea, PR = Paraná, RA = Rio Apa, WA = West Africa. (c) Ama = Amazonia, Ant = Antarctica, Ara = Arabia, Arm = Armorica, Aus = Australia, Ava = Avalonia, Bal = Baltica, Con = Congo, Ind = India, Kal = Kalahari, Lau = Laurentia, Rio = Rio de la Plata, São = São Francisco, Sib = Siberia, Waf = West Africa. (d) Amz = Amazonia, Ant = Antarctica, Au = Australia, Bal = Baltica, Co = Congo, Ind = India, Kal = Kalahari, Lau = Laurentia, Rio = Rio de la Plata, SF = São Francisco, Sib = Siberia, WAf = West Africa. (e) East Ant = East Antarctic, (f) A = Pannotia, Ba = Barents, Grn = Greenland, GT India = Greater India, Ib = Iberia, Indo = Indochina, Lh = Lhasa, Lut = Lut Block (Iran), Md = Madagascar, Mx = northern Mexico, QT = QiangTang, Sbm = Sibumasu (Siam, Burma, Malaysia, and Sumatra), Trm = Tarim. (g) Am = Amazonia, Az = Azania, Ba = Baltica, Bo = Borborema, By = Bayuda, C = Congo, Ca = Cathaysia (South China), Ch = Chortis, G = Greenland, H = Hoggar, I = India, K = Kalahari, L = Laurentia, Ma = Mawson, NAC = North Australian Craton, N-B = Nigeria-Benin, NC = North China, Pp = Paranapanema, Ra = Rayner (Antarctica), RDLP = Rio de la Plata, SAC = South Australian Craton, SF = São Francisco, Si = Siberia, SM = Sahara Metacraton, WAC = West African Craton. For further details on these reconstructions, the reader is refered to the original publication.

(Kamo et al., 1989; Kamo and Gower, 1994; Bingen et al., 1998; Weber et al., 2019), but magmatism is likely to have remained within a rift setting until ca. 570-550 Ma (e.g., Puffer, 2002). The youngest rift-related magmatism is ca. 555-550 Ma in Newfoundland (Cawood et al., 2001), ca. 550 Ma in the Central Iapetus Magmatic Province (CIMP; e.g., Ernst et al., 2013; Youbi et al., 2020) of the northern Appalachians and Morocco, and ca. 540-530 Ma in the Wichita igneous province of southern Oklahoma (Hanson et al., 2013; Wall et al., 2021). Collectively, these data suggest a southward propagating rift-drift transition starting at ca. 540-535 Ma. The earliest drift-related sedimentation is probably no older than ca. 525-520 Ma (Cawood et al., 2001). Mafic magmatism attributed to rift and drift leading to the opening of the Tornquist Ocean has been dated at ca. 550 Ma (Compston et al., 1995; Vidal and Moczydlowska, 1995; Krzywiec et al., 2018), which broadly coincides with some estimates for the onset of spreading between Siberia and Laurentia (e.g., Sears and Price, 2003; Merdith et al., 2017).

The assembly of Pan African and related orogens clearly began well before the opening of these oceans. But was it complete by this time? Gondwana was largely assembled by ca. 550 Ma (Meert, 2003; Meert and Lieberman, 2008), but uncertainty surrounds the timing of its final amalgamation. Consequently, while many of the younger Pan African ages date post-tectonic events, the possibility remains that important tectonic elements of Gondwana did not finally assemble until the Cambrian. Among these are the São Francisco and Rio de Plata cratons and their assembly to Amazonia at ca. 540-510 Ma (e.g., Tohver et al., 2006, 2010; Schmitt et al., 2008; McGee et al., 2018; Rapalini, 2018), and those elements of eastern Gondwana (Australia-East Antarctica) that were assembled during the ca. 570-500 Ma Kuunga orogeny (e.g., Meert, 2003; Collins and Pisarevsky, 2005; Boger, 2011; Schmitt et al., 2018). Hence, it remains unclear whether there is leeway for the amalgamation of a short-lived supercontinent sometime in the interval ca. 620-550 Ma.

So while a wealth of data indicates that the Ediacaran-Cambrian interval starts with widespread orogenesis and ends with widespread rifting, serious questions remain as to whether the period witnessed the assembly and breakup of a supercontinent. In the absence of compelling paleomagnetic data and a clear geochronologic record, cases for (Nance and Murphy, 2019) and against (Evans, 2021) the existence of Pannotia have turned to the interpretation of proxy signals.

2.2. Proxy evidence for supercontinent assembly and breakup

When supercontinents are viewed not as isolated phenomena, but as a stage in the supercontinent cycle, a variety of tectonic, climatic and biogeochemical signals associated with the cycle can be used to infer intervals of supercontinent amalgamation and break-up (e.g., Worsley et al., 1985; Bradley, 2011; Hawkesworth et al., 2010). Prominent among these signals are collisional orogeny, continental rifting, major changes in sea level and climate, and major extinctions and evolutionary radiations. Additionally, parameters such as continental perimeter/area and arc length (e.g., Merdith et al., 2019) are likely to become pivotal proxies as paleogeographic reconstructions improve.

2.2.1. Collisional orogenesis and continental rifting

Of all supercontinent proxies, the most obvious are the association of worldwide collisional orogenesis, zircon age peaks and granitoid magmatism with continental assembly (e.g., Condie and Aster, 2013); and the association of mafic dike swarms, rift magmatism and large igneous provinces (LIPs) with continental breakup and dispersal (e.g., Yale and Carpenter, 1998; Ernst et al., 2008, 2013; Condie et al., 2021). Indeed, it was through interpretation of the geologic significance of these proxy records that the supercontinent cycle was first proposed (Fischer, 1984; Worsley et al., 1984, 1985). For Pannotia, the associated Pan African-Brasiliano collisional orogens, which climaxed over the interval ca. 650-530 Ma, were some of the most widespread in Earth history (Rino et al., 2008). This global-scale orogenic activity is coeval with a strong zircon age peak at 630-540 Ma (e.g., Puetz et al., 2018) (Fig. 3) and a major cluster of orogenic granitoid ages at 650-550 Ma (Condie and Aster, 2010; Condie and Aster, 2013). Conversely, evidence of continental rifting occurs in the form of mafic dike swarms, most notably in Laurentia and Baltica (e.g., Cawood et al., 2001; Weber et al., 2019), rift-related igneous activity (see Cawood et al., 2001, Fig. 7) and LIPs such as the Wichita (e.g., Hanson et al., 2013; Wall et al., 2021), Baltoscandian (e.g., Kumpulainen et al., 2021) and Central Iapetus Magmatic Province (e.g., Ernst et al., 2013; Youbi et al., 2020), the ages of which collectively span the interval ca. 615-530 Ma.

On the assumption that the timing of supercontinent amalgamation is recorded by the onset of collisional orogenesis rather than its termination, and that supercontinent breakup is diachronous, these temporally overlapping proxies have been considered permissive of the assembly and breakup of a short-lived supercontinent sometime in the interval 620-550 Ma (e.g., Nance and Murphy, 2019). The counterargument, summarized by Evans (2021), contends that the chronologic constraints only barely permit the existence of Pannotia and, then, only under the most favorable of tectonic interpretations. These constraints raise the question as to whether Pannotia, if it existed, survived for a sufficient length of time to have any effect on the broader Earth system, including mantle convection patterns that are geodynamically connected to plate motions and the supercontinent cycle. Furthermore, Ediacaran orogenesis, and the zircon and granitoid age peaks with which it is associated, could simply record the assembly of Gondwana rather than a full Pannotia supercontinent. Likewise, the Cambrian rifting events described above can be interpreted as either a continuation of the mid-Neoproterozoic breakup of Rodinia (e.g., Li et al., 2008) or merely the separations of smaller continental fragments unrelated to classic notions of the supercontinental cycle. Indeed, the early Paleozoic LIP record is modest in comparison with those associated with the fragmentation of both mid-Neoproterozoic Rodinia and Mesozoic Pangea (Ernst et al., 2021; Condie et al., 2021).

2.2.2. Global sea level

Supercontinent assembly and breakup should also be accompanied by major changes in global sea level (e.g., Fischer, 1984; Worsley et al., 1984; Heller and Angevine, 1985). Supercontinent amalgamation should be associated with very low sea level if supercontinents are thermally uplifted as a result of mantle insulation and continental lid epeirogeny (e.g., Coltice et al., 2007; Ganne et al., 2016; Guillaume et al., 2016) or the rise of mantle plumes beneath them (e.g., Zhong et al., 2007; Li and Zhong, 2009; Mitchell et al., 2021). Conversely, supercontinent breakup should be associated with rapid sea level rise as the dispersing continental fragments cool and subside and new oceans open at the expense of old ones with a consequent increase in ridge volume (e.g., Cogné et al., 2006; Wright et al., 2020). Conventional sea level curves (e.g., Vail et al., 1977; Hallam, 1992; Haq and Schutter, 2008) broadly support this relationship for Pannotia (Nance and Murphy, 2019), with the pattern of Ediacaran to Ordovician sea level change – very low sea level followed by rapid sea level rise – being similar to the Permian-Cretaceous pattern of sea level change associated with the amalgamation and breakup of Pangea (Fig. 4a).

However, as pointed out by Evans (2021), traditional estimates of Phanerozoic sea level carry large uncertainties, including an assumption of continental hypsometry (e.g., Hallam, 1992; Algeo and Seslavinsky, 1995) and the weighting of various cratonic records (e.g., Conrad, 2013). Furthermore, recent estimates of Phanerozoic sea level that attempt to avoid these potential pitfalls, such as those of Vérard et al. (2015), which employs a bathymetry based on global plate reconstructions, and van der Meer et al. (2017), which uses Sr isotopic data as a proxy for sea level (Fig. 4b), show patterns of sea level change

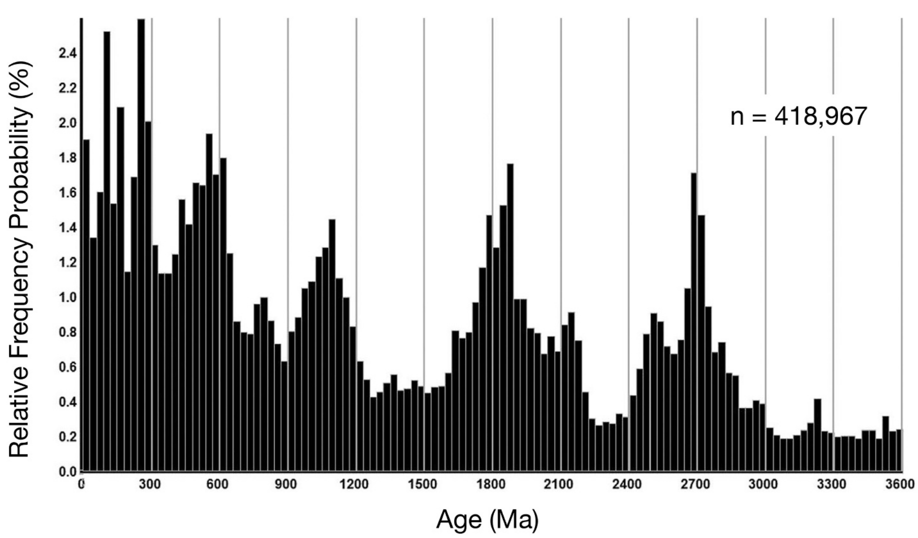

Fig. 3. Global U-Pb age-histograms (30-Myr bin-sizes) weighted by area and converted to relative frequency probability (Puetz et al., 2018).

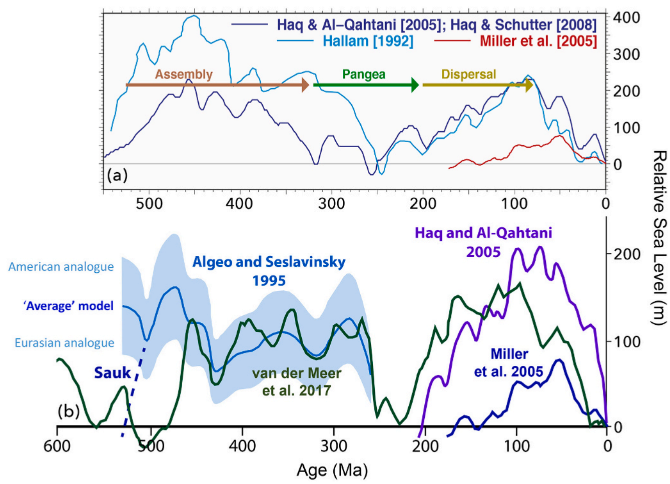

Fig. 4. Estimates of Phanerozoic sea-level change: (a) Sea-level curves of Hallam (1992), Haq and Al-Qahtani (2005), Miller et al. (2005) and Haq and Schutter (2008) compared with timing of Pangea assembly, tenure and breakup (after Conrad, 2013), and, in addition, (b) those of Algeo and Seslavinsky (1995) based on Paleozoic modelling using alternative 'analogues' for continental hypsometry based on modern elevation profiles, and van der Meer et al. (2017) based on Sr isotopic data (modified after Evans, 2021). Sauk transgression of Laurentia stylized from Miller et al. (2005).

at the Ediacaran-Cambrian boundary that are less consistent with the existence of Pannotia. Although these estimates are also laden with assumptions, they raise legitimate concerns regarding the fidelity of Pannotia's sea-level proxy record.

2.2.3. Climate

Supercontinents can be expected to perturb global climate through their influence on silicate weathering (e.g., Marshall et al., 1988; Kump et al., 2000; Goddéris et al., 2014). Following supercontinent amalgamation, silicate weathering of an epeirogenically uplifted supercontinent and the orogenic belts associated with its assembly should lead to drawdown of atmospheric carbon dioxide and consequent climatic cooling. Conversely, supercontinent breakup should be associated with global warming because the dispersing continental fragments flood as they cool and subside, reducing silicate weathering and allowing atmospheric carbon dioxide levels to build (e.g., Nance et al., 1988). This pattern of icehouse climate followed by greenhouse climate (Fig. 5), which is exemplified by the Carboniferous-Permian amalgamation and Mesozoic breakup of Pangea (e.g., Goddéris et al., 2017a; Scotese et al., 2021), also broadly occurs in the Ediacaran and Early Paleozoic (Craig et al., 2009), consistent with the existence of Pannotia (Nance and Murphy, 2019).

Countering this pattern and its application to Pannotia (Evans, 2021), the protracted Sturtian glaciation (ca. 717-663 Ma; e.g., Rooney et al., 2015; Cox et al., 2018; Lan et al., 2020) demonstrably coincides with the breakup of the supercontinent Rodinia rather than its amalgamation (e.g., Li et al., 2008, 2013), whereas the shorter-lived Marinoan glaciation (ca. 650-635 Ma; e.g., Rooney et al., 2015; Hoffman et al., 2017; Bao et al., 2018) occurred prior to the proposed timing of Pannotia amalgamation. Likewise, refined chronostratigraphy (e.g., Boucot et al., 2013; Evans, 2021) suggests that the Late Paleozoic Gondwana glaciation likely preceded the peak of Pangea's amalgamation. Evans (2021) has further cautioned that, whereas it can be argued that the venting of carbon dioxide associated with the emplacement of LIPs during rifting might transiently add to the warming trend following supercontinent breakup (e.g., Ernst and Youbi, 2017), in the longer term, the effect of LIP basalt weathering should be one of climatic cooling (e.g., Donnadieu et al., 2004).

2.2.4. Biological diversity

Given the profound effects of the supercontinent cycle on global sea level, and the direct connectivity of continents and their margins (e.g., Worsley et al., 1984; Cogné et al., 2006; Wright et al., 2020),

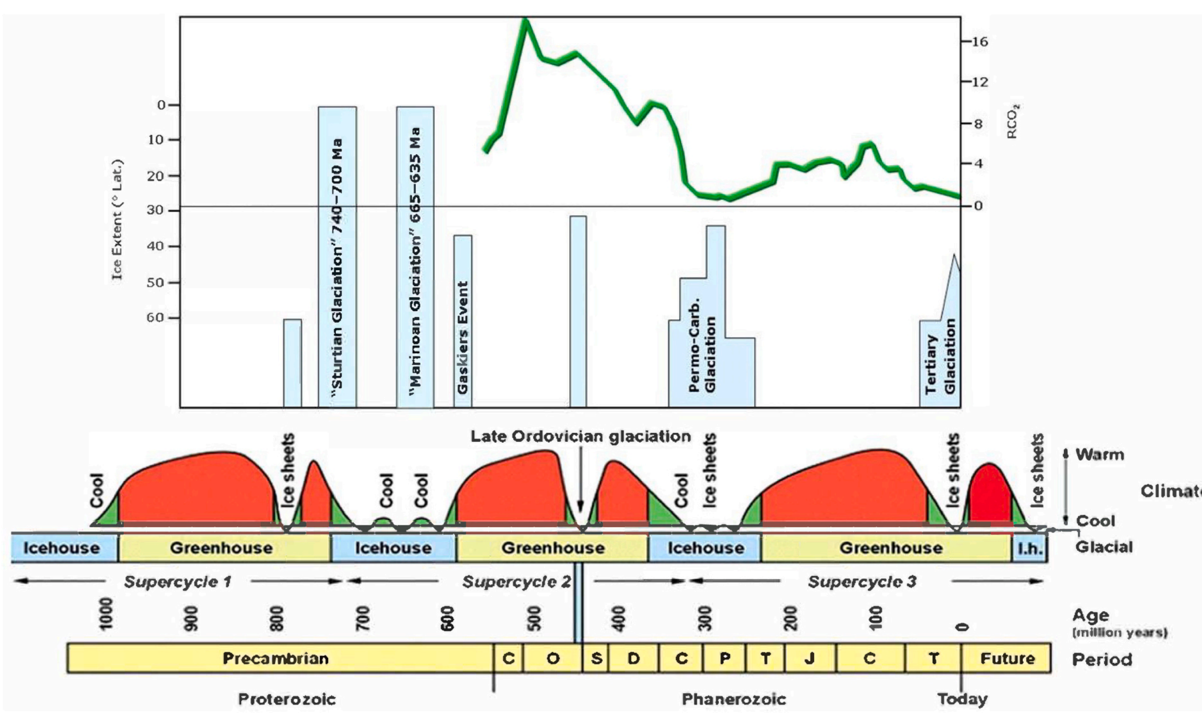

Fig. 5. Global climate, episodes and extent of continental glaciation, and atmospheric CO_2 levels relative to present day for the past billion years (from Craig et al., 2009). Maximum ice cover during the main periods of glaciation (shown in degrees of latitude from the poles), is inferred from the preservation of glacigenic sediments and climate modelling (after Crowell, 1999). Global climate change (red and green identifying periods of warm and cool climate, respectively) based on geological data summarized by Coppold and Powell (2000).

supercontinent amalgamation and breakup can be expected to have a major influence on biological diversity (e.g., Valentine and Moores, 1970, 1972). A variety of factors are likely to promote extinctions during supercontinent amalgamation, including increased competition among species as the number of independent continents decreases, and loss of much of the shallow-marine habitat as mantle insulation and continental lid epeirogeny combine to raise the continental shelves above sea level (e.g., Haq and Schutter, 2008; Vérard et al., 2015). Conversely, supercontinent breakup is likely to be accompanied by major evolutionary radiation and enhanced marine productivity as a result (among other causes) of the creation of new, underpopulated shallow-marine habitat as sea level rises and the continents flood (Nance et al., 1988; Peters and Gaines, 2012), and the increased release of nutrients from continental weathering (e.g., Campbell and Allen, 2008; Zhu et al., 2022).

In support of this relationship, the major end-Permian extinction that defines the end of the Paleozoic nearly coincides with the final amalgamation of Pangea, whereas the major biological radiation that characterizes the onset of the Mesozoic coincides with Pangea breakup, as evidenced by the total diversity curve for the Phanerozoic (Fig. 6a). Likewise, the assembly of Pannotia reportedly coincides with major extinctions among stromatolites, acritarchs and other palynoflora (e.g., Grey et al., 2003; Young, 2015; Peters et al., 2017), and was followed during breakup by a rapid increase in diversity, first with appearance of Ediacara biota (e.g, Narbonne and Gehling, 2003; Meert and Lieberman, 2008) and then with the Cambrian explosion (e.g., Briggs, 2015; Darroch et al., 2018; Landing et al., 2018; Bowyer et al., 2022).

Countering this argument, the nature and timing of Pannotia-linked extinctions is fraught with uncertainty (Evans, 2021), for example, in imprecise taxonomy (Riding, 2011) and uneven preservation (Cohen and Macdonald, 2015). In addition, the overall decline in stromatolites appears to have started well before the Ediacaran (Peters et al., 2017) and the Cambrian explosion may have been initiated in the Ediacaran (e.g., Erwin et al., 2011; Schiffbauer et al., 2016; Darroch et al., 2018). Furthermore, if the total diversity curve is subdivided into its component (Cambrian, Paleozoic and modern) faunal associations (Fig. 6b), the two-peaked synoptic curve of Figure 6a can be seen to superimpose subsets that, with exception of the Paleozoic fauna, show little similarity to the pattern of the overall curve. Finally, climatic and environmental deterioration as a consequence of rift-related LIP volcanism may cause major extinction events (e.g., end-Triassic) during supercontinent breakup (e.g., Blackburn et al., 2013; Bond and Grasby, 2017; Percival et al., 2017), which would disrupt any long-term biological radiation.

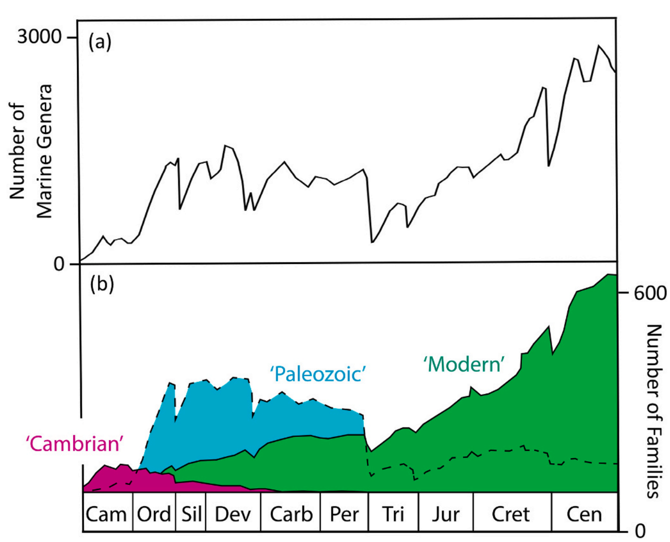

Fig. 6. Phanerozoic faunal diversity. (a) Total number of marine genera (from Sepkoski Jr., 1982), and (b) family-level diversity curves for three component (Cambrian, Paleozoic and Modern = Mesozoic/Cenozoic) faunal associations identified by Sepkoski Jr. (1984) (from Evans, 2021).

2.2.5. *Other proxies*

In addition to these conspicuous proxies of supercontinent assembly and breakup, there are other, more subtle tracers that include: (i) extreme (granulite-UHT, eclogite-HP and HP-UHP) conditions of metamorphism during the collisional orogenesis of supercontinent amalgamation (Brown, 2007a, 2007b); (ii) negative εHf and elevated $\delta^{18}O$ values in zircon as a result, respectively, of enhanced crustal recycling and reworking of sedimentary material during supercontinent assembly (e.g., Collins et al., 2011; Condie and Aster, 2013; Van Kranendonk and Kirkland, 2016), and more juvenile εHf values in zircon indicative of crustal growth during periods of break-up (Gardiner et al., 2016); (iii) major changes in atmospheric composition, including carbon dioxide levels and an abrupt increase in oxygen following breakup, possibly as a result of enhanced marine photosynthesis associated with increased biological activity (Campbell and Allen, 2008; Zhu et al., 2022); (iv) major changes in ocean geochemistry including possible $^{87}Sr/^{86}Sr$ maxima in seawater during supercontinent amalgamation and breakup due to the erosional influx of strongly radiogenic strontium from elevated continental crust coupled with a reduced input of low $^{87}Sr/^{86}Sr$ flux from fewer ocean spreading centers (e.g., Bradley, 2011; Condie and Aster, 2013; Goddéris et al., 2017b; van der Meer et al., 2017; Paulsen et al., 2022); (vi) major potential negative $\delta^{13}C$ excursions indicative of a reorganization of the Earth's carbon cycle in response to the influence of supercontinent assembly on life (e.g., Kaufman et al., 1993; Ripperdan, 1994; Payne et al., 2004); (vii) low marine platform $\delta^{34}S$ during amalgamation as a possible result of the sequestering of isotopically heavy sulfur in evaporites (Worsley et al., 1985; Worsley and Nance, 1989; Condie et al., 2001); and (viii) extensive passive margin development during the continental dispersal that follows supercontinent breakup (Bradley, 2008).

The assembly and breakup of Pangea is clearly evident in the Phanerozoic record of these proxies and it can be argued that the Ediacaran record is likewise consistent with the existence of Pannotia (Nance and Murphy, 2019). However, as with the more prominent proxies, the record of these tracers and their link to supercontinent assembly and breakup is open to alternative interpretations (Evans, 2021). It can be argued, for example, that (i) the proxies for supercontinent amalgamation reflect the universally accepted assembly of Gondwana rather than a full-fledged Pannotia supercontinent; (ii) the interpretation of the $^{87}Sr/^{86}Sr$ record in seawater and, to a lesser degree, εHf values in zircon is inconsistent with the assembly and breakup of Pangea (e.g., Algeo et al., 2015; Van Kranendonk and Kirkland, 2016), negating any straightforward link to the supercontinent cycle; (iii) the overall Cambrian to Permian decline in zircon εHf and marine $^{87}Sr/^{86}Sr$ values (e.g., Collins et al., 2011; Condie and Aster, 2013; Paulsen et al., 2022) argues against a Paleozoic supercontinent cycle; (iv) recent studies of atmospheric and marine oxygenation note the limitations of the proxy record, the temporal resolution of which is inadequate to be confidently linked to any global tectonic setting (Cole et al., 2020; Tostevin and Mills, 2020); (v) a variety of causes and interpretation have been proposed to account for the large carbon isotopic variations that characterize the Ediacaran-Cambrian (e.g., Grotzinger et al., 2011; Boyle et al., 2018; Shields, 2018; Hoffman and Lamothe, 2019); (vi) the marine ^{34}S record is more sensitive to pyrite burial than evaporite formation and is difficult to interpret due to a complex interplay between oxygenation and cycling of carbon, iron and sulfur (Berner, 2006); and (vii) the increase in the length of passive margins attributed to Pannotia breakup is modest compared to that accompanying the dispersal of Pangea and Rodinia (Bradley, 2008).

Finally, supercontinent amalgamation is likely to be associated with episodes of true polar wander (Evans, 1998, 2003; Zhong et al., 2007; Li and Zhong, 2009) as a result of the accompanying change in the distribution of mass in the Earth's mantle and lithosphere. True polar wander occurs in response to the need for Earth's axis of maximum moment of inertia to be aligned with its rotation axis in order to minimize the planet's rotational energy (Goldreich and Toomre, 1969). The effect is to bring positive mass anomalies to the equator, which, in the case of supercontinents, brings high-latitude continental masses to low latitudes.

During the Ediacaran, from 615 Ma to 590 Ma and, again, from 575 Ma to 565 Ma, such equatorial movements are seen in the apparent polar wander paths of several continents, notably Laurentia, Baltica and West Africa (e.g., Abrajevitch and Van der Voo, 2010; Robert et al., 2017). Explanations for these phenomena include unreliable paleomagnetic and/or age data (e.g., Hodych et al., 2004), an unstable geodynamo (e.g., Abrajevitch and Van der Voo, 2010; Halls et al., 2015; Meert et al., 2016; Bono et al., 2019; Thallner et al., 2021), and rapid true polar wander (e.g., Evans, 2003; McCausland et al., 2011; Mitchell et al., 2011). Major episodes of true polar wander during the Ediacaran would be consistent with the amalgamation of a supercontinent at that time. However, to what extent the highly dispersed paleomagnetic datasets characteristic of the Ediacaran-Cambrian reflect true polar wander, rather than a nonuniformitarian magnetic field or some combination of these processes, is uncertain.

Consequently, while the proxy signals for Ediacaran supercontinent assembly and breakup, and hence the existence of Pannotia, might be collectively strong, they cannot be considered definitive, and it can be argued that the case for Ediacaran continental amalgamation is stronger than that for Early Paleozoic breakup. It can also be argued that, if not a supercontinent, what global tectonic regime promoted the major changes to Earth's surface environment that characterize the Ediacaran, some of which are among the most profound in Earth history (e.g., Dalziel, 1997; McKenzie et al., 2014; Spence et al., 2016)? Yet the past 50 m.y. has likewise been a period of profound change in Earth systems, including climatic variation, evolutionary radiation, widespread orogenesis and a rapid rise in the strontium ration in seawater (e.g., Crame and Owen, 2002; Rosenbaum and Lister, 2002; Figueirido et al., 2012; Turchyn and DePaolo, 2019; Wright, 2019), without involving the assembly of a supercontinent.

2.3. Supercontinents and megacontinents

An alternative explanation for the Ediacaran proxies may lie in the existence of a proxy-producing phase of the supercontinent cycle that we have not taken into account. Such is the case for the "semi-supercontinent" of Evans et al. (2016) and the intermediate "megacontinent" stage proposed by Wang et al. (2021) that, if true, might create a landmass large enough to produce the observed proxies, but not large enough to cause cycle to repeat, as would be the case with a supercontinent. According to Wang et al. (2021), the assembly of each of the supercontinents Columbia, Rodinia and Pangea was preceded by the formation of a megacontinent, with Gondwana (ca. 520 Ma; Collins and Pisarevsky, 2005; see also Grenholm, 2019; Cawood et al., 2021) being the megacontinental precursor to Pangea (ca. 325-175 Ma; e.g., Stampfli et al., 2013, Peace et al., 2019). Present-day Eurasia (soon to be enlarged by Australia) is proposed as the megacontinental forerunner of the next supercontinent (ca. +200-250 Ma; e.g., Battersby, 2017; Davies et al., 2018).

The premise of the megacontinental stage is that dispersing continents move away from a fragmenting supercontinent and towards areas of mantle downwelling (e.g., Gurnis, 1988) represented by a retreating girdle of subduction (e.g., Li and Zhong, 2009; Mitchell et al., 2021). Where downwelling along this girdle is particularly intense, several such fragments may assemble to form a megacontinent, which then migrates along the girdle and, in doing so, collides with the remaining continental fragments to form a supercontinent. In this scheme, the Ediacaran proxies do not record the assembly of a supercontinent, but rather record the assembly a megacontinent (Gondwana) on the subduction girdle that had previously encircled Rodinia (Fig. 7). Motion of Gondwana along this girdle resulted in its collision with the remaining continental fragments of Rodinia breakup and the consequent assembly of the supercontinent Pangea (Wang et al., 2021). As a stage-result of the assembly of a true supercontinent (e.g., Evans et al., 2016), the Ediacaran can be expected to record proxies of continental assembly, but will not show evidence of profound change in mantle circulation that modeling suggests accompanies the assembly of a supercontinent (e.g., Zhong et al., 2007).

Although this is an appealing solution, it is not without issues. Except for major (Alpine-Himalayan) orogeny (e.g., Rosenbaum and Lister, 2002), an increase in seawater $^{87}Sr/^{86}Sr$ ratio (e.g., Goddéris et al., 2017b) and a modest zircon age peak (Puetz et al., 2018), the assembly of Eurasia, which is taken to be the megacontinental precursor to the assembly of the next supercontinent, has not yet produced proxy signatures as dramatic as those of the Ediacaran. Furthermore, the continental assembly phase of the Ediacaran was followed by a continental dispersal phase in the Lower Paleozoic marked by the opening of the Iapetus (e.g., Cawood et al., 2001), Tornquist (e.g., Krzywiec et al., 2018), paleo-Uralian (e.g., Puchkov, 2002, 2016), Rheic (e.g., Nance et al., 2010) and proto- and paleo-Tethys (e.g., Stampfli and Borel, 2002, 2004) oceans in a fashion more consistent with supercontinent breakup than with megacontinent migration unless all these oceans originated as marginal basins.

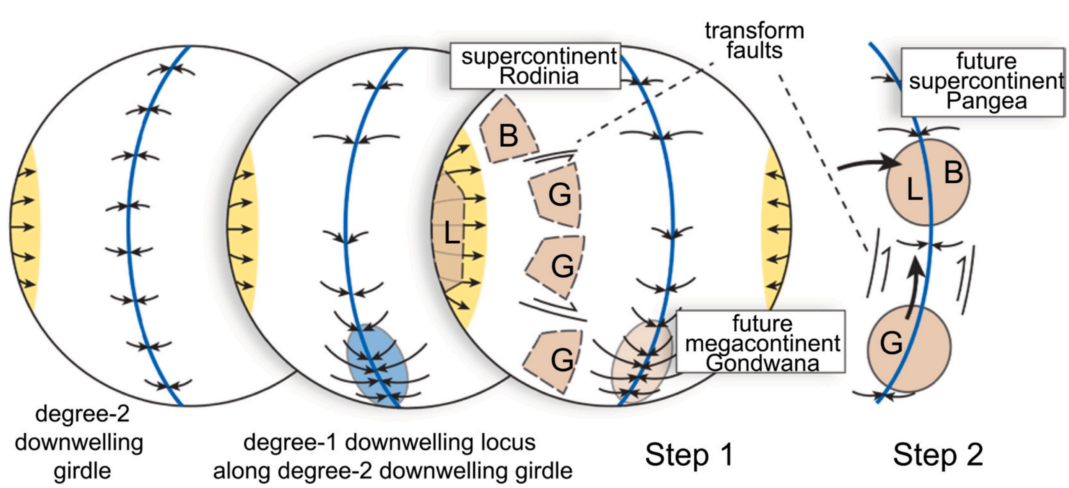

Fig. 7. Megacontinent-supercontinent geodynamics as envisaged by Wang et al. (2021). Focused downwelling along Rodinia degree-2 subduction girdle (Step 1) initially leads to the formation of a megacontinent (Gondwana) over the locus of downwelling (small arrows), following which (Step 2) convergence of continents (bold arrows) to and along the subduction girdle leads to the formation of a supercontinent (Pangea). L = Laurentia, B = Baltica, G = Gondwana.

2.4. Mantle dynamics

Another potential test of the existence or nonexistence of Pannotia lies in its expected influence on mantle dynamics. Modeling (e.g., Zhong et al., 2007; Li and Zhong, 2009; Mitchell et al., 2021) suggests that supercontinents form over areas of downwelling in a mantle with a degree-1 structure (i.e., one with antipodal areas of upwelling and downwelling), and subsequently break up because cessation of subduction of the closing oceans of supercontinent assembly and consequent initiation of subduction around the margins of the supercontinent influence mantle dynamics in such a way as to convert the downwelling into an upwelling, thereby producing a mantle with a degree-2 structure (i.e., one with two antipodal areas of upwelling bisected by a downwelling girdle). Mantle plumes emanating from the core-mantle boundary (CMB) are preferentially generated along the edges of such upwellings (e.g., Burke et al., 2008; Torsvik et al., 2006), which rise beneath the supercontinent, fostering its breakup. If this is the case, then supercontinent amalgamation and breakup can be expected to have a profound effect on mantle circulation (e.g., Yale and Carpenter, 1998; Santosh, 2010; Ernst et al., 2013; Condie et al., 2015; Heron et al., 2015; Heron, 2019) and Pannotia, if it existed, should have produced a clear mantle legacy (Murphy et al., 2021; Heron et al., 2021).

A strong link between mantle dynamics, LIPs and supercontinent breakup has long been recognized in the case of Pangea (e.g., Dalziel et al., 2000; Whalen et al., 2015; Le Pichon et al., 2019; Peace et al., 2019). For Pannotia, this would be manifest in plume-related magmatism that, in the absence of late Neoproterozoic collisional orogenies in Laurentia and Baltica (e.g., Cawood et al., 2016), would be predicted to occur around the Gondwanan portion of the supercontinent. Numerous candidates for which plume activity is inferred to exist have been identified for the interval ca. 615-450 Ma (Murphy et al., 2021), including the ca. 615-530 Ma Central Iapetus Magmatic Province (CIMP), with a main peak at 580-560 Ma (e.g., Youbi et al., 2020), and the vast ca. 511 Ma Kalkarindji LIP of western Australia (Ware et al., 2018), and their distribution closely matches the peri-Gondwanan prediction of idealized post-assembly marginal upwelling models (Tan et al., 2002) (Fig. 8). Furthermore, using a 3D mantle convection model that simulates mantle evolution in response to the amalgamation of Rodinia and Pangea based on a subduction history derived from the reconstructions of Merdith et al. (2017) and Matthews et al. (2016), Heron et al. (2021) have shown that Ediacaran continental convergence could have generated a post-Pannotia mantle signature consistent with that of a supercontinent. Likewise, while Müller et al.'s (2022) plate motion model in a mantle reference frame for the last billion years failed to produce a late Neoproterozoic supercontinent, being based on the reconstructions of Merdith et al. (2021), it did produce a degree-2 basal mantle structure between 600 and 500 Ma, as it did following Pangea breakup.

But while these studies lend support to the existence of Pannotia, they remain preliminary. Murphy et al. (2021), for example, are quick to acknowledge that their tally of plume candidates is far from complete and that many require geochemical and isotopic verification. Aside from CIMP, the Kalkarindji LIP (Ware et al., 2018), and the Volyn lavas of Baltica (e.g., Poprawa et al., 2020), they also tend to have smaller volumes and are located within narrow active margins of the Gondwana landmass, unlike the giant radiating dike swarms that penetrated deep into Pangea's interior and heralded separation of continent-sized fragments. Additionally, Evans (2021) has pointed out that the time required for subducted material to transit to the deep mantle may be too long to allow the development of CIMP and the rifting of the Iapetus Ocean to be the result of mantle plumes following Pannotia assembly, especially if CIMP started as early as 615 Ma (e.g., Kamo et al., 1989; Bingen et al., 1998; Pisarevsky et al., 2008). Although this would not be the case for shallow plumes produced as a consequence of mantle insulation following Pannotia amalgamation (i.e., continental lid tectonics), since these would not be subject to mantle transit times, the argument is

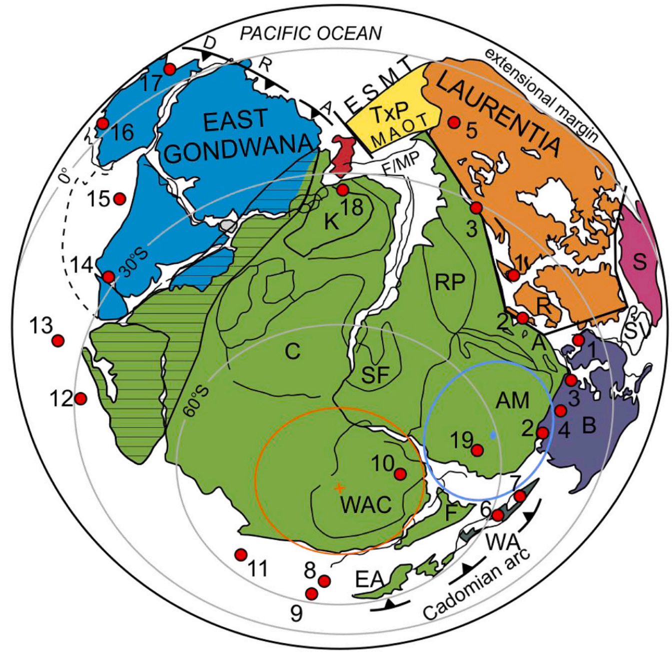

Fig. 8. Locations on Pannotia reconstruction of Dalziel (1997) of possible plume magmatism around Gondwanan portion of Pannotia following Pan-African collisional orogenesis (modified from Murphy et al., 2021). 1-3 = CIMP (Central Iapetus Magmatic Province), 1 = Egersund-Long Range (615-610 Ma: Bingen et al., 1998; Kamo and Gower, 1994), 2 = Tayvallich volcanics (595 Ma: Halliday et al., 1989), 3 = Catoctin (565 Ma: Aleinikoff et al., 1995), 4 = Volyn (590-550 Ma: Poprawa et al., 2020), 5 = Wichita (540-540 Ma: Hansen et al., 2013), 6 = Greendale (607 Ma: Murphy et al., 1997), 7 = Avalonian basalts (530 Ma; Murphy et al., 1985), 8 = Ossa Morena, southern Spain (510 Ma: Sánchez-García et al., 2008), 9 = Ollo de Sapo, northern Spain (490-480 Ma: García-Arias et al., 2018), 10 = Ouarzazate (560-580 Ma: Mills et al., 1991) 11 = Blovice, Czech Republic (>530 Ma: Ackerman et al., 2019), 12 = Soltan Maiden, Iran (450 Ma: Derakhshi and Ghasemi, 2015), 13 = paleo-Asian Ocean (540-500 Ma: Safonova, 2008; Zhang et al., 2017; Yang et al., 2020), 14 = Nongpoh-Shillong, NE India (500 Ma: Sadiq et al., 2018), 15 = Zhulongguan, NW China (600-580 Ma; Xu et al., 2015), 16 = Kalkarindji (511 Ma: Ware et al., 2018), 17 = Delamerian (570 Ma: Crawford et al., 1997), 18 = Kuboos (507 Ma: Frimmel, 2000), 19 = Piranhas-Parauapebas (535-507 Ma: Santos et al., 2002; Teixeira et al., 2019). See Figure 2 for abbreviations and Dalziel (1997) for details of the reconstruction.

potentially crucial to the issue of Pannotia's viability as a landmass capable of significantly influencing mantle convection. Estimates suggest that the time it has taken for subducted material to reach the deep mantle since the amalgamation of Pangea is at least 150 Myr and probably greater than 200 Myr (van der Meer et al., 2010; van der Meer et al., 2018; Domeier et al., 2016; Le Pichon et al., 2019). The time required for plumes generated at the CMB to reach the surface is estimated to be greater than 50 Myr (Davies et al., 2000; Steinberger and Antretter, 2006). According to these estimates, a full circuit would take a minimum of 200 to 250 Myr. Given the timing of orogenic assembly relevant to the Pannotia debate (650-520 Ma), the arrival at the Earth's surface of plumes formed as a consequence would not be expected much before mid-Paleozoic time. On the other hand, it could be argued that these timescales accord tolerably with Cambrian-formed Gondwana having its own effect on mantle circulation, expressed in the form of Mesozoic plumes.

However, these inferences are model dependent and the processes by which supercontinents (and possibly megacontinents) influence mantle dynamics and the time scales over which they operate are still far from understood. Nevertheless, the argument raises fundamental questions regarding mantle circulation and its link to supercontinent breakup. If the change from downwelling to upwelling beneath a supercontinent following its amalgamation is a CMB-driven process, then mantle-transit times will play a key role in its timing since upwelling must await the descent of the subducting slabs of the closing oceans of supercontinent assembly. On the other hand, if upwelling is initially generated by lateral movement of the shallow mantle in response to the detachment of these slabs, the change would be largely independent of mantle transit times and might take effect soon after initiation of the collisional orogenesis of supercontinent assembly.

2.5. Duration of the supercontinent cycle

Another avenue of enquiry into the validity of Pannotia involves the duration of the supercontinent cycle, which the existence or nonexistence of the supercontinent clearly affects. Neither the interval of the supercontinent cycle nor what constitutes a supercontinent are well-defined (e.g., Bradley, 2011; Meert, 2014; Nance and Murphy, 2019; Pastor-Galán et al., 2019). However, if we ignore Pannotia and use ages of ca. 1.6-1.4 Ga for Nuna/Columbia (Pisarevsky et al., 2014; Pehrsson et al., 2016), 950-800 Ma for Rodinia (e.g., Torsvik, 2003; Li et al., 2008) and ca. 325-175 Ma for Pangea (e.g., Stampfli et al., 2013; Peace et al., 2019), the cycle shows a fairly steady post-Archean repetition at an interval of ca. 600-650 Myr (Fig. 9a). On the other hand, adding putative Pannotia at ca. 600 Ma (e.g., Scotese, 2009) produces a cycle that would appear to be accelerating toward a repetition interval of ca. 300-350 Myr (Fig. 9b). This apparent acceleration is further enhanced with the inclusion of Kenorland at ca. 2.7-2.5 Ga (e.g., Williams et al., 1991; Aspler and Chiarenzelli, 1998; Lubnina and Slabunov, 2011).

These two contrasting outcomes (an accelerating versus steady state cycle) represent fundamentally different pathways in Earth's history of mantle dynamics and global tectonics, and serve to emphasize the importance of resolving the existence or non-existence of Pannotia as well as its status as a supercontinent. Both pathways are tenable, although a ca. 600 Myr supercontinent cycle is favored by most recent studies (e.g., Gardiner et al., 2016; Mitchell et al., 2019; Doucet et al., 2020). As a case in point, Li et al. (2019) have argued that the geologic record of passive margin development, orogenesis and mineral deposits point to both a 500-700 Ma supercontinent cycle and one with a signal of twice this duration (1.0-1.5 Ga) that they term the superocean cycle. To account for this, they suggest that supercontinent assembly has alternated between extroversion (assembly though closure of the exterior ocean that surrounded the previous supercontinent) and introversion (assembly through closure of interior oceans formed when the previous supercontinent broke up), such that the exterior superocean and subduction girdle survive every second (introverted) supercontinent. However, their model requires that the breakup of Rodinia led directly to the assembly of Pangea and breaks down if Pannotia was also a supercontinent.

Conversely, Korenaga (2006) has argued that plate motion modulated by strong, depleted lithosphere created by mid-ocean ridge processes would have been more sluggish when the mantle was hotter and, in a model that incorporates Pannotia, has used the accelerating frequency of supercontinent formation to support his case that plate tectonics has gradually sped up since the Archean. Although this provocative hypothesis runs counter to the traditionally held view that geodynamics should slow as the planet cools (e.g., Burke et al., 1976; Hargraves, 1986; Pollack, 1997; Blake et al., 2004), it finds support in the decreasing time interval between peaks in the global distribution of zircon ages (Fig. 3).

An accelerating versus steady state supercontinent cycle would also impact the expected time interval to the assembly of the next supercontinent. Given a ca. 600 Myr steady-state cycle that excludes Pannotia, the next supercontinent would not be expected to assemble for some 400 million years. Conversely, an accelerating cycle that includes Pannotia and, as a result, has a decreasing duration, would predict that the next supercontinent might assemble in as little as 100 million years. Hence, the potential validity of a Pannotia-inclusive cycle affects our understanding of the time interval needed to amalgamate the next supercontinent, several reconstructions of which have been proposed (e.g., Battersby, 2017). These have been dubbed Novopangea (Nield, 2007), Pangea Proxima (Scotese, 2007), Amasia (Hoffman, 1992, 1997; Mitchell et al., 2012) and Aurica (Duarte et al., 2018) depending on which present-day ocean is predicted to close in order to affect the assembly. Thus, Novopangea is produced by closing the Pacific Ocean, Pangea Proxima by closing the Atlantic Ocean, Amasia by closing the

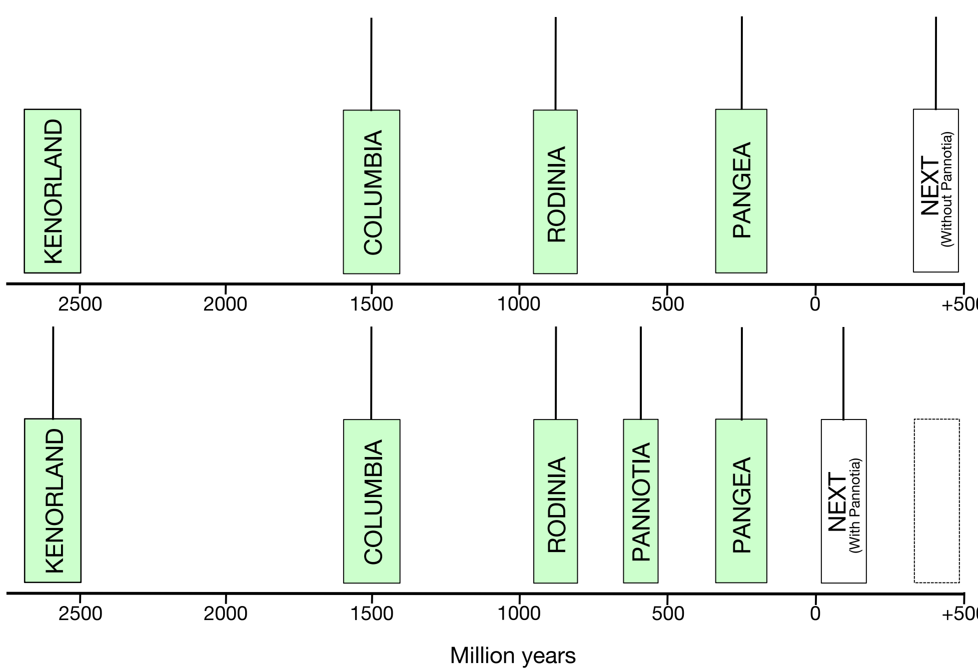

Fig. 9. Significance of Pannotia to the duration of the supercontinent cycle. (a) Without Pannotia, cycle shows post-Archean repetition at interval of ca. 600-650 million years, predicting next supercontinent to assemble at ca. +400 Ma. (b) With Pannotia, cycle shows accelerating trend toward ca. 300-350 million years (enhanced with inclusion of Kenorland), predicting next supercontinent to assemble at ca. +100 Ma.

Arctic Ocean, and Aurica by closing both the Atlantic and Pacific oceans while opening a new ocean in central Asia.

Although assumptions are involved in all of these assemblies, each is predicted to occur in about 200-250 million years' time (e.g., Yoshida and Santosh, 2011; Davies et al., 2018). This would equate to a cyclicity of ca. 450-500 Ma, consistent with the considerations of Duarte et al. (2018) and the numerical simulations of Yoshida (2016). But the time interval lies halfway between those predicted for an accelerating and steady-state cycle and, hence, does not discriminate between them.

However, in their analysis of Novopangea, Davies et al. (2018) predict closure of most of the Pacific in about 100 million years. This timing is consistent with the 3D numerical modeling of Trubitsyn et al. (2008) and would reassemble a supercontinent in an interval closer to that predicted for an accelerating supercontinent cycle. It should be noted, however, that Rolf et al. (2014), also on the basis of 3D dynamic numerical models, dismissed any regularity in the assembly and breakup of supercontinents in favor of a statistical cyclicity with a characteristic period dictated by mantle and lithosphere properties. Their results suggest an average duration of 640 ± 105 Myr, consistent with an essentially steady-state cycle.

2.6. Discussion and conclusions

Valid cases can be presently made both for and against the legitimacy of Ediacaran-Cambrian Pannotia, so the question of its existence remains unresolved. Although it can be argued that the proxy signals for supercontinent assembly and breakup, and the magmatic record of a mantle legacy, collectively provide some support for the supercontinent (Nance and Murphy, 2019), they do not demonstrate its existence conclusively. Likewise, the counterarguments to the proxy record (Evans, 2021) do not completely preclude its validity. Questions also exist as to which proxies are most relevant to the Pannotia debate (see Gernon et al., 2021), which are crustal proxies driven by plate reorganization, and which are mantle proxies driven by mantle dynamics. Hence, just as the authors of this contribution retain differing viewpoints in healthy and amicable debate on the issue, there is currently no clear answer to the question as to whether Pannotia should be or should not be.

Nevertheless, the question of Pannotia's existence is a vitally important one. The answer speaks fundamentally to the nature of supercontinent cycles, dictating whether they are in steady state or accelerating, and determining the geodynamic pathway followed by the cycle from the breakup of Rodinia to the assembly of Pangea. Pannotia's existence also bears upon the fundamental questions of the mantle dynamics involved in bringing continents together and then driving them apart, the role played in this process by descending oceanic slabs, and whether or not mantle plumes emanating from the CMB are a cause or a consequence of it. In an academic forum where supercontinent cycles are widely discussed, the question of Pannotia's existence is not, therefore, one that can be ignored or overlooked.

From a geological perspective, the existence of Pannotia hinges most critically on the timing of Laurentia's separation from Amazonia and the resulting opening of the Iapetus Ocean. If the initial separation of these cratons coincided with the onset of the North American passive margin at ca. 530 Ma (e.g., Cawood et al., 2001), well after the initial collisions of Gondwana, the existence of a short-lived supercontinent in the interval preceding it remains plausible. If, however, the separation of Laurentia occurred with the opening of a Paleo-Iapetus Ocean at ca. 700 Ma, as advocated by Robert et al. (2020), the case for an Ediacaran supercontinent is lost. The question of Pannotia's existence consequently rests, above all, on the resolution of this uncertainty.

Other promising avenues for further research into the existence or nonexistence of Pannotia concern its mantle legacy and dynamic modeling aimed at constraining the timing of the next supercontinent. But the question warrants a concerted international effort like that undertaken for Rodinia in the years following the turn of the millenium. Indeed, had it not been for the great success of IGCP Project 440 and the international research endeavor it inspired, we would likely be asking the same questions of Rodinia that we are now asking of Pannotia. Our concluding statement is consequently a plea to the international geologic community to initiate a cooperative plan of action aimed at addressing the question of Pannotia.

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.

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