Pannotia under prosecution

David A. D. Evans

Department of Earth and Planetary Sciences, Yale University, 210 Whitney Avenue, New Haven, CT 06520-8109, USA

0000-0001-8952-5273
david.evans@yale.edu

Abstract: Pannotia is a hypothetical supercontinent that may have existed briefly during the Proterozoic–Cambrian transition. Various lines of evidence used to argue for its existence include global orogenesis in Ediacaran–Cambrian time, the development of Cambrian passive margins and some (but not all) tectonic reconstructions. Indirect measures used to infer Pannotia's veracity include patterns of biological diversity, palaeoclimate, sea level, magmatism and other palaeoenvironmental proxies. It is shown herein that neither the direct records nor the indirect proxies provide compelling support for Pannotia. If that ephemeral contiguous landmass existed at all, its effects on the broader Earth system are inextricably tied to the more fundamental processes of Gondwanaland assembly. This perspective emphasizes the remarkable consolidation of Gondwanaland as a semi-supercontinent within the early stages of the Pangaea cycle. Gondwanaland's size combined with its *c.* 300 myr longevity might have greater significance for mantle dynamics than the larger, but shorter-lived, Pangaea landmass.

Despite earlier brief references to ancient continental landmasses preceding Pangaea (summarized by Nance *et al.* 2014), the first serious analysis of Paleozoic or older plate mobilism (Wilson 1966) led to the concept of a 'Wilson cycle' of oceanic basins opening and closing through geological history. Given the vast length of Precambrian time, some researchers naturally inferred that ancient continent-collisional sutures are the last remnants of long-vanished oceans (Dewey and Burke 1973). Although others suggested less mobilistic Precambrian tectonic regimes (e.g. McElhinny and McWilliams 1977; Kröner 1981), exhaustive syntheses of stratigraphic architecture in well-exposed Precambrian terrains have led to the dominance of fully mobile plate-tectonic models for most Proterozoic orogens (e.g. Hoffman 1988).

Fischer (1984) introduced a holistic model of two Phanerozoic supercycles, including the concept of a 'Protopangaea' in latest Precambrian time. According to that model, Laurentia's rifted passive margins on nearly all sides (well documented by Stewart 1972) were direct evidence of supercontinental fragmentation, followed by a dramatic early Paleozoic sea-level highstand thought to correspond with a more active plate-tectonic regime and a broad-scale greenhouse state of global climate. These attributes were attested to mirror the Cretaceous world, in contrast to periods of supercontinentality (Pangaea, Protopangaea) with more sluggish tectonics, low sea levels and a broad-scale icehouse state of global climate. Aside from the global glacial record, however, many of these inferences rested on predominantly North American geological records, such as the level of epicratonic flooding and granite production.

Worsley *et al.* (1984, 1986) and Nance *et al.* (1986) expanded on the theme of Phanerozoic supercycles to extend Earth's supercontinental history across billions of years. Although Precambrian sea levels cannot be ascertained quantitatively by direct flooding records (due to poorer sedimentary preservation: see Korenaga *et al.* 2017), global peaks in orogenesis were evident from the earliest compilations of isotopic ages of rocks (e.g. Gastil 1960) and have stood the test of time (see Hoffman 1989; Puetz *et al.* 2018). Speculative correlations between putative Precambrian supercycles and global climate, as well as biological evolution, were permissible in the 1980s according to the relatively lax temporal control on the latter phenomena. Despite a subsequent renaissance in U–Pb geochronology (reviewed by Kamo *et al.* 2011; Mattinson 2011), substantial uncertainties in those deep-time environmental and evolutionary records still remain and preclude definitive links to global tectonism.

In the same year as the presentation of the Fischer (1984) and Worsley *et al.* (1984) hypotheses, advances in quantitative sedimentary basin analysis permitted Bond *et al.* (1984) to refine the age of rift–drift transitions along the peri-Laurentian margins, as well as some other localities around the world, in earliest Cambrian time. They suggested that Laurentia broke out of a latest Precambrian supercontinent as those rifted margins were established. It was recognized that a contiguous landmass of supercontinental proportions might be feasible if Laurentia, Baltica and Gondwanaland were united (Fig. 1a). Of course, such a notion is possible only

From: Murphy, J. B., Strachan, R. A. and Quesada, C. (eds) 2020. *Pannotia to Pangaea: Neoproterozoic and Paleozoic Orogenic Cycles in the Circum-Atlantic Region*. Geological Society, London, Special Publications, **503**,
https://doi.org/10.1144/SP503-2020-182

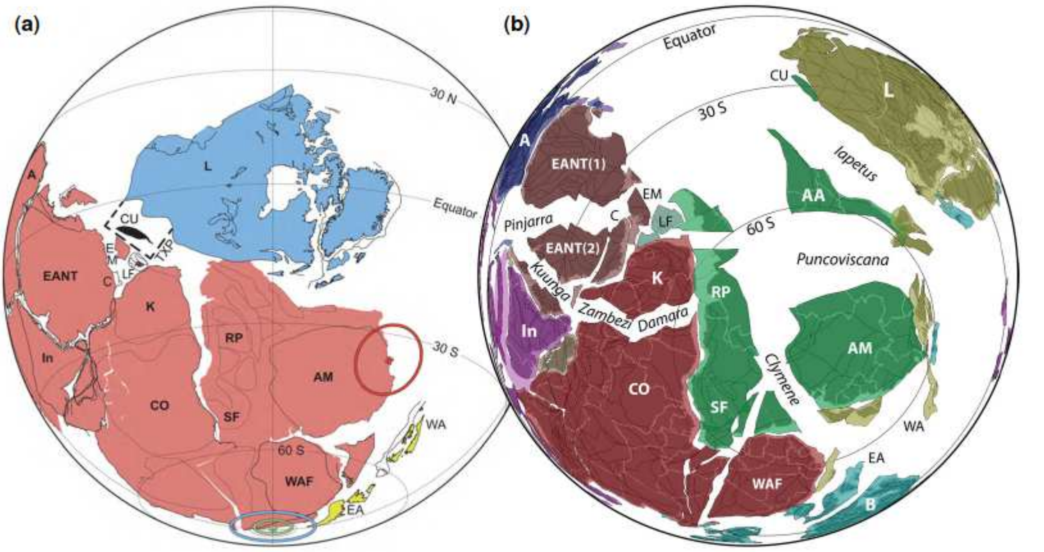

Fig. 1. Alternative palaeogeographies proposed for 550 Ma. (**a**) Pannotia reconstruction of Dalziel and Dewey (2019) showing Laurentia conjoined with Gondwanaland immediately prior to the opening of the Iapetus Ocean. The palaeomagnetic discordance illustrated in this model was noted by those authors. (**b**) Palaeogeographical model produced by the author in collaboration with Bruce Eglington (colours correspond to present continental associations) showing several Gondwanaland-closing oceanic tracts (e.g. Pinjarra, Kuunga–Zambezi–Damara, Clymene and Puncoviscana) coexisting with Iapetus; Pannotia does not exist in this model preferred herein. Abbreviations: A, Australia; AA, Antofalla–Arequipa; AM, Amazonia; B, Baltica; C, Coats Land; CO, Congo; CU, Cuyania; EA, East Avalonia; EANT, East Antarctica; EM, Ellsworth Mountains; In, India; K, Kalahari; L, Laurentia; LF, Lafonian microplate; RP, Rio Plata; SF, São Francisco; WA, West Avalonia; WAF, West Africa.

if Gondwanaland itself were tectonically coherent prior to the earliest Cambrian rifting.

Whether an Ediacaran–Cambrian supercontinent existed depends crucially on the timing of Gondwanaland assembly. Referring to the widespread Neoproterozoic–Cambrian orogens across present-day Africa (the so-called 'Pan-African belts' of Kennedy 1964) in addition to any possible conjoined neighbouring cratons including Laurentia, Williams *et al.* (1991) postulated a hypothetical landmass at *c.* 600 Ma named 'Pan-Africaland'. Because orogens of similar age are found throughout the southern-hemisphere descendants of Gondwanaland, Stump (1987) coined the more inclusive name 'Pannotios' for that orogenic network (*notios* = 'southern' in Greek, thus 'all southern'). Using this terminology (Powell 1995), Pannotia is now recognized as the name of the hypothetical supercontinent that would have included a united Gondwanaland plus enough additional cratons to warrant supercontinental status.

As Nance and Murphy (2019) have pointed out, how one defines a supercontinent is of obvious importance when deciding whether Pannotia qualifies for such distinction. Possible defining factors include size/area, longevity or a combination of those effecting significant influence on the broader Earth system. If considered alone, the former factor (size or area) gives some guidance via historical usage: Pangaea is the archetypal supercontinent, whereas Gondwanaland cannot then be considered at the same hierarchical level because it is a component of Pangaea. Meert's (2012) minimum threshold of 75% extant continental crust assembled at a given age would permit this established dichotomy. Alternative measures of size, including the perimeter/area ratio (Merdith *et al.* 2019), also distinguish Gondwanaland from Pangaea, albeit with a continuous transition through the Paleozoic rather than any discernible threshold. Longevity by itself cannot qualify a craton for supercontinental status (e.g. Slave Craton, home to the world's oldest rock, is clearly too small), but a combination of longevity with areal extent that is substantially larger than all present continents may exert profound influence particularly on mantle convection. This topic will be discussed further, below.

The central question regarding the existence of Pannotia as a supercontinent, then, is whether a landmass of sufficient size and/or longevity to exert influence on the broader Earth system existed near the Ediacaran–Cambrian boundary. Evidence will be marshalled from: (1) the palaeogeographical/

tectonic record of that specific time interval; (2) indirect or proxy records of a broader Earth history that have been used to represent supercontinentality at various ages; and (3) possible links between Earth's surface tectonics and the machinations of its deep interior. This review takes the stance of a prosecution: Pannotia is charged with the most serious crime imaginable, that of masquerading its very existence through the imperfect lens of obsolete or incomplete geological records, blurry geochronology and ambiguous interpretation of geological causality from temporal coincidence.

Palaeogeography

Attempts to define the configuration of a late Proterozoic supercontinent began in the 1970s. Piper (1974, 1976) was the first to attempt palaeomagnetic reconstructions, following an initial earlier suggestion (Piper *et al.* 1973), with the following features: Gondwanaland largely intact; Laurentia adjoined to the Nubian margin of Africa; Baltica adjacent to Greenland; and evolution of these elements towards Pangaea being accommodated mainly by sinistral transform tectonics. Piper's (1974, 1976) models eventually incorporated the suggestion by Sears and Price (1978) that Siberia once lay adjacent to Laurentia's present western margin. The first palaeomagnetists to suggest large-scale crossings of wide Paleozoic oceans were Morel and Irving (1978), who introduced 'Pangea E' at *c.* 600 Ma in reference to the proposed subsequent mid–late Paleozoic evolution of what they named 'Pangea D–A'.

In contrast to these models positing Laurentian pre-Iapetus connections with various margins of Africa, Eisbacher (1985) and Bell and Jefferson (1987) proposed west Laurentian late Neoproterozoic connections with Australia, which would inspire the SWEAT (SW US–East Antarctica) hypothesis (Moores 1991) and now-classic notions of Rodinia (Dalziel 1991; Hoffman 1991). Even though present-day western Laurentia experienced initial extension during Tonian time (Stewart 1972; Harlan *et al.* 2003), significant margin-wide tectonic subsidence did not commence until the Ediacaran–Cambrian transition (Bond *et al.* 1983). In principle, if the 'inside-out' model of Rodinia–Gondwanaland transition (Hoffman 1991) is followed, an intervening Pannotia supercontinent is possible if Gondwanaland assembled prior to *either* of the western or eastern Laurentian rift separations. In practice, however, ever since Bond *et al.* (1984) presented their terminal Proterozoic supercontinent reconstruction, palaeogeographers have considered the western Laurentian (proto-Cordilleran) Tonian rifting to be 'successful' in early ocean opening (although doubt remains on this point: e.g. Nelson *et al.* 2020), and thus the most commonly hypothesized Pannotia palaeogeography entails the enduring connection of eastern Laurentia with South American cratons.

A note on nomenclature: McMenamin and McMenamin (1990) coined 'Rodinia' as the supercontinent that 'begat' (from Russian *rodit*) other continents via break-up near the Proterozoic–Cambrian boundary. Soon thereafter, Hoffman (1991) acknowledged that many of the Cambrian passive margins had origins as mid-Neoproterozoic rifts, and recognized that the preceding interval of 'Grenvillian' (late Mesoproterozoic) orogenesis was likely to have assembled the supercontinent; thus, he used the name 'Rodinia' as it is now widely recognized: the alleged supercontinent formed by early Neoproterozoic time, and beginning to break up in the mid-Neoproterozoic. Young (1995) suggested that Hoffman's (1991) terminology had strayed from the original definition of McMenamin and McMenamin (1990), and that the early Neoproterozoic supercontinent should be given a separate name (he coined 'Kanatia'). The supercontinent name 'Pannotia' derives from Powell's (1995) critical comment on Young's (1995) paper, following the etymology described above with the additional relevance not only that Gondwanaland-forming orogens exist throughout today's southern continents, but also that the ancient landmass reconstructs mainly within southern palaeolatitudes in earliest Cambrian time. Regardless of the merits of Young's (1995) arguments, Rodinia and Pannotia are now deeply entrenched in the literature as the mid- and latest-Neoproterozoic (hypothetical) supercontinents, respectively.

The most recent iterations of Pannotia's palaeogeography, among those that permit existence of an Ediacaran–Cambrian supercontinent (e.g. Dalziel and Dewey 2019), preserve the essential elements of the Bond *et al.* (1984) reconstruction: Laurentia and Baltica are juxtaposed against the Amazonian Craton, the latter already attached to a coherent Gondwanaland assemblage (Fig. 1a). Such a model permits chronological testing of Pannotia's existence by comparing the ages of Iapetus rifting with Gondwanaland assembly. To wit: Pannotia in the standard palaeogeographical sense is plausible only if Iapetus opened *after* Gondwanaland became united. The following paragraphs test this prerequisite condition by exploring those records in detail.

Gondwanaland assembled through a spectacular set of collisional orogens through the Neoproterozoic–Cambrian transition (Oriolo *et al.* 2017; Schmitt *et al.* 2018). Many of these belts are polyorogenic, with ages of deformation as old as *c.* 700 Ma and as young as *c.* 500 Ma. The timing of collision within many orogens is controversial, but only those with possible Cambrian ages of suturing are described here (Fig. 1b).

The Kuunga Orogeny was originally defined as a peak in magmatic and deformational ages specifically around the Proterozoic–Cambrian boundary interval in eastern Africa, and is now more broadly located between India, Sri Lanka, East Antarctica and westernmost Australia (summarized by Meert 2003; Boger 2011). Although largely under cover of Phanerozoic sedimentary basins, the Indian Ocean, or the Antarctic ice cap, the Pinjarra orogen, recently referred to as 'Kuunga', contains sporadic but compelling records of early Cambrian deformation, metamorphism and magmatism in those regions (e.g. Halpin *et al.* 2017; Markwitz *et al.* 2017; Daczko *et al.* 2018; He *et al.* 2018; Grantham *et al.* 2019; Mulder *et al.* 2019; Clark *et al.* 2020). Possible continuation of a Kuunga-aged suture into Madagascar, either in its southwestern region (Boger *et al.* 2015, 2019) or eastern areas (e.g. Armistead *et al.* 2020), is debated (Tucker *et al.* 2014; Zhou *et al.* 2018).

Masterful reviews of the Damara Belt (Goscombe *et al.* 2017, 2018) and the Zambezi orogen (Goscombe *et al.* 2020) document terminal collision of the Congo and Kalahari cratons commencing around 550 Ma and continuing into early Cambrian time. This relatively young suture probably continues southwestwards through the Gariep and Saldania belts rather than northwestwards through the Kaoko orogen (Lehmann *et al.* 2016; Konopásek *et al.* 2020).

One of the more contentious debates concerning the age of a Gondwanaland-forming collision surrounds the accretion of the Amazonian Craton, which was traditionally considered to be an early Ediacaran event (Cordani *et al.* 2009). However, Cambrian ages for significant remagnetization and vertical-axis rotations (Tohver *et al.* 2010) and foreland-basin sedimentation (McGee *et al.* 2015, 2018) in the Paraguay Belt support the alternative notion of a hypothesized Clymene Ocean separating Amazonia from other Gondwanaland cratons until closure around 530 Ma (Trindade *et al.* 2006). One could argue that the Paraguay Belt is more akin to Mediterranean-style tectonism involving slab rollback across remnant ocean basins following an earlier continent–continent collision (Murphy *et al.* 2020), so investigation of the adjacent but poorly exposed Araguaia Belt (and its likely continuation into the Rokelide Belt of West Africa) is of paramount importance in the debate (Cordani *et al.* 2013; Tohver and Trindade 2014). Recent geochronology of the Araguaia Belt suggests earliest Cambrian ages for late- to post-orogenic magmatism (Alves *et al.* 2019; Gorayeb *et al.* 2019) and Late Cambrian ages for post-orogenic exhumation (Dias *et al.* 2017), thus further supporting the Clymene Ocean concept and the late timing of Amazonia's accretion to Gondwanaland.

Independent of the tectonostratigraphic records from Gondwanaland-forming orogens, a common palaeomagnetic apparent polar wander (APW) path for all of Gondwanaland is feasible throughout the early–middle Cambrian interval (Meert and Van der Voo 1996; McElhinny *et al.* 2003; Mitchell *et al.* 2010; Rapalini 2018). This permits the possibility that Gondwanaland was fully or nearly assembled by earliest Cambrian time (within palaeomagnetic resolution); however, unquantifiable palaeolongitude uncertainties in palaeomagnetic reconstructions also permit the possibility of subsequent suturing between constituent cratons regardless of their APW concordance. Late Ediacaran palaeomagnetic records, globally, seem to document a rapidly reversing and, perhaps, unstable geomagnetic field (Meert *et al.* 2016; Pavlov *et al.* 2018), perhaps coincident in time with substantial true polar wander (i.e. shift of the entire mantle plus overlying plates relative to the core and spin axis) that could be undersampled by studies of individual cratons (Robert *et al.* 2017). Thus, palaeomagnetism is less definitive than the orogenic record on the timing of Gondwanaland-forming collisions. In summary for Gondwanaland assembly, then, it appears that several important orogens remained actively shortening, and quite possibly continuing to close significant expanses of ocean basins, into early Cambrian time.

The second part of Pannotia's palaeogeographical prerequisite concerns the opening of the Iapetus oceanic tract between Laurentia, Baltica and Amazonia. Despite revision to the Cambrian chronostratigraphic timescale in the mid-1990s, tectonic subsidence curves were defined mainly with biostratigraphic age constraints; thus, the extrapolated initial rift ages for Iapetus margins remained around earliest Cambrian time (Bond 1997). Further assessment of the timing for Iapetus rifting has been convoluted with data from palaeomagnetism and tectonic reconstructions: for example, Cawood *et al.* (2001) suggested that a mid-Ediacaran stage of initial rifting between Laurentia and Amazonia (based on one interpretation of palaeomagnetic data) preceded a second-stage separation (based on subsidence curves) of a ribbon-like microcontinent or terrane into the already-widened Iapetus Ocean tract. As noted above, however, mid–late Ediacaran palaeomagnetic data are notorious to interpret. The idea of an already-wide Iapetus Ocean tract between Laurentia and West Gondwanaland cratons, into which various terranes rifted subsequently during the Ediacaran–Cambrian transition, has proliferated (Chew *et al.* 2008; Escayola *et al.* 2011; Casquet *et al.* 2012; Rapela *et al.* 2016). In fact, if Amazonia is considered as one of these 'terranes' then the aforementioned Clymene Ocean could itself be a kind of 'Palaeo-Iapetus' in the same relationship to Iapetus (*sensu stricto*) as the generations of the

Palaeo-Tethys, Neo-Tethys and Indian oceans interrupted by numerous successive northward crossings by continental fragments (Dewey *et al.* 1988). Amid all these uncertainties, the only way that Pannotia is plausible in its standard palaeogeography is for all of the early stages of rifting along the proto-Iapetan margin to have 'failed' prior to successful opening of the seaway in earliest Cambrian time, and for proposed subduction relicts within that realm (e.g. Escayola *et al.* 2011) to require reinterpretation.

Summary of palaeogeography

The Pannotia hypothesis in its current form juxtaposes Laurentia and Baltica with Amazonia, and thus requires Iapetan rifting to follow Gondwanaland assembly. If interpreted at the extremities of their uncertainties, and under favourable tectonic interpretations for the hypothesis, the available chronological constraints from these regions barely permit Pannotia to exist as a fleeting entity during late Ediacaran–early Cambrian time. Does such a tightly constrained geological window permit Pannotia to have profound effects on the broader Earth system? The following sections will evaluate that manner of claims.

Biological diversity

Very early in the consideration of Wilson cycles, Valentine and Moores (1970) introduced a thought-provoking hypothesis of supercontinental tectonics and animal evolution through the Phanerozoic. They proposed that supercontinental fragmentation should enhance evolutionary vicariance: that is, diversification within increasingly isolated biogeographical realms (Fig. 2a). By contrast, supercontinental amalgamation should promote extinction via competitive intermingling of those clades. At the time, the Phanerozoic fossil record showed smoothly varying diversity trends in broad accordance with the notion of a latest Precambrian supercontinent that broke up and reassembled to form Pangaea. Subsequent analysis and refinement of the global chronostratigraphic timescale emphasized the importance of episodic mass extinctions imparting pronounced asymmetry to family-level diversity curves (Raup and Sepkoski 1982), but the broad Phanerozoic cycles could still be distinguished. A closer investigation into the nature of these fluctuations, however, reveals that the aggregate family-level curve contains nuances that may be difficult to reconcile with a putative two-supercycle history of Phanerozoic evolution (Sepkoski 1984). As shown in Figure 3a, the total diversity curve can be segregated into three broad associations of fauna, with distinct logistic curve progressions punctuated by mass-extinction perturbations. Both the 'Cambrian' and 'Paleozoic' fauna followed more complete logistic functions with both initial exponential rise and steady decline; whereas the 'Modern' association shows mainly an exponential rise with relative immunity to the end-Permian mass extinction. This pattern suggests that the two-peaked summation of these curves actually superimposes somewhat independent subsets; and of those three subsets, only the 'Paleozoic' association shows a weak similarity to the two-cycle Phanerozoic idealization. Recently, Zaffos *et al.* (2017) recapitulated the conclusions of Valentine and Moores (1970) and linked faunal diversity to a novel 'fragmentation index' of continental palaeogeography, with modest but temporally robust rank-order correlation factors that, notably, dwindled when Cambrian–Ordovician data were included. Using a separate dataset mainly from China, spanning Cambrian–Triassic time, Fan *et al.* (2020) found no such correlation; this is unsurprising since the strength of the Zaffos *et al.* (2017) correlation derives mainly from substantial rises in both diversity and continental fragmentation beginning in Jurassic time.

Suggestions that Pannotia assembly coincided with great extinctions of clades, such as declining stromatolites and acritarchs (Nance and Murphy 2019), are fraught with uncertainties of imprecise taxonomy and interpretation in the former case (Riding 2011), and uneven preservation potential in the latter instance (Cohen and Macdonald 2015). The decline in stromatolites appears to span the entire Neoproterozoic Era (Awramik and Sprinkle 1999; Peters *et al.* 2017) rather than a brief fall during Pannotia's alleged Ediacaran assembly and tenure.

Proponents of early Paleozoic supercontinental break-up may link the Cambrian radiation of animals and the ensuing Great Ordovician Biodiversification Event to increased evolutionary vicariance across post-Pannotia continental shelves (Fig. 2a). However, there is increasing recognition that the great spread of animal diversity had evolutionary roots deep within Ediacaran time (Erwin *et al.* 2011), including numerous fundamental developments of body plans dated by phylogenetic analyses and molecular clocks (e.g. dos Reis *et al.* 2015) (Fig. 3a). Most of the recent discussion on early animal evolution focuses on oxygenation of the Neoproterozoic ocean (e.g. Cole *et al.* 2020), with global tectonics playing at most an indirect role. It has been proposed that Cambrian eustatic transgression created abundant ecological niches for rapid animal radiation (Peters and Gaines 2012). Enhanced global weathering at the Ediacaran–Cambrian transition may have delivered more Ca^{2+} ions (and other nutrients) to the oceans, altering the saturation state and promoting biomineralization among distinct animal clades (Brennan *et al.* 2004), but such

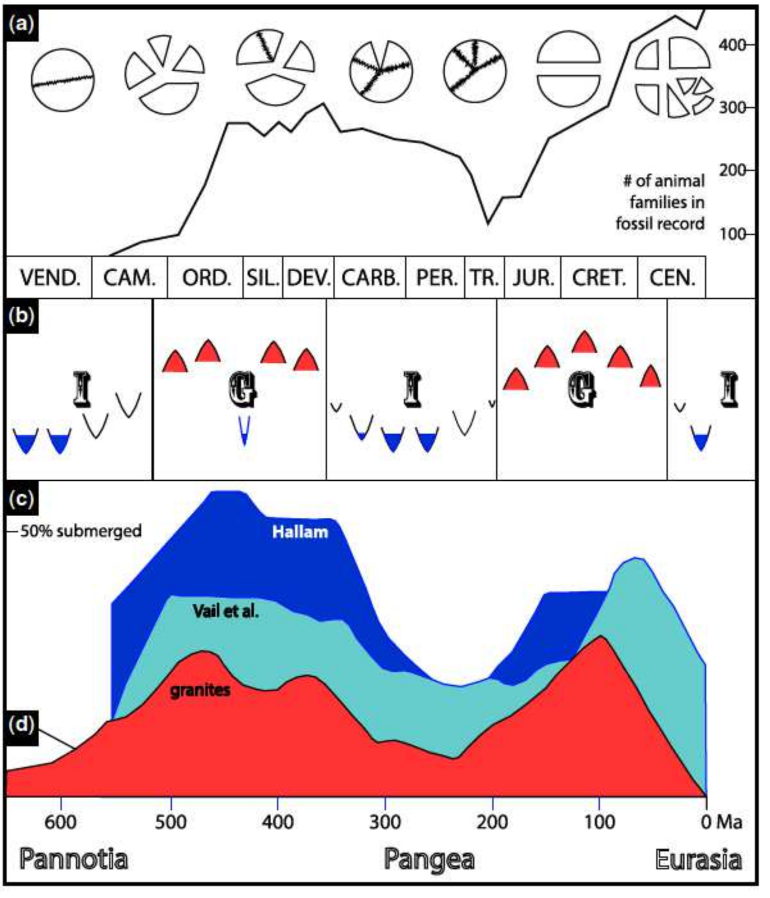

Fig. 2. Traditional notions of two Phanerozoic supercycles. (**a**) Modified from Valentine and Moores (1970), schematic illustration of terminal Proterozoic supercontinent break-up, reassembly into Permian–Triassic Pangaea (jagged lines mark collisional sutures) and fragmentation into the present continents; superimposed upon a family-level diversity curve for Phanerozoic macrofauna. (**b**) Alternating idealized palaeoclimate states (I, icehouse; G, greenhouse) with schematic indications of global temperature (blue, glacial; red, extraordinarily warm). (**c**) Two first-order sea-level curves (dark and light blue) based primarily on continental flooding records. (**d**) Abundance curve of North American granites. (b)–(d) are from Fischer (1984) with appropriate references therein. Note that the name 'Pannotia' was coined after the initial construction of these diagrams.

a process could well be attributed to the profundity of Gondwanaland-forming orogenic climax (Squire *et al.* 2006) rather than continental fragmentation.

Summary of biological diversity

Different associations of major animal fossil groups exhibit logistical functions of growth that are not well correlated to proposed supercontinental cycles. Phylogenetic diversification of major animal clades occurred substantially prior to a putative Pannotia break-up event. The role of supercontinental connectivity in shaping animal diversity, especially in the Paleozoic, is tentative.

Palaeoclimate

By the late 1970s, Earth's pre-Pleistocene glacial record was fully catalogued (Hambrey and Harland 1981), and it was recognized that ice ages have recurred several times in the last billion years. Fischer (1981, 1984) recognized that greenhouse forcing by atmospheric carbon dioxide should be linked to global fluctuations in plate tectonics via changes in the rate of volcanic outgassing: enhanced plate tectonic activity would lead to warmer climate. Nance *et al.* (1986) and Worsley *et al.* (1986) also recognized the importance of global carbon burial that should be enhanced by a high-freeboard supercontinent, promoting glaciation at the nadir of the

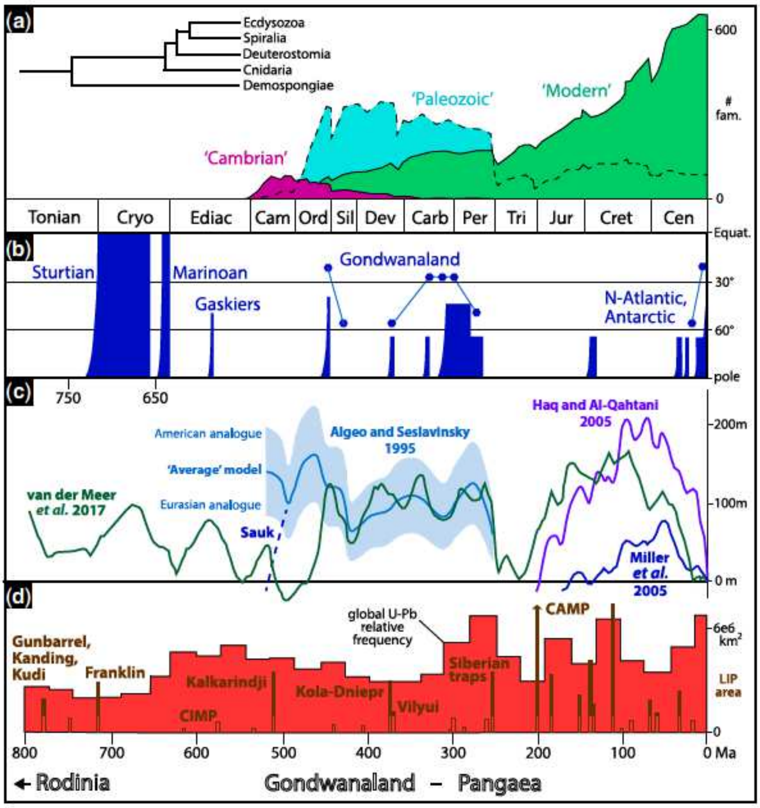

Fig. 3. Current estimates of Phanerozoic and late Neoproterozoic trends updating those shown in Figure 2. (**a**) Molecular clock estimates of major diversification events within crown-group Metazoa, after dos Reis *et al.* (2015), with generalized names of clades; and family-level diversity curves of three broad faunal associations by Sepkoski (1984). (**b**) Maximal equatorward extents of ice ages, irrespective of hemisphere. Shaded depictions of ice-sheet extent, and names, are from P. Hoffman (unpublished teaching slide freely available on snowballearth.org). Data points with tie lines for the maximum equatorward extent of low-altitude glacial deposits (including glaciomarine facies that might be far removed from the ice sheets) from Evans (2003*a*, *b*). (**c**) Estimates of past sea-level changes. Sequence–stratigraphic or back-stripped estimates of younger epochs from Arabia (Haq and Al-Qahtani 2005) and New Jersey, USA (Miller *et al.* 2005). Paleozoic modelling (Algeo and Seslavinsky 1995) utilizes alternative 'analogues' for continental hypsometry based on modern elevation profiles. The Sauk transgression of Laurentia is stylized from the records depicted in Miller *et al.* (2005). Sr isotopic data converted into a proxy for sea level generates a continuous curve (van der Meer *et al.* 2017). (**d**) Relative frequency (red) of a spatially filtered, global U–Pb age database in 30 myr bins (Puetz *et al.* 2018); and inferred areal extents (brown) of continental LIPs (Ernst *et al.* 2020) (notable events are named or abbreviated as in the text; filled boxes represent the portions of areas exceeding 1×10^6 km^2).

climatic cycle. A summary illustration of the concept is shown in Figure 2b, with alternating intervals of so-called greenhouse ('G') and icehouse ('I') climate states. Within the early Paleozoic broad interval of greenhouse conditions, the ephemeral end-Ordovician ice age stood out as an anomaly.

The fundamental causes of ice ages in Earth history remain contentious, with some groups favouring atmospheric carbon dioxide sinks, mainly through silicate weathering, as playing the predominant role (Macdonald *et al.* 2019), others emphasizing variations in the sources via volcanic outgassing (McKenzie *et al.* 2016) and some models suggesting a time-varying shift in dominance between those two processes (Mills *et al.* 2019). In an idealized supercontinental cycle, both processes can act in concert: assembly and highstanding supercontinental existence could promote CO_2 drawdown and glaciation, whereas advanced stages of break-up and rapid drift of isolated continental fragments could promote CO_2 outgassing and warm climates. A complicating factor is that emplacement of large igneous provinces

(LIPs) during rifting might produce an ephemeral warming via outgassing, followed by more enduring basalt weathering, CO_2 sequestration and, thus, cooling in the supercontinental fragmentation stage (Donnadieu *et al.* 2004; Cox *et al.* 2016).

The geological history of ice ages through the last billion years has become more finely tuned since initial development of broad-scale supercontinental models of the 1980s (Fig. 3b). Cryogenian glaciations are now known to have encroached well into tropical palaeolatitudes, and latest iterations of the Snowball Earth model highlight the profound differences between a nearly 60 myr-long Sturtian ice age (Rooney *et al.* 2014) v. a short-lived but equally severe Marinoan glacial spell (for review of both, see Hoffman *et al.* 2017). With ages between 717 and 635 Ma, Cryogenian glaciations are confidently dated to the tectonically overlapping intervals of Rodinia break-up and early Gondwanaland amalgamation, significantly older than any purported Pannotia tenure. Mid–late Ediacaran ice ages exist (e.g. Gaskiers, Luoquan) but are less common, and of unknown palaeogeographical extent (Evans and Raub 2011).

Paleozoic glacial centres across Gondwanaland tracked the south pole as that continent drifted between latest Ordovician and early Permian time (Caputo and Crowell 1985; Evans 2003*a*). Rather than occurring in widely separated late Ordovician and late Paleozoic episodes, ice ages through that interval are now recognized in more of a continuum of consistently cool climates with only a brief mid-Devonian respite (Boucot *et al.* 2013). Figure 3b shows the palaeolatitude extent of ice sheets and glaciomarine deposits through time. Instead of icehouse states corresponding strictly with the Pangaean interval, the Gondwanaland glacial epoch largely preceded Pangaea's apex in development.

Summary of palaeoclimate

Initial suggestions that climates of the last 600 myr correlated to two climate supercycles are now considered obsolete due to refined chronostratigraphy. Ice ages can occur at any stage of a supercontinental cycle as long as atmospheric CO_2 and effective solar radiation are reduced, by a variety of processes.

Sea level

Fischer (1981, 1984) utilized contemporary compilations of Phanerozoic continental flooding to infer prominent Cretaceous and early Paleozoic eustatic highstands. Complementary to late Precambrian and late Paleozoic lowstands, these records suggested two Phanerozoic 'supercycles' and the notion of a pre-Pangaea supercontinent (Fig. 2c). Quantifying this inference with a model of sea level responding to young and shallow oceanic basins replacing old and deep basins upon supercontinental break-up, Worsley *et al.* (1984, 1986) and Nance *et al.* (1986) were able to explain first-order features of the flooding records.

As pointed out by Hallam (1992), in order to calculate past global sea levels from flooding records one must assume an average hypsometry of continents. Even modest variations in the assumed continental hypsometric analogue produce highly discrepant sea-level curves (Algeo and Seslavinsky 1995) (Fig. 3c). Furthermore, the analysis is sensitive to the weighting of various cratonic records; regional variations can be deflected by regional subsidence or dynamic topography (Conrad 2013) or global-scale quadrantal patterns of true polar wander (Wegener 1929, pp. 176–177; Mound and Mitrovica 1998). As an example of the former, note the stark contrast between flooding records of Arabia (Haq and Al-Qahtani 2005) v. New Jersey, USA (Miller *et al.* 2005). As for the latter, the prominent Cambrian Sauk transgression across Laurentia is less noteworthy on other cratons (Algeo and Seslavinsky 1995) (Fig. 3c) and is, perhaps, explained in large part by an early Cambrian inertial interchange true polar wander event (Mound *et al.* 1999).

Additional methods to calculate Phanerozoic sea level have arisen in recent years. Utilizing a global plate reconstruction model and an associated synthetic topography/bathymetry, Verard *et al.* (2015) computed global sea level for the last 600 myr. The method avoids the pitfalls of continental flooding records as noted above, but it relies heavily on estimated bathymetries of the Panthalassan Ocean basin surrounding the Paleozoic continents; the resulting sea-level curves are highly sensitive to such assumptions (Rowley 2008; Conrad 2013; Williams *et al.* 2020). The use of marine strontium isotopes as a proxy for global continental emergence and, thus indirectly, sea level (van der Meer *et al.* 2017) is replete with numerous assumptions as duly noted by its practitioners; nonetheless, the method generates a more muted Paleozoic sea-level highstand than the traditional flooding-derived curves (cf. Figs 2c & 3c).

Amid all the uncertainties regarding Phanerozoic sea-level variations, there does appear to be a prominent Triassic lowstand that might have been caused fundamentally by the existence of Pangaea, with the ensuing Jurassic–Cretaceous transgression caused by the initiation of Atlantic seafloor spreading. Whether that model translates to the early Paleozoic is less certain: different global sea-level models place a transgression either before, during or after the early Cambrian break-up age of a putative Pannotia landmass.

Summary of sea level

When assessing compilations of sea level through the past 600 myr, care must be taken to ensure the global scope of the constituent records and the assumptions inherent to the various methods. Current evidence for a sea-level proxy record of Pannotia and its break-up is not as strong as it appeared in the 1980s.

Global magmatism

Initial notions of two Phanerozoic supercycles were bolstered by the tectonic proxy of granite ages, which showed two prominent peaks that mirrored the sea-level curves (Fig. 2d) and were interpreted in the context of enhanced global kinematics accompanying supercontinental break-up (Fischer 1981, 1984). However, the widely illustrated granite-age curve (Engel and Engel 1964) derives exclusively from North America. The prominent Paleozoic peak from that dataset almost certainly reflects the dominance of ages from the Appalachian orogen, which represents serial subduction-zone magmatism within the single Iapetus–Rheic oceanic tract that closed to form Pangaea (Hibbard *et al.* 2006). In general, global zircon peaks are more cogently associated with enhanced preservation potential in collisional settings (Cawood *et al.* 2013). When a more recent, spatially binned, global U–Pb age dataset is consulted (Puetz *et al.* 2018), the aforementioned Paleozoic peak largely disappears (Fig. 3d). The global U–Pb record does show a pronounced increase of ages through the late Neoproterozoic interval, which is likely to document the formation of Gondwanaland via a series of collisions culminating in Cambrian time (Schmitt *et al.* 2018). Such a profound peak in magmatism and uplift of a 'super' mountain chain (Squire *et al.* 2006) represent a first-order feature of global tectonics, regardless of whether Laurentia and Baltica were attached to the rapidly assembling Gondwanaland amalgam.

Proponents of a Pannotia supercycle point to several episodes of Ediacaran–Cambrian magmatism in defence of a supercontinental influence on mantle convection (Murphy *et al.* 2020). A complete reading of the global record of LIPs (Ernst *et al.* 2020), however, shows their Paleozoic abundance to be much less than that related to Pangaea break-up (Fig. 3d). The two pulses of Central Iapetus Magmatic Province (CIMP) and magmatism in the Oklahoma aulacogen, all crucial to the hypothesis of Iapetus rifting as the break-up phase in a post-Pannotia supercycle, are diminutive when compared to the Mesozoic LIPs. Among the three sizable early–middle Paleozoic LIPs (Kalkarindji, Kola-Dniepr and Vilyui: Fig. 3d), the former was marginal to the Gondwanaland amalgam (in northern Australia) and the latter two were emplaced on smaller blocks (Baltica and Siberia, respectively) that appear to have no relationship to any major continental fragmentation. The end-Permian Siberian traps are spatio-temporally embedded within the marginal and final stages of Pangaea's amalgamation.

Summary of global magmatism

Despite previous depictions of a bimodality in Phanerozoic magmatism through time, which were biased towards just the North American record, updated global compilations of magmatism instead emphasize the profound influence of Gondwanaland's Neoproterozoic–Cambrian assembly (from zircons) and Mesozoic break-up (from LIPs).

Mantle dynamics

The idea that a supercontinent may influence mantle convection (Holmes 1929; Anderson 1982) first received modern quantitative physical support by Gurnis (1988). Since then, more sophisticated computational models have explored geophysical parameter space with increasing realism of Earth-like values. Note the physical distinction between two related processes: thermal *insulation* by thick continental lithosphere and thermal *isolation* of underlying mantle from cooling by subducted slabs. Numerical models of thermal influence by a supercontinental lid now usually incorporate both of these processes acting in tandem. Some models advocate for timescales as short as 50 myr for the development of upwelling beneath a supercontinent (Zhong *et al.* 2007), whereas other models require 100 myr or longer for development of a *c.* 50°C thermal anomaly (Yoshida 2013) or *c.* 100°C anomaly (Rolf *et al.* 2012) with high sensitivity to convective vigour of the underlying mantle (Heron and Lowman 2014).

In defending a mid-Ediacaran age for Pannotia assembly, which could permit its existence for as much as *c.* 50 myr prior to Iapetan rifting, Nance and Murphy (2019) and Murphy *et al.* (2020) asserted that the timing of collisional onset, rather than termination, is most relevant to mantle geodynamics. The logic is based on the recognition of Mediterranean-style slab rollback into remnant ocean basins following major 'head-on' collisions between continents, and is applied to various Gondwanaland-forming orogens as described above. It is true, in this author's opinion, that Mediterranean-style orogenesis may be underappreciated in deep-time tectonics; however, a four-dimensional perspective on these modern systems illustrates the prevalence of actively subducting slabs throughout the orogenic region (Wortel and Spakman 2000) for as long as tens of millions of years after the initial collision. Thereafter, slabs will continue to sink slowly into the mantle (van der Meer *et al.* 2018) beneath the newly formed (super) continent, postponing further (of the order of *c.* 100 myr) any deep-mantle isolational thermal effects that the landmass may have.

The radiogenic effects of continental collision, in the sense of a thermal lid developing above the site of former subduction, may begin to accumulate from the onset of slab breakoff or detachment. Insofar as slab breakoff may generate local asthenospheric upwelling and elevated surface topography due to isostatic rebound, the stratigraphic record of slab detachment is likely to be a suite of post-collisional magmatism (Davies and von Blanckenburg 1995) and molasse sedimentation (Sinclair 1997). Where preserved, the molassic units across most of the Gondwanaland orogens are Cambrian rather than Ediacaran in age (Squire *et al.* 2006) and are replete with geon-5 detrital zircons from late-orogenic granitoid source areas (Veevers 2017). Thus, post-collisional slab breakoff was largely a Cambrian phenomenon through much of the Gondwanaland region.

Given these constraints, it is highly unlikely that the mantle effects of Gondwanaland assembly could have induced rifting in the Iapetan realm, as proposed by Murphy *et al.* (2020). Iapetus Ocean opening, which is one of the classic hallmarks of a Pannotia break-up phase in an alleged supercontinental cycle (Nance and Murphy 2019), is simply too close in age to the Gondwanaland collisions and slab breakoff events. (In the converse sense, however, Iapetus opening may have caused some Gondwanaland orogens to close shortly thereafter, via immediate plate reorganization: Grunow *et al.* 1996.) Heron *et al.* (2020) developed mantle convection models based on the kinematic reconstructions of Merdith *et al.* (2017) for Neoproterozoic–Paleozoic time, and Matthews *et al.* (2016) for the interval 410 Ma–present. Although they label the Laurentia–Siberia–Baltica–Amazonia amalgam 'Pannotia', those connections were inherited from Rodinia; such a definition strays from traditional notions of the supercontinent, which should include a united Gondwanaland. Still, one may ask whether this areally reduced landmass could have influenced mantle circulation. Heron *et al.* (2020) do find modest increases in basal mantle heat flux and plume coverage at about 550 Ma (although not as large as those accompanying Pangaea break-up), but the palaeogeographical distribution of modelled plumes follows a similar global pattern to those of preceding time intervals accompanying Rodinia break-up. Thus, the alleged Pannotia influence on convection could be interpreted instead as the final stage of a protracted Rodinia-induced mantle structure.

The thermal effects of Gondwanaland assembly were probably not realized until at least mid-Paleozoic time, and perhaps not fully until the Mesozoic. It remains conceivable that some early–middle Paleozoic intraplate magmatism around the margins of Gondwanaland could relate to the effects of reorganized subduction geometry following its Cambrian amalgamation (Murphy *et al.* 2020), and that the edge effects of continental lithosphere on regional-scale mantle circulation may even have induced rifting of ribbon-like fragments such as the Appalachian and Tethyan terranes; but only the post-Cambrian instances of these can be plausibly linked to large-scale Gondwanaland assembly.

Summary of mantle dynamics

Even considering the most favourable geochronological interpretations of tectonic events for the Pannotia hypothesis, the vertical transit times of sinking slabs and rising mantle plumes are too long to support the idea that Iapetus rifting was an immediate geodynamic consequence of Gondwanaland assembly. Even if a Pannotia landmass existed briefly, as an entity of its own, it probably had little influence on mantle convection. Longer-lived Gondwanaland, however, may have exerted a profound influence on mantle dynamics.

Additional proxies

Bradley (2011) discussed a wide range of possible proxy records of supercontinentality, ranging from tectonics and geophysics to geochemistry, mineral deposits and palaeoclimate. Many of these were additionally discussed by Nance *et al.* (2014), Pastor-Galán *et al.* (2018) and Nance and Murphy (2019). Among those not already noted above in the historical development of Phanerozoic supercycles, additional proxies are grouped below by: (i) those related directly to late Neoproterozoic global orogenesis and hypothesized post-Pannotia break-up in the early Paleozoic; and (ii) palaeoenvironmental proxies with indirect links to global tectonics:

(i) Most proxies related to late Neoproterozoic global orogenesis are adequately explained by profound collisional tectonism accompanying Gondwanaland amalgamation. An abundance of high-pressure and high-temperature metamorphic terrains within Neoproterozoic orogens (Brown 2007) indicates continental collisions under a variety of thermal regimes, but does not specify whether a full-scale supercontinent formed at that time. Anomalously high ratios of $^{87}Sr/^{86}Sr$ in Ediacaran marine carbonates are attributed to the predominance of continental weathering during late Neoproterozoic collisions (Goddéris *et al.* 2017) but also not explicitly requiring Pannotia's existence. Intriguingly, $^{87}Sr/^{86}Sr$ ratios decline through Paleozoic time, such that Pangaea's tenure coincides with some of the *least* radiogenic values of the last 600 myr. As noted by Halverson *et al.* (2007), the marine strontium isotopic record may be sensitive to particular geographical distributions of juvenile and evolved orogens, in ways that might be difficult to generalize. The hafnium isotopic composition of magmatic zircons shows similar trends to the marine strontium record, with the most evolved continental signal corresponding to Gondwanaland assembly (Collins *et al.* 2011), and this is also attributed to particular geometries of subduction and collision relative to other continental assemblages (Spencer *et al.* 2013). As with strontium, there is a stark contrast in hafnium isotopic values between end-Neoproterozoic and end-Paleozoic orogenic stages, emphasizing their non-equivalence and negating any straightforward interpretation of two Phanerozoic supercycles. Other geochemical records of zircon show similarly incompatible trends between those two eras (Spencer *et al.* 2014; Van Kranendonk and Kirkland 2016).

Perhaps the most directly telling proxy for a full-fledged supercontinental break-up event would be a global peak in passive margins. If Pannotia and Pangaea were considered to be distinct supercontinents with intervening break-up and assembly phases, then one would expect the aggregate length of passive margins to increase dramatically in early Paleozoic time. Indeed, the Cambrian passive margins around Laurentia (Stewart 1972) were among the first evidence marshalled for an end-Proterozoic supercontinent.

Considered globally, however, the increase in passive-margin length begins in mid-Neoproterozoic time, with only a modest subsidiary peak at the dawn of the Paleozoic (Bradley 2008). The passive-margin proxy, therefore, emphasizes Rodinia and Pangaea break-up, concordant with the global LIP record as noted above – but not Pannotia.

(ii) Palaeoenvironmental proxies, reflecting atmospheric or oceanic biogeochemical trends, usually have multiple interpretations. Although Campbell and Allen (2008) correlated a Neoproterozoic rise in atmospheric oxygen with the formation of Gondwanaland (thus considered by some as a proxy for Pannotia supercontinent formation), such an increase is itself based on geochemical proxies that need to be evaluated in their own right. The most recent compilations of these proxies note their limitations and distinct applications to the atmosphere and various depths of the global ocean (Cole *et al.* 2020; Tostevin and Mills 2020), and point to a prolonged interval of oxygenation that presently lacks the temporal resolution to be ascribed confidently to any particular global tectonic regime. The sulfate isotopic record of seawater shows a pronounced Neoproterozoic–Cambrian peak and steady decline through the Paleozoic (Och and Shields-Zhou 2012; Algeo *et al.* 2015). Nance and Murphy (2019) suggested that a supercontinent should be marked by low ^{34}S values of seawater, due to isotopically heavy sulfur sequestered in evaporites, but the marine ^{34}S record is more sensitive to variations in the efficiency of pyrite burial (due to its stronger 'lever' with highly negative values), and the record is difficult to interpret due to a complex interplay between oxygenation and cycling of carbon, iron and sulfur (Berner 2006). In any case, much like the strontium and hafnium isotopic trends described above, the nearly monotonically decreasing Paleozoic sulfate record argues against an equivalence of Pannotia and Pangaea. Finally, the ^{13}C record of marine carbonates has comparably complex associations with supercontinentality (Worsley and Nance 1989). Although the late Neoproterozoic Shuram negative ^{13}C excursion has been highlighted as an example of extreme carbon-cycle perturbation commensurate with supercontinent formation (Nance and Murphy 2019), it occurred within a milieu of extraordinarily large carbon isotopic varations throughout the Ediacaran–Cambrian interval, with a variety of proposed causes and interpretations (e.g. Boyle *et al.* 2018; Cui *et al.* 2018; Shields 2018; Hoffman and Lamothe 2019). If tectonic forcing is identified as a contributing factor to large ^{13}C excursions (e.g. the weathering of Tonian evaporites in Gondwanaland-forming orogens for the Shuram event: Shields *et al.* 2019), then merely a prominent set of collisional belts with appropriate lithologies can suffice to generate the signal – but not necessarily the assembly of a complete supercontinent.

Summary of additional proxies

Although Nance and Murphy (2019, p. 76) wrote that 'the proxy signals for the existence of an Ediacaran supercontinent are unmistakable', it is argued here that those proxies can adequately apply to the latest Neoproterozoic–Cambrian assembly of Gondwanaland, without requiring a full-fledged Pannotia supercontinent, or are ambiguous with respect to supercontinental cycles. It could be argued that the strength of the Pannotia proxy record is *collective*, in that each item could have its flaws but together the evidence favours an Ediacaran–Cambrian supercontinent. In rebuttal, this review suggests that the proxies for continental amalgamation indeed provide a strong collective argument for the fundamental global significance of Gondwanaland assembly; but the proxies for early Paleozoic continental fragmentation are too weak to provide such a rationale.

Discussion: semi-supercontinents and global cycles

In the hierarchy of ancient landmasses, Gondwanaland must be considered as a subset of Pangaea. Because Pangaea is the type example of a 'supercontinent', there should be a suitable term for Gondwanaland as an exceptionally large continental plate. Evans *et al.* (2016) coined the term 'semi-supercontinent' on the recognition that Gondwanaland's area was roughly half that of Pangaea. Given that Gondwanaland is an essential component of hypothetical Pannotia: if Pannotia were to have existed, then it would have hierarchical status comparable to that of Pangaea. The Siberian Craton's exclusion from Pannotia is similar in stature to the exclusion of East Asian blocks from Pangaea (Torsvik and Cocks 2017), and by itself would not compromise Pannotia's hierarchical status as a supercontinent – if it existed.

Gondwanaland endured as a giant continental cap over the mantle between Cambrian and Jurassic time, a period of more than 300 myr. By contrast, Pangaea only lasted for about 120 myr at most (Torsvik and Cocks 2017). Gondwanaland's thermal effects on the underlying mantle would be more significant if it had remained stationary during its tenure. If the substantial Paleozoic apparent polar wander of Gondwanaland (Meert *et al.* 1993; McElhinny *et al.* 2003) is interpreted predominantly as the record of large-scale true polar wander (Evans 1998), then the interior sub-Gondwanaland mantle would have been devoid of subducted slabs for sufficient time to influence first-order global convection patterns. According to this view, addition of Laurasia to form Pangaea (via predominant transform motion along Gondwanaland's northern margin: Domeier 2016) might be considered as a mere addendum to the convective legacy already established by the aging semi-supercontinent (Evans 2003*b*). Insofar as global peaks in continental rift length (Merdith *et al.* 2019) and LIPs (Ernst *et al.* 2020) reflect major episodes of mantle upwelling, the extraordinary Mesozoic fragmentation of Gondwanaland is unique to Phanerozoic time (Fig. 3d) and may divulge the importance of that semi-supercontinent's longevity in geodynamic terms.

Conclusions

When considering both direct palaeogeographical evidence and various indirect or proxy records for supercontinents, there appears to be no strong case for Pannotia. One might rightly ask, however, if there is a strong case for the non-existence of Pannotia? Since the nuances of proxy records are now better appreciated than when the concept of two Phanerozoic supercycles were first introduced in the 1980s, we turn to the direct evidence in terms of the global orogenic and taphrogenic history of collisional and break-up events through the Neoproterozoic–Cambrian transition. Such history indicates that Gondwanaland amalgamation was very likely to have completed its assembly in Cambrian time. The magmatic and passive-margin records of early Paleozoic time are minor when compared to the preceding interval of Rodinia fragmentation and the extensive Mesozoic plume–rift systems that dismembered Pangaea. Transit times of slabs and upwellings through the mantle are so slow that Gondwanaland assembly could not have caused Iapetan rifting via convective overturn. Gondwanaland's effects on mantle circulation were only realized later, perhaps as small marginal magmatic events along its periphery but most spectacularly in the form of Mesozoic LIPs and rifts that ended the Gondwanaland–Pangaea supercontinent cycle.

Global tectonic/geodynamic episodicity of the last billion or more years consists of the following rounded intervals in broad terms: Rodinia supercontinental assembly (1100–900 Ma), Rodinia tenure (900–800 Ma), Rodinia break-up (800–650 Ma), Gondwanaland semi-supercontinental assembly (650–500 Ma), Pangaea supercontinental assembly (500–300 Ma), Pangaea tenure (300–200 Ma), Pangaea break-up (200–50 Ma), and the imminent assembly of future semi- and complete supercontinents around Eurasia (since 50 Ma). Proxy records of global tectonism can be explained suitably by this history. There is no pre-Pannotia assembly phase distinct from the well-accepted orogenic amalgamation of Gondwanaland, and there is no global-scale post-Pannotia break-up event. This prosecution therefore declares Pannotia guilty of a masqueraded existence.

Acknowledgments This paper, written in deep admiration of Damian Nance's career, is testament to the ability of good friends to enjoy a lively academic debate. He and Brendan Murphy provided many constructive discussions and comments on the ideas presented herein, including refereeing and patient editorial handling. Paul Hoffman gave helpful suggestions regarding Neoproterozoic sea level. Peter Cawood is also thanked for a careful manuscript review.

Author contributions **DADE**: conceptualization (lead), investigation (lead), methodology (lead), writing – original draft (lead), writing – review & editing (lead).

Funding This research is associated with the project, 'Collaborative Research: Co-evolution of Earth and life across the Proterozoic-Phanerozoic transition: Integrated perspectives from outcrop and drill core', funded by the U.S. National Science Foundation (EAR-2021319).

Data availability statement Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

References

Algeo, T.J. and Seslavinsky, K.B. 1995. The Paleozoic world: Continental flooding, hypsometry, and sealevel. *American Journal of Science*, **295**, 787–822, https://doi.org/10.2475/ajs.295.7.787

Algeo, T.J., Luo, G.M., Song, H.Y., Lyons, T.W. and Canfield, D.E. 2015. Reconstruction of secular variation in seawater sulfate concentrations. *Biogeosciences*, **12**, 2131–2151, https://doi.org/10.5194/bg-12-2131-2015

Alves, P.V.F., de, S., Botelho, N.F., Dantas, E.L. and Cuadros, F.A. 2019. The Cambrian peraluminous Santa Luzia granite suite in the Araguaia Belt, central Brazil: Evidence for closure of the Clymene Ocean based on zircon and monazite U–Pb data. *Journal of South American Earth Sciences*, **92**, 116–133, https://doi.org/10.1016/j.jsames.2019.03.007

Anderson, D.L. 1982. Hotspots, polar wander, Mesozoic convection and the geoid. *Nature*, **297**, 391–393, https://doi.org/10.1038/297391a0

Armistead, S.E., Collins, A.S. *et al.* 2020. Structural evolution and medium-temperature thermochronology of central Madagascar: implications for Gondwana amalgamation. *Journal of the Geological Society, London*, **177**, 784–798, https://doi.org/10.1144/jgs2019-132

Awramik, S.M. and Sprinkle, J. 1999. Proterozoic stromatolites: The first marine evolutionary biota. *Historical Biology*, **13**, 241–253, https://doi.org/10.1080/08912969909386584

Bell, R. and Jefferson, C.W. 1987. An hypothesis for an Australia–Canadian connection in the Late Proterozoic and the birth of the Pacific Ocean. *In*: *Proceedings of the Pacific Rim Congress '87: An International Congress On the Geology, Structure, Mineralisation and Economics of the Pacific Rim*. Australian Institute of Mining and Metallurgy, Carlton Victoria, Australia, 39–50.

Berner, R.A. 2006. GEOCARBSULF: a combined model for Phanerozoic atmospheric O_2 and CO_2. *Geochimica et Cosmochimica Acta*, **70**, 5653–5664, https://doi.org/10.1016/j.gca.2005.11.032

Boger, S.D. 2011. Antarctica – Before and after Gondwana. *Gondwana Research*, **19**, 335–371, https://doi.org/10.1016/j.gr.2010.09.003

Boger, S.D., Hirdes, W., Ferreira, C.A.M., Jenett, T., Dallwig, R. and Fanning, C.M. 2015. The 580–520 Ma Gondwana suture of Madagascar and its continuation into Antarctica and Africa. *Gondwana Research*, **28**, 1048–1060, https://doi.org/10.1016/j.gr.2014.08.017

Boger, S.D., Maas, R. *et al.* 2019. The tectonic domains of southern and western Madagascar. *Precambrian Research*, **327**, 144–175, https://doi.org/10.1016/j.precamres.2019.03.005

Bond, G.C. 1997. New constraints on Rodinia breakup ages from revised tectonic subsidence curves. *Geological Society of America Abstracts with Programs*, **29**, 280.

Bond, G.C., Kominz, M.A. and Devlin, W.J. 1983. Thermal subsidence and eustasy in the Lower Palaeozoic miogeocline of western North America. *Nature*, **306**, 775–779, https://doi.org/10.1038/306775a0

Bond, G.C., Nickeson, P.A. and Kominz, M.A. 1984. Breakup of a supercontinent between 625 Ma and 555 Ma: new evidence and implications for continental histories. *Earth and Planetary Science Letters*, **70**, 325–345, https://doi.org/10.1016/0012-821X(84)90017-7

Boucot, A., Xu, C., Scotese, C.R. and Morley, R.J. 2013. *Phanerozoic Paleoclimate: An Atlas of Lithologic Indicators of Climate*. SEPM Concepts in Sedimentology and Paleontology, **11**, https://doi.org/10.2110/sepmcsp.11

Boyle, R.A., Dahl, T.W., Bjerrum, C.J. and Canfield, D.E. 2018. Bioturbation and directionality in Earth's carbon isotopic record across the Neoproterozoic–Cambrian transition. *Geobiology*, **16**, 252–278, https://doi.org/10.1111/gbi.12277

Bradley, D.C. 2008. Passive margins through earth history. *Earth-Science Reviews*, **91**, 1–26, https://doi.org/10.1016/j.earscirev.2008.08.001

Bradley, D.C. 2011. Secular trends in the geologic record and the supercontinent cycle. *Earth and Planetary Science Letters*, **108**, 16–33, https://doi.org/10.1016/j.earscirev.2011.05.003

Brennan, S.T., Lowenstein, T.K. and Horita, J. 2004. Seawater chemistry and the advent of biocalcification. *Geology*, **32**, 473–476, https://doi.org/10.1130/G20251.1

Brown, M. 2007. Metamorphic conditions in orogenic belts: A record of secular change. *International Geology Review*, **49**, 193–234, https://doi.org/10.2747/0020-6814.49.3.193

Campbell, I.H. and Allen, C.M. 2008. Formation of supercontinents linked to increases in atmospheric oxygen. *Nature Geoscience*, **1**, 554–558, https://doi.org/10.1038/ngeo259

Caputo, M.V. and Crowell, J.C. 1985. Migration of glacial centers across Gondwana during Paleozoic Era. *Geological Society of America Bulletin*, **96**, 1020–1036, https://doi.org/10.1130/0016-7606(1985)96<1020:MOGCAG>2.0.CO;2

Casquet, C., Rapela, C.W. *et al.* 2012. A history of Proterozoic terranes in Southern South America: From Rodinia to Gondwana. *Geoscience Frontiers*, **3**, 137–145, https://doi.org/10.1016/j.gsf.2011.11.004

Cawood, P.A., McCausland, P.J.A. and Dunning, G.R. 2001. Opening Iapetus: Constraints from the Laurentian margin in Newfoundland. *Geological Society of America Bulletin*, **113**, 443–453, https://doi.org/10.1130/0016-7606(2001)113<0443:OICFTL>2.0.CO;2

Cawood, P.A., Hawkesworth, C.J. and Dhuime, B. 2013. The continental record and the generation of continental crust. *Geological Society of America Bulletin*, **125**, 14–32, https://doi.org/10.1130/B30722.1

Chew, D.M., Magna, T., Kirkland, C.L., Miskovic, A., Cardona, A., Spikings, R. and Schaltegger, U. 2008. Detrital zircon fingerprint of the Proto-Andes: evidence for a Neoproterozoic active margin? *Precambrian Research*, **167**, 186–200 https://doi.org/10.1016/j.precamres.2008.08.002

Clark, C., Collins, A.S., Taylor, R.J.M. and Hand, M. 2020. Isotopic systematics of zircon indicate an African affinity for the rocks of southernmost India. *Scientific Reports*, **10**, 5421, https://doi.org/10.1038/s41598-020-62075-y

Cohen, P.A. and Macdonald, F.A. 2015. The Proterozoic record of eukaryotes. *Paleobiology*, **41**, 610–632, https://doi.org/10.1017/pab.2015.25

Cole, D.B., Mills, D.B., Erwin, D.H., Sperling, E.A., Porter, S.M., Reinhard, C.T. and Planavsky, N.J. 2020. On the co-evolution of surface oxygen levels and animals. *Geobiology*, **18**, 260–281, https://doi.org/10.1111/gbi.12382

Collins, W.J., Belousova, E.A., Kemp, A.I.S. and Murphy, J.B. 2011. Two contrasting Phanerozoic orogenic systems revealed by hafnium isotope data. *Nature Geoscience*, **4**, 333–337, https://doi.org/10.1038/ngeo1127

Conrad, C.P. 2013. The solid Earth's influence on sea level. *Geological Society of America Bulletin*, **125**, 1027–1052, https://doi.org/10.1130/B30764.1

Cordani, U.G., Teixeira, W., D'Agrella-Filho, M.S. and Trindade, R.I.F. 2009. The position of the Amazonian Craton in supercontinents. *Gondwana Research*, **15**, 396–407, https://doi.org/10.1016/j.gr.2008.12.005

Cordani, U.G., Pimentel, M.M., de Araújo, C.E.G., Basei, M.A.S., Fuck, R.A. and Girardi, V.A.V. 2013. Was there an Ediacaran Clymene Ocean in central South America? *American Journal of Science*, **313**, 517–539, https://doi.org/10.2475/06.2013.01

Cox, G.M., Halverson, G.P. *et al.* 2016. Continental flood basalt weathering as a trigger for Neoproterozoic Snowball Earth. *Earth and Planetary Science Letters*, **446**, 89–99, https://doi.org/10.1016/j.epsl.2016.04.016

Cui, H., Kaufman, A.J., Peng, Y., Liu, X.-M., Plummer, R.E. and Lee, E.I. 2018. The Neoproterozoic Hüttenberg δ^{13}C anomaly: genesis and global implications. *Precambrian Research*, **313**, 242–262, https://doi.org/10.1016/j.precamres.2018.05.024

Daczko, N.R., Halpin, J.A., Fitzsimons, I.C.W. and Whittaker, J.M. 2018. A cryptic Gondwana-forming orogen located in Antarctica. *Scientific Reports*, **8**, 8371, https://doi.org/10.1038/s41598-018-26530-1

Dalziel, I.W.D. 1991. Pacific margins of Laurentia and East Antarctica–Australia as a conjugate rift pair: Evidence and implications for an Eocambrian supercontinent. *Geology*, **9**, 598–601, https://doi.org/10.1130/0091-7613(1991)019<0598:PMOLAE>2.3.CO;2

Dalziel, I.W.D. and Dewey, J.F. 2019. The classic Wilson cycle revisited. *Geological Society, London, Special Publications*, **470**, 19–38, https://doi.org/10.1144/SP470.1

Davies, J.H. and von Blanckenburg, F. 1995. Slab breakoff: a model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. *Earth and Planetary Science Letters*, **129**, 85–102, https://doi.org/10.1016/0012-821X(94)00237-S

Dewey, J.F. and Burke, K.C.A. 1973. Tibetan, Variscan and Precambrian basement reactivation: products of continental collision. *Journal of Geology*, **81**, 683–692, https://doi.org/10.1086/627920

Dewey, J.F., Shackleton, R.M., Chang, C. and Sun, Y. 1988. The tectonic evolution of the Tibetan Plateau. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **327**, 379–413, https://doi.org/10.1098/rsta.1988.0135

Dias, A.N.C., Moura, C.A.V., Milhomem Neto, J.M., Chemale, F., Jr, Girelli, T.J. and Masuyama, K.M. 2017. Geochronology and thermochronology of the gneisses of the Brasiliano/Pan-African Araguaia Belt: records of exhumation of West Gondwana and Pangea break up. *Journal of South American Earth Sciences*, **80**, 174–191, https://doi.org/10.1016/j.jsames.2017.09.027

Domeier, M. 2016. A plate tectonic scenario for the Iapetus and Rheic oceans. *Gondwana Research*, **36**, 275–295, https://doi.org/10.1016/j.gr.2015.08.003

Donnadieu, Y., Goddéris, Y., Ramstein, G., Nédélec, A. and Meert, J. 2004. A 'snowball Earth' climate triggered by continental break-up through changes in runoff. *Nature*, **428**, 303–306, https://doi.org/10.1038/nature02408

Dos Reis, M., Thawomwattana, Y., Angelis, K., Telford, M.J., Donoghue, P.C.J. and Yang, Z. 2015. Uncertainty in the timing of origin of animals and the limits of precision in molecular timescales. *Current Biology*, **25**, 2939–2950, https://doi.org/10.1016/j.cub.2015.09.066

Eisbacher, G.H. 1985. Late Proterozoic rifting glacial sedimentation and sedimentary cycles in the light of Windermere deposition, western Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **51**, 231–254, https://doi.org/10.1016/0031-0182(85)90087-2

Engel, A.E.J. and Engel, C.G. 1964. Continental accretion and the evolution of North America. *In*: Subramaniam, A.P. and Balakrishna, S. (eds) *Advancing Frontiers in Geology and Geophysics*. Indian Geophysical Union, Hyderabad, India, 17–37.

Ernst, R.E., Bond, D.P.G. *et al.* 2020. Large igneous province record through time and implications for secular environmental changes and geological time-scale boundaries. *In*: Ernst, R.E., Dickson, A.J. and Bekker, A. (eds) *Large Igneous Provinces: A Driver of Global Environmental and Biotic Changes*. AGU Geophysical Monograph, **255**, https://doi.org/10.1002/9781119507444.ch1

Erwin, D.H., Laflamme, M., Tweedt, S.M., Sperling, E.A., Pisani, D. and Peterson, K.J. 2011. The Cambrian conundrum: early divergence and later ecological success in the early history of animals. *Science*, **334**, 1091–1097, https://doi.org/10.1126/science.1206375

Escayola, M.P., van Staal, C.R. and Davis, W.J. 2011. The age and tectonic setting of the Puncoviscana Formation in northwestern Argentina: An accretionary complex related to Early Cambrian closure of the Puncoviscana Ocean and accretion of the Arequipa–Antofalla block. *Journal of South American Earth Sciences*, **32**, 438–459, https://doi.org/10.1016/j.jsames.2011.04.013

Evans, D.A.D. 2003*a*. A fundamental Precambrian–Phanerozoic shift in earth's glacial style? *Tectonophysics*, **375**, 353–385, https://doi.org/10.1016/S0040-1951(03)00345-7

Evans, D.A. 1998. True polar wander, a supercontinental legacy. *Earth and Planetary Science Letters*, **157**, 1–8.

Evans, D.A.D. 2003*b*. True polar wander and supercontinents. *Tectonophysics*, **362**, 303–320, https://doi.org/10.1016/S0040-1951(02)000642-X

Evans, D.A.D. and Raub, T.D. 2011. Neoproterozoic glacial palaeolatitudes: a global update. *Geological Society, London, Memoirs*, **36**, 93–112, https://doi.org/10.1144/M36.7

Evans, D.A.D., Li, Z.X. and Murphy, J.B. 2016. Four-dimensional context of Earth's supercontinents. *Geological Society, London, Special Publications*, **424**, 1–14, https://doi.org/10.1144/SP424.12

Fan, J.-X., Shen, S.-Z. *et al.* 2020. A high-resolution summary of Cambrian to Early Triassic marine invertebrate biodiversity. *Science*, **367**, 272–277, https://doi.org/10.1126/science.aax4953

Fischer, A.G. 1981. Climatic oscillations in the biosphere. *In*: Nitecki, M.H. (ed.) *Biotic Crises in Ecological and Evolutionary Time*. Academic Press, New York, 103–131.

Fischer, A.G. 1984. The two Phanerozoic supercycles. *In*: Berggren, W.A. and Van Couvering, J.A. (eds) *Catastrophes in Earth History, the New Uniformitarianism*. Princeton University Press, Princeton, NJ, 129–150.

Gastil, G. 1960. The distribution of mineral dates in time and space. *American Journal of Science*, **258**, 1–35, https://doi.org/10.2475/ajs.258.1.1

Goddéris, Y., Le Hir, G. *et al.* 2017. Paleogeographic forcing of the strontium isotopic cycle in the Neoproterozoic. *Gondwana Research*, **42**, 151–162, https://doi.org/10.1016/j.gr.2016.09.013

Gorayeb, P.S.de S., dos Santos, W.P., Moura, C.A.V. and Sousa, L.H. 2019. Petrologia, geoquímica e geocronologia dos granitos Presidente Kennedy e Barrolândia: contextualização na evolução do Cinturão Araguaia. *Geologia USP. Série Científica*, **19**, 89–116, https://doi.org/10.11606/issn.2316-9095.v19-137160 [in Portuguese with English abstract].

Goscombe, B., Foster, D.A., Gray, D. and Wade, B. 2020. Assembly of central Gondwana along the Zambezi Belt: Metamorphic response and basement reactivation during the Kuunga Orogeny. *Gondwana Research*, **80**, 410–465, https://doi.org/10.1016/j.gr.2019.11.004

Goscombe, B., Foster, D.A., Gray, D. and Wade, B. 2017. Metamorphic response and crustal architecture in a classic collisional orogen: the Damara Belt, Namibia. *Gondwana Research*, **52**, 80–124, https://doi.org/10.1016/j.gr.2017.07.006

Goscombe, B., Foster, D.A., Gray, D. and Wade, B. 2018. The evolution of the Damara Orogenic System: a record of West Gondwana assembly and crustal response. *In*: Siegesmund, S., Basei, M.A.S., Oyhantçabal, P. and Oriolo, S. (eds) *Geology of Southwest Gondwana*. Springer, Cham, Switzerland, 303–352.

Grantham, G.H., Kramers, J.D., Eglington, B. and Burger, E.P. 2019. The Ediacarian–Cambrian uplift history of western Dronning Maud Land: New $^{40}Ar–^{39}Ar$ and Sr/Nd data from Sverdrupfjella and Kirwanveggan, the source of the Urfjell Group and tectonic evolution of Dronning Maud Land within the Kuunga Orogeny and Gondwana amalgamation. *Precambrian Research*, **333**, 105444, https://doi.org/10.1016/j.precamres.2019.105444

Grunow, A., Hanson, R. and Wilson, T. 1996. Were aspects of Pan-African deformation linked to Iapetus opening? *Geology*, **24**, 1063–1066, https://doi.org/10.1130/0091-7613(1996)024<1063:WAOPAD>2.3.CO;2

Gurnis, M. 1988. Large-scale mantle convection and the aggregation and dispersal of supercontinents. *Nature*, **332**, 695–699, https://doi.org/10.1038/332695a0

Hallam, A. 1992. *Phanerozoic Sea-Level Changes*. Columbia University Press, New York.

Halpin, J.A., Daczko, N.R., Kobler, M.E. and Whittaker, J.M. 2017. Strike-slip tectonics during the Neoproterozoic–Cambrian assembly of East Gondwana: Evidence from a newly discovered microcontinent in the Indian Ocean (Batavia Knoll). *Gondwana Research*, **51**, 137–148, https://doi.org/10.1016/j.gr.2017.08.002

Halverson, G.P., Dudás, F.Ö., Maloof, A.C. and Bowring, S.A. 2007. Evolution of the $^{87}Sr/^{86}Sr$ composition of Neoproterozoic seawater. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **256**, 103–129, https://doi.org/10.1016/j.palaeo.2007.02.028

Hambrey, M.J. and Harland, W.B. 1981. *Earth's Pre-Pleistocene Glacial Record*. Cambridge University Press, Cambridge, UK.

Haq, B.U. and Al-Qahtani, A.M. 2005. Phanerozoic cycles of sea-level change on the Arabian Platform. *Geoarabia*, **10**, 127–160.

Harlan, S.S., Heaman, L., LeCheminant, A.N. and Premo, W.R. 2003. Gunbarrel mafic magmatic event: A key 780 Ma time marker for Rodinia plate reconstructions. *Geology*, **31**, 1053–1056, https://doi.org/10.1130/G19944.1

He, X.-F., Hand, M., Santosh, M., Kelsey, D.E., Morrissey, L.J. and Tsunogae, T. 2018. Long-lived metamorphic *P–T–t* evolution of the Highland Complex, Sri Lanka: insights from mafic granulites. *Precambrian Research*, **316**, 227–243, https://doi.org/10.1016/j.precamres.2018.08.008

Heron, P.J. and Lowman, J.P. 2014. The impact of Rayleigh number on assessing the significance of supercontinent insulation. *Journal of Geophysical Research: Solid Earth*, **119**, 711–733, https://doi.org/10.1002/2013JB010484

Heron, P.J., Murphy, J.B., Nance, R.D. and Pysklywec, R.N. 2020. Pannotia's mantle signature: the quest for supercontinent identification. *Geological Society, London, Special Publications*, **503**, https://doi.org/10.1144/SP503-2020-7

Hibbard, J.P., van Staal, C.R., Rankin, D.W. and Williams, H. 2006. *Lithotectonic Map of the Appalachian Orogen, Canada–United States of America. Map 2096A (Scale 1:1 500 000)*. Geological Survey of Canada, Ottawa, Ontario, Canada.

Hoffman, P.F. 1988. United Plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia. *Annual Reviews of Earth and Planetary Sciences*, **16**, 543–603, https://doi.org/10.1146/annurev.ea.16.050188.002551

Hoffman, P.F. 1989. Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga). *Geology*, **17**, 135–138, https://doi.org/10.1130/0091-7613(1989)017<0135:SOLSFG>2.3.CO;2

Hoffman, P.F. 1991. Did the breakout of Laurentia turn Gondwanaland inside-out? *Science*, **252**, 1409–1412, https://doi.org/10.1126/science.252.5011.1409

Hoffman, P.F. and Lamothe, K.G. 2019. Seawater-buffered diagenesis, destruction of carbon isotope excursions and the composition of DIC in Neoproterozoic oceans. *Proceedings of the National Academy of Sciences of the United States of America*, **116**, 18 874–18 879, https://doi.org/10.1073/pnas.1909570116

Hoffman, P.F., Abbot, D.S. *et al*. 2017. Snowball Earth climate dynamics and Cryogenian geology–geobiology. *Science Advances*, **3**, e1600983, https://doi.org/10.1126/sciadv.1600983

Holmes, A. 1929. A review of the continental drift hypothesis. *Mining Magazine*, **40**, 205–209, 286–288, 340–347.

Kamo, S.L., Corfu, F., Heaman, L.M. and Moser, D.E. 2011. The Krogh revolution: advances in the measurement of time. *Canadian Journal of Earth Sciences*, **48**, 87–94, https://doi.org/10.1139/E11-003

Kennedy, W.Q. 1964. The structural differentiation of Africa in the Pan-African (+/−500 m.y.) tectonic episode. University of Leeds, Research Institute of African Geology. *Annual Report on Scientific Results*, **8**, 48–49.

Konopásek, J., Cavalcante, C., Fossen, H. and Janoušek, V. 2020. Adamastor – an ocean that never existed? *Earth-Science Reviews*, **205**, 103201, https://doi.org/10.1016/j.earscirev.2020.103201

Korenaga, J., Planavsky, N.J. and Evans, D.A.D. 2017. Global water cycle and the coevolution of the Earth's interior and surface environment. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **375**, 20150393, https://doi.org/10.1098/rsta.2015.0393

Kröner, A. 1981. Precambrian plate tectonics. *In*: Kröner, A. (ed.) *Precambrian Plate Tectonics*. Elsevier, Amsterdam, 57–90.

Lehmann, J., Saalmann, K. *et al*. 2016. Structural and geochronological constraints on the Pan-African tectonic evolution of the northern Damara Belt, Namibia. *Tectonics*, **35**, 103–135, https://doi.org/10.1002/2015TC003899

Macdonald, F.A., Swanson-Hysell, N.L., Park, Y., Lisiecki, L. and Jagoutz, O. 2019. Arc–continent collisions in the tropics set Earth's climate state. *Science*, **364**, 181–184, https://doi.org/10.1126/science.aav5300

Markwitz, V., Kirkland, C.L. and Evans, N.J. 2017. Early Cambrian metamorphic zircon in the northern Pinjarra Orogen: implications for the structure of the West Australian Craton margin. *Lithosphere*, **9**, 3–13, https://doi.org/10.1130/L569.1

Matthews, K., Maloney, K., Zahirovic, S., Williams, S., Seton, M. and Müller, R.D. 2016. Global plate boundary evolution and kinematics since the late Paleozoic. *Global and Planetary Change*, **146**, 226–250, https://doi.org/10.1016/j.gloplacha.2016.10.002

Mattinson, J.M. 2011. Extending the Krogh legacy: development of the CA-TIMS method for zircon U–Pb geochronology. *Canadian Journal of Earth Sciences*, **48**, 95–105, https://doi.org/10.1139/E10-023

McElhinny, M.W. and McWilliams, M.O. 1977. Precambrian geodynamics – A palaeomagnetic view. *Tectonophysics*, **40**, 137–159, https://doi.org/10.1016/0040-1951(77)90032-4

McElhinny, M.W., Powell, C.McA. and Pisarevsky, S.A. 2003. Paleozoic terranes of eastern Australia and the drift history of Gondwana. *Tectonophysics*, **362**, 41–65, https://doi.org/10.1016/S0040-1951(02)00630-3

McGee, B., Collins, A.S., Trindade, R.I.F. and Payne, J. 2015. Age and provenance of the Cryogenian to Cambrian passive margin to foreland basin sequence of the northern Paraguay Belt, Brazil. *Geological Society of America Bulletin*, **127**, 76–86, https://doi.org/10.1130/B30842.1

McGee, B., Babinski, M., Trindade, R. and Collins, A.S. 2018. Tracing final Gondwana assembly: age and provenance of key stratigraphic units in the southern Paraguay Belt, Brazil. *Precambrian Research*, **307**, 1–33, https://doi.org/10.1016/j.precamres.2017.12.030

McKenzie, N.R., Horton, B.K., Loomis, S.E., Stockli, D.F., Planavsky, N.J. and Lee, C.-T.A. 2016. Continental arc volcanism as the principal driver of icehouse–greenhouse variability. *Science*, **352**, 444–447, https://doi.org/10.1126/science.aad5787

McMenamin, M.A.S. and McMenamin, D.S. 1990. *The Emergence of Animals: The Cambrian Breakthrough*. Columbia University Press, New York.

Meert, J.G. 2003. A synopsis of events related to the assembly of eastern Gondwana. *Tectonophysics*, **362**, 1–40, https://doi.org/10.1016/S0040-1951(02)00629-7

Meert, J.G. 2012. What's in a name? The Columbia (Paleopangaea/Nuna) supercontinent. *Gondwana Research*, **21**, 987–993, https://doi.org/10.1016/j.gr.2011.12.002

Meert, J.G. and Van der Voo, R. 1996. Paleomagnetic and $^{40}Ar/^{39}Ar$ study of the Sinyai dolerite, Kenya: implications for Gondwana assembly. *Journal of Geology*, **104**, 131–142, https://doi.org/10.1086/629810

Meert, J.G., Van der Voo, R., Powell, C.McA., Li, Z.-X., McElhinny, M.W., Chen, Z. and Symons, D.T.A. 1993. A plate-tectonic speed limit? *Nature*, **363**, 216–217, https://doi.org/10.1038/363216a0

Meert, J.G., Levashova, N.M., Bazhenov, M.L. and Landing, E. 2016. Rapid changes of magnetic Field polarity in the late Ediacaran: linking the Cambrian evolutionary radiation and increased UV-B radiation. *Gondwana Research*, **34**, 149–157, https://doi.org/10.1016/j.gr.2016.01.001

Merdith, A.S., Collins, A.S. *et al*. 2017. A full-plate global reconstruction of the Neoproterozoic. *Gondwana Research*, **50**, 84–134, https://doi.org/10.1016/j.gr.2017.04.001

Merdith, A.S., Williams, S.E., Brune, S., Collins, A.S. and Müller, R.D. 2019. Rift and plate boundary evolution across two supercontinent cycles. *Global and Planetary Change*, **173**, 1–14, https://doi.org/10.1016/j.gloplacha.2018.11.006

Miller, K.G., Kominz, M.A. *et al*. 2005. The Phanerozoic record of global sea-level change. *Science*, **310**, 1293–1298, https://doi.org/10.1126/science.1116412

Mills, B.J.W., Krause, A.J., Scotese, C.R., Hill, D.J., Shields, G.A. and Lenton, T.M. 2019. Modelling the long-term carbon cycle, atmospheric CO_2 and Earth surface temperature from late Neoproterozoic to present day. *Gondwana Research*, **67**, 172–186, https://doi.org/10.1016/j.gr.2018.12.001

Mitchell, R.N., Evans, D.A.D. and Kilian, T.M. 2010. Rapid Early Cambrian rotation of Gondwana. *Geology*, **38**, 755–758, https://doi.org/10.1130/G30910.1

Moores, E.M. 1991. Southwest US–East Antarctic (SWEAT) connection: a hypothesis. *Geology*, **19**, 425–428, https://doi.org/10.1130/0091-7613(1991)019<0425:SUSEAS>2.3.CO;2

Morel, P. and Irving, E. 1978. Tentative paleocontinental maps for the Early Phanerozoic and Proterozoic. *Journal of Geology*, **86**, 535–561, https://doi.org/10.1086/649724

Mound, J.E. and Mitrovica, J.X. 1998. True polar wander as a mechanism for second-order sea-level variations. *Science*, **279**, 534–537, https://doi.org/10.1126/science.279.5350.534

Mound, J.E., Mitrovica, J.X., Evans, D.A.D. and Kirschvink, J.L. 1999. A sea-level test for inertial interchange true polar wander events. *Geophysical Journal International*, **136**, F5–F10, https://doi.org/10.1046/j.1365-246x.1999.00791.x

Mulder, J.A., Halpin, J.A., Daczko, N.R., Orth, K., Meffre, S., Thompson, J.M. and Morrissey, L.J. 2019. A Multiproxy provenance approach to uncovering the assembly of East Gondwana in Antarctica. *Geology*, **47**, 645–649, https://doi.org/10.1130/G45952.1

Murphy, J.B., Nance, R.D. *et al.* 2020. Pannotia: in defence of its existence and geodynamic significance. *Geological Society, London, Special Publications*, **503**, https://doi.org/10.1144/SP503-2020-96

Nance, R.D. and Murphy, J.B. 2019. Supercontinents and the case for Pannotia. *Geological Society, London, Special Publications*, **470**, 65–85, https://doi.org/10.1144/SP470.5

Nance, R.D., Worsley, T.R. and Moody, J.B. 1986. Post-Archean biogeochemical cycles and long-term episodicity in tectonic processes. *Geology*, **14**, 514–518, https://doi.org/10.1130/0091-7613(1986)14<514:PBCALE>2.0.CO;2

Nance, R.D., Murphy, J.B. and Santosh, M. 2014. The supercontinent cycle: a retrospective essay. *Gondwana Research*, **25**, 4–29, https://doi.org/10.1016/j.gr.2012.12.026

Nelson, L.L., Smith, E.F., Hodgin, E.B., Crowley, J.L., Schmitz, M.D. and Macdonald, F.A. 2020. Geochronological constraints on Neoproterozoic rifting and onset of the Marinoan glaciation from the Kingston Peak Formation in Death Valley, California (USA). *Geology*, **48**, https://doi.org/10.1130/G47668.1

Och, L.M. and Shields-Zhou, G.A. 2012. The Neoproterozoic oxygenation event: Environmental perturbations and biogeochemical cycling. *Earth-Science Reviews*, **110**, 26–57, https://doi.org/10.1016/j.earscirev.2011.09.004

Oriolo, S., Oyhantçabal, P., Wemmer, K. and Siegesmund, S. 2017. Contemporaneous assembly of Western Gondwana and final Rodinia break-up: Implications for the supercontinent cycle. *Geoscience Frontiers*, **8**, 1431–1445, https://doi.org/10.1016/j.gsf.2017.01.009

Pastor-Galán, D., Nance, R.D., Murphy, J.B. and Spencer, C.J. 2018. Supercontinents: myths, mysteries, and milestones. *Geological Society, London, Special Publications*, **470**, 39–64, https://doi.org/10.1144/SP470.16

Pavlov, V.E., Pasenko, A.M., Shatsillo, A.V., Powerman, V.I., Shcherbakova, V.V. and Malyshev, S.V. 2018. Systematics of Early Cambrian paleomagnetic directions from the northern and eastern regions of the Siberian Platform and the problem of an anomalous geomagnetic field in the time vicinity of the Proterozoic–Phanerozoic boundary. *Izvestiya, Physics of the Solid Earth*, **54**, 782–805, https://doi.org/10.1134/S1069351318050117

Peters, S.E. and Gaines, R.R. 2012. Formation of the 'Great Unconformity' as a trigger for the Cambrian explosion. *Nature*, **484**, 363–366, https://doi.org/10.1038/nature10969

Peters, S.E., Husson, J.M. and Wilcots, J. 2017. The rise and fall of stromatolites in shallow marine environments. *Geology*, **45**, 487–490, https://doi.org/10.1130/G38931.1

Piper, J.D.A. 1974. Proterozoic crustal distribution, mobile belts and apparent polar movements. *Nature*, **251**, 381–384, https://doi.org/10.1038/251381a0

Piper, J.D.A. 1976. Palaeomagnetic evidence for a Proterozoic super-continent. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **280**, 469–490, https://doi.org/10.1098/rsta.1976.0007

Piper, J.D.A., Briden, J.C. and Lomax, K. 1973. Precambrian Africa and South America as a single continent. *Nature*, **245**, 244–248, https://doi.org/10.1038/245244a0

Powell, C.McA. 1995. Are Neoproterozoic glacial deposits preserved on the margins of Laurentia related to the fragmentation of two supercontinents?: Comment and Reply. *Geology*, **23**, 1053–1054, https://doi.org/10.1130/0091-7613(1995)023<1053:ANGDPO>2.3.CO;2

Puetz, S.J., Ganade, C.E., Zimmermann, U. and Borchardt, G. 2018. Statistical analyses of Global U–Pb Database 2017. *Geoscience Frontiers*, **9**, 121–145, https://doi.org/10.1016/j.gsf.2017.06.001

Rapalini, A.E. 2018. The assembly of Western Gondwana: Reconstruction based on paleomagnetic data. *In*: Siegesmund, S., Basei, M.A.S., Oyhantçabal, P. and Oriolo, S. (eds) *Geology of Southwest Gondwana*. Springer, Cham, Switzerland, 3–18.

Rapela, C.W., Verdecchia, S.O. *et al.* 2016. Identifying Laurentian and SW Gondwana sources in the Neoproterozoic to Early Paleozoic metasedimentary rocks of the Sierras Pampeanas: Paleogeographic and tectonic implications. *Gondwana Research*, **32**, 193–212, https://doi.org/10.1016/j.gr.2015.02.010

Raup, D.M. and Sepkoski, J.J., Jr. 1982. Mass extinctions in the marine fossil record. *Science*, **215**, 1501–1503, https://doi.org/10.1126/science.215.4539.1501

Riding, R. 2011. The nature of stromatolites: 3500 million years of history and a century of research. *In*: Reitner, J., Quéric, N.-V. and Arp, G. (eds) *Advances in Stromatolite Geobiology*. Springer, Heidelberg, Germany, 29–74.

Robert, B., Besse, J. *et al.* 2017. Constraints on the Ediacaran inertial interchange true polar wander hypothesis: a new paleomagnetic study in Morocco (West African Craton). *Precambrian Research*, **295**, 90–116, https://doi.org/10.1016/j.precamres.2017.04.010

Rolf, T., Coltice, N. and Tackley, P.J. 2012. Linking continental drift, plate tectonics and the thermal state of the Earth's mantle. *Earth and Planetary Science Letters*,

351–352, 134–146, https://doi.org/10.1016/j.epsl.2012.07.011

Rooney, A.D., Macdonald, F.A., Strauss, J.V., Dudás, F.Ö., Hallmann, C. and Selby, D. 2014. Re–Os geochronology and coupled Os–Sr isotope constraints on the Sturtian snowball Earth. *Proceedings of the National Academy of Sciences of the United States of America*, **111**, 51–56, https://doi.org/10.1073/pnas.1317266110

Rowley, D.B. 2008. Extrapolating oceanic age distributions: Lessons from the Pacific region. *Journal of Geology*, **116**, 587–598, https://doi.org/10.1086/592276

Schmitt, R.S., Fragoso, R.A. and Collins, A.S. 2018. Suturing Gondwana in the Cambrian: the orogenic events of the final amalgamation. *In*: Siegesmund, S., Basei, M.A.S., Oyhantçabal, P. and Oriolo, S. (eds) *Geology of Southwest Gondwana*. Springer, Cham, Switzerland, 411–432.

Sears, J.W. and Price, R.A. 1978. The Siberian Connection: a case for Precambrian separation of the North American and Siberian cratons. *Geology*, **6**, 267–270, https://doi.org/10.1130/0091-7613(1978)6<267:TSCACF>2.0.CO;2

Sepkoski, J.J., Jr. 1984. A kinetic model of Phanerozoic taxonomic diversity. III. Post-Paleozoic families and mass extinctions. *Paleobiology*, **10**, 246–267, https://doi.org/10.1017/S0094837300008186

Shields, G.A. 2018. Carbon and carbon isotope mass balance in the Neoproterozoic Earth system. *Emerging Topics in Life Sciences*, **2**, 257–265, https://doi.org/10.1042/ETLS20170170

Shields, G.A., Mills, B.J.W., Zhu, M., Raub, T.D., Daines, S.J. and Lenton, T.M. 2019. Unique Neoproterozoic carbon isotope excursions sustained by coupled evaporite dissolution and pyrite burial. *Nature Geoscience*, **12**, 823–827, https://doi.org/10.1038/s41561-019-0434-3

Sinclair, H.D. 1997. Flysch to molasse transition in peripheral foreland basins: the role of the passive margin v. slab breakoff. *Geology*, **25**, 1123–1126, https://doi.org/10.1130/0091-7613(1997)025<1123:FTMTIP>2.3.CO;2

Spencer, C.J., Hawkesworth, C., Cawood, P.A. and Dhuime, B. 2013. Not all supercontinents are created equal: Gondwana–Rodinia case study. *Geology*, **41**, 795–798, https://doi.org/10.1130/G34520.1

Spencer, C.J., Cawood, P.A., Hawkesworth, C.J., Raub, T.D., Prave, A.R. and Roberts, N.M.W. 2014. Proterozoic onset of crustal reworking and collisional tectonics: Reappraisal of the zircon oxygen isotope record. *Geology*, **42**, 451–454, https://doi.org/10.1130/G35363.1

Squire, R.J., Campbell, I.H., Allen, C.M. and Wilson, C.J.L. 2006. Did the Transgondwanan Supermountain trigger the explosive radiation of animals on Earth? *Earth and Planetary Science Letters*, **250**, 116–133, https://doi.org/10.1016/j.epsl.2006.07.032

Stewart, J.H. 1972. Initial deposits in the Cordilleran Geosyncline: Evidence of a Late Precambrian (<850 m.y.) continental separation. *Geological Society of America Bulletin*, **83**, 1345–1360, https://doi.org/10.1130/0016-7606(1972)83[1345:IDITCG]2.0.CO;2

Stump, E. 1987. Construction of the Pacific margin of Gondwana during the Pannotios cycle. *American Geophysical Union Geophysical Monographs Series*, **40**, 77–87.

Tohver, E. and Trindade, R.I.F. 2014. Comment on 'Was there an Ediacaran Clymene Ocean in central South America?' by U. G. Cordani and others. *American Journal of Science*, **314**, 805–813, https://doi.org/10.2475/03.2014.03

Tohver, E., Trindade, R.I.F., Solum, J.G., Hall, C.M., Riccomini, C. and Nogueira, A.C. 2010. Closing the Clymene ocean and bending a Brasiliano belt: evidence for the Cambrian formation of Gondwana, southeast Amazon craton. *Geology*, **38**, 267–270, https://doi.org/10.1130/G30510.1

Torsvik, T.H. and Cocks, R.M. 2017. *Earth History and Palaeogeography*. Cambridge University Press, Cambridge UK.

Tostevin, R. and Mills, B.J.W. 2020. Reconciling proxy records and models of Earth's oxygenation during the Neoproterozoic and Palaeozoic. *Interface Focus*, **10**, 20190137, https://doi.org/10.1098/rsfs.2019.0137

Trindade, R.I.F., D'Agrella-Filho, M.S., Epof, I. and Brito Neves, B.B. 2006. Paleomagnetism of Early Cambrian Itabaiana mafic dikes (NE Brazil) and the final assembly of Gondwana. *Earth and Planetary Science Letters*, **244**, 361–377, https://doi.org/10.1016/j.epsl.2005.12.039

Tucker, R.D., Roig, J.Y., Moine, B., Delor, C. and Peters, S.G. 2014. A geological synthesis of the Precambrian shield in Madagascar. *Journal of African Earth Sciences*, **94**, 9–30, https://doi.org/10.1016/j.jafrearsci.2014.02.001

Valentine, J.W. and Moores, E.M. 1970. Plate-tectonic regulation of faunal diversity and sea level: a model. *Nature*, **228**, 657–659, https://doi.org/10.1038/228657a0

van der Meer, D.G., van den Berg van Saparoea, A.P.H., van Hinsbergen, D.J.J., van de Weg, R.M.B., Godderis, Y., Le Hir, G. and Donnadieu, Y. 2017. Reconstructing first-order changes in sea level during the Phanerozoic and Neoproterozoic using strontium isotopes. *Gondwana Research*, **44**, 22–34, https://doi.org/10.1016/j.gr.2016.11.002

van der Meer, D.G., van Hinsbergen, D.J.J. and Spakman, W. 2018. Atlas of the underworld: Slab remnants in the mantle, their sinking history and a new outlook on lower mantle viscosity. *Tectonophysics*, **723**, 309–448, https://doi.org/10.1016/j.tecto.2017.10.004

Van Kranendonk, M.J. and Kirkland, C.L. 2016. Conditioned duality of the Earth system: Geochemical tracing of the supercontinent cycle through Earth history. *Earth-Science Reviews*, **160**, 171–187, https://doi.org/10.1016/j.earscirev.2016.05.009

Veevers, J.J. 2017. West Gondwanaland during and after the Pan-African and Brasiliano orogenies: Downslope vectors and detrital-zircon U–Pb and T_{DM} ages and εHf/Nd pinpoint the provenances of the Ediacaran–Paleozoic molasse. *Earth-Science Reviews*, **171**, 105–140, https://doi.org/10.1016/j.earscirev.2017.05.010

Verard, C., Hochard, C., Baumgartner, P.O. and Stampfli, G.M. 2015. 3D palaeogeographic reconstructions of the Phanerozoic v. sea-level and Sr-ratio variations. *Journal of Palaeogeography*, **4**, 64–84, https://doi.org/10.3724/SP.J.1261.2015.00068

Wegener, A. 1929. *The Origin of Continents and Oceans* [English translation, published 1966, of the 4th German edition]. Dover, New York.

Williams, H., Hoffman, P.F., Lewry, J.F., Monger, J.W.H. and Rivers, T. 1991. Anatomy of North America: thematic geologic portrayals of the continent. *Tectonophysics*, **187**, 117–134, https://doi.org/10.1016/0040-1951(91)90416-P

Williams, S., Wright, N.M., Cannon, J., Flament, N. and Müller, R.D. 2020. Reconstructing seafloor age distributions in lost ocean basins. *Geoscience Frontiers*, https://doi.org/10.1016/j.gsf.2020.06.004

Wilson, J.T. 1966. Did the Atlantic close and then reopen? *Nature*, **211**, 676–681, https://doi.org/10.1038/211676a0

Worsley, T.R. and Nance, R.D. 1989. Carbon redox and climate control through Earth history: A speculative reconstruction. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **75**, 259–282.

Worsley, T.R., Nance, D. and Moody, J.B. 1984. Global tectonics and eustasy for the past 2 billion years. *Marine Geology*, **58**, 373–400, https://doi.org/10.1016/0025-3227(84)90209-3

Worsley, T.R., Nance, D. and Moody, J.B. 1986. Tectonic cycles and the history of the Earth's biogeochemical and paleoceanographic record. *Paleoceanography*, **1**, 233–263, https://doi.org/10.1029/PA001i003p00233

Wortel, M.J.R. and Spakman, W. 2000. Subduction and slab detachment in the Mediterranean–Carpathian region. *Science*, **290**, 1910–1917, https://doi.org/10.1126/science.290.5498.1910

Yoshida, M. 2013. Mantle temperature under drifting deformable continents during the supercontinent cycle. *Geophysical Research Letters*, **40**, 681–686, https://doi.org/10.1002/grl.50151

Young, G.M. 1995. Are Neoproterozoic glacial deposits preserved on the margins of Laurentia related to the fragmentation of two supercontinents? *Geology*, **23**, 153–156, https://doi.org/10.1130/0091-7613(1995)023<0153:ANGDPO>2.3.CO;2

Zaffos, A., Finnegan, S. and Peters, S.E. 2017. Plate tectonic regulation of global marine animal diversity. *Proceedings of the National Academy of Sciences of the United States of America*, **114**, 5653–5658, https://doi.org/10.1073/pnas.1702297114

Zhong, S., Zhang, N., Li, Z.-X. and Roberts, J.H. 2007. Supercontinent cycles, true polar wander, and very long-wavelength mantle convection. *Earth and Planetary Science Letters*, **261**, 551–564, https://doi.org/10.1016/j.epsl.2007.07.049

Zhou, J.-L., Li, X.-H., Tang, G.-Q., Liu, Y. and Tucker, R.D. 2018. New evidence for a continental rift tectonic setting of the Neoproterozoic Imorona–Itsindro Suite (central Madagascar). *Precambrian Research*, **306**, 94–111, https://doi.org/10.1016/j.precamres.2017.12.029