Nature Reviews Earth & Environment

The supercontinent cycle: Linking mantle convection and plate tectonic theory

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Abstract | Supercontinents are a representation of self-organization in plate tectonics. Over the past ~2 billion years, 3 major cycles of supercontinent assembly and breakup have been identified, with increasing age: Pangaea, Rodinia, and Columbia/Nuna. In a prototypal form, such a pattern of continental assembly and breakup likely extends back to ~3 billion years ago, albeit on the smaller scale of Archaean "supercratons" which, unlike global supercontinents, were potentially segregated. The emergence of supercontinents provides a firm minimum age for the onset of the modern global plate tectonic network, whereas supercratons might reflect an earlier geodynamic and nascent tectonic regime. Modern understanding of the assembly and breakup of Pangaea attests that the supercontinent cycle is intimately linked with whole mantle convection. The supercontinent cycle is both an effect and a cause of mantle convection, emphasizing the importance of both top-down and bottom-up geodynamics and the coupling between them. However, the nature of this coupling and how it has evolved over time remains highly controversial, resulting in strikingly contrasting models for supercontinent formation. Conceptual models can be informed by quantitative geodynamic models, and geochemical proxies offer additional clues that can test competing models.

Introduction

The supercontinent cycle is one of the grandest spatiotemporal themes in Earth history and plays a major role in how Earth's interior and surface both operate, interact, and evolve with each other[1-6]. Supercontinent kinematics are a critical boundary condition for the evolution of Earth's surface[1,2,7-10]. The existence of the supercontinent Pangaea is a consequence of continental drift—Alfred Wegener's prototypical theory[11-13]—evidenced by the fit of continents that would evolve into the theory of plate tectonics decades later[14-18]. One would naturally expect the possible existence of pre-Pangaea supercontinents as plate tectonics has been operational for at least 2 Ga[19-22], if not longer[23,24]. Because at least three supercontinents have now been identified (with increasing age: Pangaea, Rodinia, and Columbia; Fig. 1), it is appropriate to use the term "supercontinent cycle", as three recurrences are the bare minimum such that one can reasonably talk about cyclicity. Each supercontinent cycle has two phases, assembly and breakup. It is, however, a common misconception to think of the supercontinent cycle as a binary process (i.e., supercontinent or no supercontinent) because the assembly and breakup phases can temporally overlap, e.g., the East African rift[25] (continued breakup of Pangaea) and the continental collision of India with Eurasia[26] (assembly of the next supercontinent) both occur simultaneously in Cenozoic time. Figure 1 presents a timeline of the supercontinent cycle through Earth history and palaeogeographic reconstructions for each supercontinent. Box 1 provides an overview of the methods used to generate such supercontinent reconstructions.

What is a supercontinent? Any operational definition needs to arguably include several aspects, which are not mutually exclusive: (i) large size, (ii) a mantle legacy, (iii) and longevity. Size cannot simply represent the amalgamation of *all* continents as even Pangaea did not include North and South China and other Cimmerian blocks (Fig. 1). The size criterion is typically considered either qualitatively to include "most" continents[27], or quantitatively to meet a threshold of 75% of available continental crust at any given time[28]. The second criterion (a mantle legacy) has been suggested to offer a more geodynamically meaningful solution: a supercontinent must have been large enough to have affected mantle convection[29]. Another aspect of such a mantle legacy, however, is longevity, as a supercontinent must have existed for a sufficient amount of time for the various mechanisms through which it can affect mantle flow to take effect. A supercontinent cycle is often considered to last 400-800 Myr[30], where a statistical basis for such a ~600 Myr duration has recently been identified using time series analysis of hafnium isotopes of zircon[31], a geochemical proxy for the supercontinent cycle[32]. To be clear, the stable "tenure" period of a supercontinent (i.e., after assembly and before breakup) represents only a small duration of this full cycle, where tenures of the past known supercontinents have lasted between 100 and 300 Myr[33] (Fig. 1).

In this Review, we combine geological evidence with insights from geodynamic modeling to suggest that supercontinent cycles can be explained within a theory that connects plate tectonics and mantle dynamics. Plate tectonic theory was first inspired by reductionism: the idea that a complex system can be broken down into smaller, simpler parts (i.e., defining the force balance on plates in terms of a few forces such as slab pull, ridge push and basal drag).

However, such a description of the fundamental parts of the system does not provide an explanation why plate tectonics occurs as a consequence of mantle dynamics[34,35]. Plate tectonics is a prime example of "self-organization" or "emergence" in a system, which refers to the collective phenomena of a complex, evolving system not apparent in its parts[36,37], and supercontinents emerge as a result of these collective, interrelated processes. The Review aims to provide an understanding of the supercontinent cycle by including it in a linked plate tectonic and mantle convective theory.

The Supercontinent Cycles

Pangaea

The history of Pangaea's existence and tectonic kinematics have been debated and refined for over a century[11,13,38-48]. As most of this history is well documented, we focus on how our understanding of the most recent supercontinent informs us about linkages between its tectonic evolution (assembly and breakup) and mantle convection, i.e. its geodynamics **[G]**. Established linkages between Pangaea and the underlying convecting mantle include large igneous provinces (LIPs) **[G]** emplaced by mantle plumes **[G]** sourced from the edges of large low shear-wave velocity provinces (LLSVPs) **[G]** in the deep mantle[49-55]; net characteristics of plate motions during Pangaea breakup that reflect coupling with long-wavelength mantle convective patterns[56-60]; and repeated oscillatory true polar wander (TPW) **[G]** events occurring about a stable axis controlled by supercontinent-reinforced long-wavelength mantle flow[44,54,58,61-69].

Currently, very divergent views on the evolution of mantle convection exist. On Earth today, mantle convection is dominated by large-wavelength cells[70,71], yielding most power at harmonics degree-1 (one upwelling and one downwelling hemisphere) and degree-2 (two antipodal upwellings separated by a great-circle girdle of downwelling)[72]. Recent plate motions exhibit net characteristics that follow these longest wavelength patterns in mantle flow, although the relative dominance of degree-1 and degree-2 may have fluctuated[56]. Some have speculated that mantle flow has always followed degree-2 structure in essentially its present form[49,51,52,54,73], but others have argued that such longevity is unlikely beyond 300 Myr ago[74]. Those considering the possibility of dynamic and evolving mantle convection patterns have attempted to model mantle flow farther back in time with proxy plate motion reconstructions and subduction histories[71,75]. For example, constraining numerical modelling of mantle convection with plate reconstructions as an upper boundary condition, some have argued that the Palaeozoic (before 300 Myr ago) was characterized by the dominance of degree-1 flow[71]. "Orthoversion" theory[58] hypothesizes that each supercontinent cycle shifts the longitude of degree-2 flow orthogonally (~90°), such that the degree-2 flow planforms of each supercontinent cycle can be spatially linked and palaeolongitude can thus be constrained.

Figure 2 suggests a link between the Pangaea supercontinent and present-day mantle structure[44,76]. Figure 3 shows the numerical modeling of the two main long-wavelength mantle convection patterns (degree-1 and degree-2 flow [**G**]) that are related to supercontinents. One hypothesis is that the supercontinent cycle causes an alternation between the dominance of these two strongest long convective wavelengths[72,74]: (i) supercontinent assembly is dominated by degree-1 where continents would collect over the hemispheric 'superdownwelling', (ii) then circum-supercontinent subduction forms a degree-2 downwelling girdle and, due to return flow, an upwelling beneath the supercontinent, (iii) and finally supercontinent breakup occurs as continents drift away off the upwelling toward the degree-2 downwelling girdle.

Principally, whether the degree-2 mantle flow pattern inferred from data (Fig. 2) and modelling (Fig. 3) is supercontinent-induced or whether it already existed is unclear. There are two competing end-member hypotheses about the origin of the mantle flow pattern as it relates to supercontinent formation (Fig. 2): (i) the "stationary" or quasi-stationary hypothesis[49,51,52,54,73] that the degree-2 pattern (as represented today by two antipodal LLSVPs under the African and Pacific plates) is relatively stable and long-lived, i.e., it existed before supercontinent Pangaea formed or move to above one of current LLSVP locations or (ii) the "dynamic" hypothesis[71,72,74,75,77-80] where degree-2 flow reflects coupling between the supercontinent cycle and convecting mantle with a new LLSVP forming beneath the nascent supercontinent.

Both end-member hypotheses have unresolved issues. The stationary hypothesis has the geodynamic problem of how a supercontinent would form or move over an LLSVP (Fig. 2), which is presumably associated with an upwelling, with divergent flow in the shallow mantle, and a dynamic topography high[72,79,81]. Continents are rather expected to drift toward downwellings and dynamic topography lows[82,83] between the two LLSVPs, as observed in the dispersion of continents since the breakup of Pangaea[56-58]. The dynamic hypothesis, by design, cannot rely on the detailed seismically inferred structure of the present-day lower mantle (Fig. 2), and thus most of the evidence purported to support it is indirect (e.g., TPW[58], LIP cyclicity[74,78], and geochemistry[77]), or involves back-calculating mantle structure with numerical modelling as influenced by plate tectonics reconstructions, both of which have large individual uncertainties, let alone those related to how mantle flow and plate tectonics interact.

Rodinia and Columbia

Peaks in global isotopic ages[84-87] and other geologic occurrences[88,89] have long indicated the likelihood of at least two pre-Pangean supercontinents: Rodinia ca. 1 Gyr ago [90-96] and Columbia ca. 1.5 Gyr ago[19,28,33,97-106] (also known as Nuna; a recent solution to the semantic standoff is that Nuna represents the megacontinent [**G**] building block of the larger Columbia supercontinent, like Gondwana in Pangaea[107]). Palaeogeographic reconstructions in Precambrian time are inherently controversial given the lack of constraints from seafloor spreading that make the reconstruction of Pangaea relatively straightforward. Nonetheless, great strides have been taken in recent decades to reconstruct pre-Pangaean supercontinents[6] and detailed and robust reconstructions of both Proterozoic supercontinents Rodinia and

Columbia are starting to emerge (Fig. 1). The reconstructions depicted have not yet reached a level of consensus, as many uncertainties and debates remain[6,30]. For example, in supercontinent Columbia it is debated whether Siberia had a tight fit[98,108,109] or a loose fit[110,111] with Laurentia. Nonetheless, there is generally first-order agreement on the existence of both pre-Pangaean supercontinents and their general timing of assembly and breakup, and several relative continental configurations are becoming more widely accepted (Fig. 1). Furthermore, the most quantitative means of supercontinent reconstruction in deep time, apparent polar wander (APW) **[G]** path comparison (Box 1), has been effectively applied to both Rodinia and Columbia and tested independently by more qualitative means such as the correlation of geologic piercing points (Box 1).

It has been suggested that Rodinia might have been geologically distinct from both Columbia and Pangaea[89,112,113], in that Rodinia is relatively poorly endowed in mineral deposits[114] and is also the only one of the three known supercontinents to have experienced low-latitude “snowball Earth” glaciations[115-117]. The configuration of Rodinia is thought to have played a central role in the development of snowball Earth because the dominantly tropical to subtropical distribution of its continents facilitated global-scale glaciation by enhanced drawdown of CO_2 due to enhanced continental weathering[95,117]. The late Neoproterozoic Cryogenian Era of snowball Earth episodes coincided with the rifting of Rodinia and increased glacial erosion[118] (with deep glacial incisions occurring in rift-related uplifted horsts[119]), processes which collectively profoundly influenced the geochemistry of the oceans[120]. The uniqueness of Rodinia may relate to a style of tectonic assembly contrasting with that of other supercontinents[89,112,113].

Columbia is Earth’s oldest-known supercontinent. Columbia assembled ca. 2.0-1.6 billion years [Gyr] ago, from the Thelon orogen 1970 million years [Myr] ago[121] with Rae craton serving as the upper plate in the collisions that formed Laurentia[122], which in turn formed the core megacontinent of Nuna[98,107], to the final suturing ca. 1.6 Gyr ago of Australia[123] that was peripheral in the larger supercontinent Columbia[33,100]. The occurrence of voluminous anorogenic granite-anorthosite complexes, characteristic of middle Proterozoic time, suggests extensive and prolonged melting of the crust and mantle. In the absence of evidence for either crustal stretching (which would cause decompression melting) or subduction (hydrous melting), this magmatism has been widely attributed to mantle upwelling beneath a supercontinent[124]. Such observations led to the speculation that Palaeoproterozoic-Mesoproterozoic supercontinent Columbia was Earth’s first “true” supercontinent[124]. It should also be noted that Columbia is the most endowed supercontinent in terms of mineral deposits[114], however, the reasons for this remain unclear.

Evidence of plate tectonics coupling with mantle convection can be deduced from the geologic record for pre-Pangaea supercontinents, albeit less directly than comparison with mantle seismic structure (Fig. 2). Like Pangaea, both Proterozoic supercontinents exhibit a close association with mantle-related features including rifts and large igneous provinces **[G]** sourced from mantle plumes[33,94,95,98,108,125,126] as well as intervals of TPW controlled by an axis central to each supercontinent[58,62,63,127-131].

Unknown Archaean

Although the history of crustal growth is hotly debated[132-134], most models propose that a majority of Earth's continental crust formed prior to the assembly of Columbia. If crustal volume was insufficient during Archaean time to affect mantle convection patterns, or if underlying Archaean mantle flow occurred on shorter wavelengths with many small cells possibly because of a hotter ambient mantle[135], crustal assembly into a truly large supercontinent may not have occurred until a threshold volume of continental crust was attained.

Archaean cratons are uniformly bounded by Proterozoic rifted margins, implying inclusion in some ancestral landmass(es)[97]. A cycle of continental assembly and breakup appears to operate in Late Archaean times, inspiring speculation about the possibility of an Archaean supercontinent, dubbed Kenorland[136]. Unlike Columbia and Rodinia, however, no robust near-global reconstructions have been made for time intervals of either assembly or breakup of the putative Kenorland. The only palaeomagnetic reconstructions of Kenorland that have been made thus far are single-pole comparisons, *i.e.*, constrained by palaeomagnetic poles of only one age[137,138]. While single-pole comparisons effectively compare palaeolatitude, they are completely unconstrained in the relative palaeolongitude of component blocks (e.g., Australia and South America are presently at similar latitudes, but they are widely separated in longitude by the large Pacific Ocean). APW path comparisons (Box 1), with a precision comparable to those of Proterozoic supercontinents, have yet to be done for Archaean cratons due to the general paucity of palaeomagnetic data from most cratons.

Thus, interpretations of late Archaean palaeogeography has relied on geologic means of correlation, using approaches such as comparing magmatic barcodes[139,140], i.e. the timings of major magmatic events (Box 1). As an alternative to an Archaean supercontinent, the existence of smaller and segregated "supercratons" **[G]** has been proposed, in which clusters of cratons occurred without them ever becoming connected[141] or affecting global-scale mantle convection patterns. The appeal of the supercratons hypothesis is that it may explain the long-known diachroneity of late Archaean cratonization[142,143]. Reconstructions based primarily on emplacement ages of radiating dyke swarms[144], correlative rift basin successions[144,145], and at least one instance of matching APW paths of two cratons[146] are consistent with the idea of a "Superia" supercraton surrounding the Superior craton.

Distinguishing between these rival hypotheses of Archaean-Proterozoic continental clustering has implications for mantle convection. A few factors could have prevented the dominance of large-scale flow: small sizes and/or short durations of continental clusters[147], and/or the lack of a global subduction girdle that could have been the primary driver for the formation of LLSVPs[74,94]. The proposed connection between Kaapvaal and Pilbara cratons (known as the 'Vaalbara' connection) could have produced a small composite craton that was possibly long-lasting (ca. 2.8-2.1 Ga)[148], but its existence has been called into question[149]. Without contiguity with many other cratons (if any), its size would have been insufficient to steer mantle convection towards dominance of the very large scales. The 'Superia' connection may have been larger[141], with Superior being the largest craton and multiple cratons considered neighbours (e.g., Wyoming, Karelia/Kola, Hearne, etc.), but as currently reconstructed[144] (Fig. 1) is much smaller (about the size of modern-day Antarctica[72,147]) than a supercontinent. Palaeogeographic reconstructions may ultimately distinguish between the supercontinent and supercratons hypotheses for Archaean-Proterozoic time but our present understanding suggests that Archaean supercratons[141] were likely not large enough to either cause or affect a dominant degree-1 or 2 structure for underlying mantle convection patterns.

Proterozoic continents and Archaean cratons are notably different in size, with ~4 cratons on average contained within the area of each Proterozoic continent[141]. Thus, the difference between the scale of mantle convection patterns beneath supercontinents and supercratons—if due to a difference in convective length scales—may be reflected in the different surface area sizes of their rifted blocks[141,150]. According to inference, Archaean mantle convective cells associated with supercratons may have only been <40% the size of their Proterozoic-Phanerozoic successors associated with supercontinents. Smaller Archaean convective cells may account for the episodic, intermittent nature of Archaean subduction[151,152]. It is therefore possible that Archaean mantle convection may have been exclusively characterized by higher harmonics like in Figure 3a, which could also provide a ready explanation for why segregated supercratons might not have amalgamated into a supercontinent as they were quarantined within shorter-wavelength convection cells instead of degree-1 and degree-2 planforms.

Proxies and Patterns

A Supercontinent Time Series

Although there continues to be significant debate over their configuration, there is broad consensus on when individual continents assembled and rifted from each supercontinent (Fig. 1). Irrespective of their configurations (Fig. 1), recurring supercontinent cycles of continental assembly and breakup through time are clearly evidenced in both geological and geochemical proxies[88]. Geological proxies recording supercontinent cycles include the timing and locations of large igneous provinces[78], passive margins[153], orogens[154] and mineral deposits[89]. Igneous geochemistry offers additional insights into supercontinent dynamics by fingerprinting changes in subduction (arc magmatism), crustal reworking (collisional orogenesis), and mantle heat flow (plume magmatism). Signals of a supercontinent cycle have been detected in the ages and Hf isotopic compositions of robust accessory minerals such as zircon[32,84] as well as the MgO content of plume-derived basalts[155]. Comparison of the variations of these isotopic proxies with the historical record of supercontinents offers a more complete understanding of the tectonic processes related to the supercontinent cycle.

Building on this consensus of robust patterns in temporal proxies for the supercontinent cycle, we explore how geochemistry can be used to depict a timeline of assembly and breakup of the past three supercontinents. Orogenesis during supercontinent assembly should significantly increase the volume of supracrustal reworking in the magmatic systems[156], as has been argued for using Hf isotopes of zircon showing fluctuations between crustal reworking (supercontinent assembly) and mantle-derived magmatism (supercontinent breakup)[31,32]. The degree of continental contribution in magmatic systems can also be assessed with a compilation of zircon $\delta^{18}O$ measurements, a well-established proxy for the relative contributions of mantle and supracrustal material[157]. A global compilation[156] of oxygen isotopes in ~15,000 zircons through time includes analyses made by conventional laser fluorination and secondary ion mass spectrometry and is tested for statistically significant variability using change-point analysis (e.g., REF.[158]) This statistical technique[159] reveals only change points if the null hypothesis of no change (i.e., one mean value) can be rejected. The change points are automatically assigned by the outcome of this statistical test. Oxygen isotopes of zircon record increased crustal reworking associated with the assembly phases of each of the three supercontinents (Fig. 4). During the breakup phase of each of the three supercontinent cycles, $\delta^{18}O$ values decrease, trending toward more mantle-like values (+5 ‰), which is consistent with models invoking more mantle-derived magmatism associated with either mantle plumes and/or slab rollback during supercontinent breakup (Fig. 4). Using geochemical proxies such as hafnium[31,32] and oxygen (Fig. 4) isotopes on well-dated zircons as a supercontinent time series thus establishes a statistical basis for the supercontinent cycle.

A Supercontinent State

As discussed earlier, it is debatable whether the supercontinent cycle existed before ca. 2 Ga. A global cycle of continental assembly and breakup of roughly ~600 Myr may have existed, but for various reasons, large supercontinents may still have not formed—there is presently no compelling evidence that any pre-Columbia supercontinent existed. One of the possible reasons that supercontinents may not have formed until later in Earth history is secular change as the planet evolved (Box 2). The same proxies we used for a supercontinent time series also suggest a supercontinent state of cyclic variations has existed only since ca. 2 Ga (Fig. 4). Two types of variations in $\delta^{18}O$ values of zircon can be identified: 1) oscillating signals in synchroneity with collisional assembly of supercontinents (a supercontinent time series) and 2) a single state shift as the planet evolved from one tectonic regime to another (a supercontinent state). The short-term variations in the $\delta^{18}O$ supercontinent time series (Fig. 4) do not appear until ca. 2.4 Ga, i.e., immediately after the long-term state shift into the modern supercontinent state as evidenced in the geochemistry of both mafic and felsic rocks (Box 2).

Thus, geochemical proxies depict both supercontinent cycles (rhythms) as well as manifestations of secular change (trends). Secular change in the crust is largely thought to be manifest in the growth and emergence of the continents[134]. Evidence of both more crustal volume and more of that volume above sea level should result in a significant increase in supracrustal reworking in the magmatic systems associated with orogenesis[156]. As indicated by $\delta^{18}O$ values, time intervals typified by increased supracrustal reworking are associated with modern supercontinents, whereas the $\delta^{18}O$ record before ~2.4 Ga is invariant and typified by mantle-like values (Fig. 4). The supercontinent state thus likely reflects secular evolution from ancient stagnant- and/or mobile-lid tectonics[22,160,161] to modern plate tectonics[19,20].

Supercontinent Dynamics

Mantle Flow

Despite its theoretical plausibility and a wealth of empirical evidence, the coupling between mantle convection and plate tectonics remains controversial[34]. Both evidence and modeling suggest that supercontinents are both an effect and a cause of mantle convection. This feedback is exhibited in the convergence and assembly of continents over dynamic topography lows induced by mantle downwelling, followed by circum-supercontinent subduction during which subcontinental mantle flow evolves into an upwelling due to return flow[72,74,94]. The origin of Earth's present long-wavelength mantle structure and inferred flow pattern, which closely reflects the breakup of supercontinent Pangaea (Fig. 2), is therefore intimately related to supercontinent formation. Long-wavelength mantle convection may have accelerated core heat loss over time. How numerical modeling sheds light on these geodynamic processes is illustrated in Figure 3, whereas Box 3 explores the role of mantle convection in top-down versus bottom-up tectonics.

A genetic relationship between large-scale mantle flow and the dynamics of the supercontinent cycle is commonly assumed[62,72,74,82,162], although deciphering the evolution of such convective models throughout Earth history has remained elusive. Numerical simulations of mantle convection[72], particularly those including the influence of continents[162,163], initiate with random flow (Fig. 3a), but arrive at degree-1 structure as downwellings and upwellings combine and reinforce each other until only one of each remain and are antipodal (Fig. 3b). Supercontinent formation is a likely, if not inevitable, outcome of degree-1 flow as continents would converge towards and then aggregate over the developing mantle superdownwelling[72,74,82], though subduction initialization elsewhere may modify such a degree-1 planform[164]. Furthermore, supercontinent amalgamation could facilitate the transition from degree-1 to degree-2 convective mantle flow[72]. This transition would occur through the evolution of the 'superdownwelling' into a 'superupwelling'. The processes involved are debated. One contributing factor is that the downwelling may stop when subduction terminates between converging continental blocks and the corresponding slabs have sunk to the base of the mantle. Another contributing factor is the establishment of a subduction girdle around the supercontinent periphery causing upwelling via mantle return flow. The end result is the establishment of a second 'superupwelling' antipodal to the first 'superupwelling' bisected by a "ring of fire" of downwelling similar to what is observed today (Fig. 2, 3c). In this scenario, there is a feedback between mantle convection and supercontinent formation, where mantle convection may facilitate supercontinent assembly, but then the newly formed supercontinent causes profound changes to mantle convection patterns.

The evolution of mantle flow to long convective wavelengths would have increased the efficiency of convective heat transfer and thus enhanced core-mantle boundary heat flux[72,165,166] (Fig. 3d). Results in Figure 3d are shown for two cases, on the left for the transition from smaller-scale to predominantly degree-1 convection corresponding to formation of the first supercontinent, and on the right for the transition from predominantly degree-1 to degree-2 convection after supercontinent formation. Interestingly, although estimates for the age of the nucleation of the inner core range widely from 1.5 Ga[167] to 600 Ma[168], both these ages post-date the onset of the supercontinent cycle (Fig. 4; Box 2). In addition to secular cooling that would have eventually led to formation of an inner core, the onset of a global-scale subduction network[19] in which cool slabs descended to the core-mantle boundary, as well as elevated heat flow produced by long-wavelength mantle convection, both requirements of a supercontinent cycle, may have accelerated cooling of the core promoting both inner core nucleation and growth (Fig. 3).

Mechanisms of Assembly and Breakup

Both top-down and bottom-up geodynamic processes are important for both supercontinent assembly and breakup, as well as how they are coupled. Both forces acting on the plates themselves, and from interaction with the convecting mantle facilitate continental convergence. Slab-pull force is the strongest, but basal traction due to coupling between the continental lithosphere and the convecting mantle is considerable and almost as large[56]. Although these two forces can be opposed to each other, more typically they are coupled to convective mantle downwelling [57], and thus reinforce one another. Continents are therefore modelled to drift "downhill" towards dynamic topography lows, thus forming a supercontinent above a mantle downwelling[72,82]. Notably, the present-day subduction girdle surrounding the Pacific Ocean (also known as the "ring of fire") coincides with the degree-2 girdle of mantle downwelling in between the two LLSVPs. This observation is thus consistent with the theoretical expectation that continents drift, and thus eventually collect above downwellings. Supercontinent assembly is thus dependent on the wavelength of mantle flow. The longest wavelength, degree-1 mantle flow, is also favoured due to Earth's characteristic viscosity profile, which has a weak upper mantle inserted between underlying strong lower mantle and rigid lithosphere[72,169]. Thus, the 'superdownwelling' of degree-1 flow is often invoked to facilitate supercontinent assembly[71,72,74].

It has been proposed that a megacontinent[107] **[G]** (e.g., Gondwana) is a geodynamically important precursor to supercontinent amalgamation[170,171]. The recent assembly of Eurasia is considered as the fourth and most recent megacontinent associated with future supercontinent Amasia[58,172,173]. As continents disperse after supercontinent breakup, a megacontinent assembles along the subduction girdle that encircled it, at a specific location where the downwelling is most intense. Such a situation occurs today as continents aggregate over a mantle downwelling beneath south-central Asia[56,174] close to where the Tethys sutures connect to the degree-2 Pacific girdle. In this context, the formation of Eurasia as a megacontinent occurs close to the degree-1 (i.e., dipolar) locus of downwelling along the degree-2 girdle. However, after the megacontinent forms (e.g., Gondwana), the intensity of local downwelling eventually diminishes due to both return flow from circum-megacontinent subduction and subcontinental insulation[72,175], thus potentially generating plumes underneath the megacontinent and slab rollback along its periphery (as both observed in early Paleozoic Gondwana). As the downwelling beneath the megacontinent diminishes so that it becomes less intense than elsewhere along the girdle, the megacontinent will likely migrate along the girdle where it can collide with other continents to form a supercontinent[107].

The dynamics of supercontinent breakup is arguably less well understood than for supercontinent assembly. This is not because of a lack of sources of stress, but rather because there is not much consensus on the relative importance of the stresses required for breakup. Various potential sources of extensional stress for supercontinent breakup, both top-down (slab induced) and bottom-up (mantle induced) are compared in Box 3. In terms of observations, the ages of internal oceans that opened during the breakup of Pangaea provide valuable constraints on the timing and geometry of supercontinent breakup[176]. The continents have rifted away from Africa in the center, which itself is still positioned over the African LLSVP. This suggests that plume push plays a major role in the initial rifting, consistent with modelling, although the plume push force is transient[177]. Also, plumes may weaken the lithosphere as hot plume material feeds into existing rifts and sutures, where the lithosphere is already thinned, helping to trigger final continental breakup[178-181]. In some cases, plume induced melts can facilitate rifting of even initially thick cratonic lithosphere through such thinning[179,181]. The emplacement of LIPs, e.g., the central Atlantic magmatic province ~20 Myr before seafloor spreading initiated, is either a cause or an initial manifestation of breakup. The drifting of continents away from Africa is highly diachronous, with the Central Atlantic opening during the rifting of North America ~100 Myr before the opening of the South Atlantic Ocean during the rifting of South America[176]. Box 3 shows the breakaway of North America (and soon thereafter South America as well) from elevated tensile stress beneath Africa, where the African LLSVP, or mantle upwelling, is located today and likely was then too (Fig. 2). Slab rollback has also been argued to be an important force in supercontinent breakup[182], but a sensitivity analysis conducted with numerical modelling suggests that it may be secondary to plume push[177,183]. Plume push is strong but short, whereas slab rollback force is intermediate but persistent[177]. Both slab- and mantle-induced stresses can contribute to breakup of a supercontinent. Box 3 shows a model result where the top-down and bottom-up stresses, respectively, are not only roughly equal in magnitude, but also constructively interfere.

Models of Supercontinent Formation

Earth's present-day geography is in between supercontinent configurations, and represents a temporal overlap between assembly of the next supercontinent (recent collision between Asia and India, future collision of Australia) and the protracted breakup of Pangaea (East African rift). The hypothetical configuration of the next supercontinent is an illustrative way to compare and contrast models of supercontinent formation. Will the Atlantic Ocean close ("introversion" **[G]**)? Or will the Pacific Ocean close ("extroversion" **[G]**)? Or will one of the smaller seas—the Arctic, Caribbean, or Tasman Sea—orthogonal with respect to the centroid (located in Africa) of Pangaea close ("orthoversion" **[G]**)? We briefly discuss the assumptions behind each of these models and possible tests to distinguish between them using the historical record of supercontinents, geodynamic modeling, and igneous geochemistry.

Introversion and extroversion are strictly tectonic models as they are, at least as presently defined, predictions about which ocean will close: Atlantic-type or Pacific-type. The Atlantic Ocean is said to be an "internal" ocean since it opened up during the breakup of Pangaea. Supercontinent assembly by the closure of the internal ocean, or introversion[3], is essentially where a supercontinent would converge inward on itself, possibly due to incomplete breakup[89] or dispersal, and amalgamate in a similar location to the previous supercontinent. The Pacific Ocean on the other hand was "external" to Pangaea and supercontinent assembly by extroversion[184-186] stipulates that rifted continents continue to drift apart until this external ocean closes. As a result, the previous supercontinent is turned inside-out as its successor amalgamates. Another way to regard introversion and extroversion is the inheritance or the regeneration, respectively, of the circum-supercontinent subduction girdle[89]. The presence of cycles in geochemical data and geologic occurrences that is longer than even the supercontinent cycle have been used to argue for a longer period modulation[86], possibly due to an alternation between supercontinents formed by introversion and extroversion[89,187].

In contrast, orthoversion is a geodynamic model that predicts a succeeding supercontinent forms 90˚ away from the previous one, within the great circle of subduction encircling its relict predecessor[58]. On present Earth, orthoversion would thus predict one of those seas located along the subduction girdle to close, instead of the Pacific or the Atlantic oceans. It has been proposed that, after supercontinent assembly, long-wavelength mantle convection develops an upwelling beneath the supercontinent, which is associated with a geoid high. Together with the antipodal geoid high, this leads to a prolate shape of the non-hydrostatic Earth, with the minimum inertia axis centered on the supercontinent. Hence TPW, which follows a great circle around this axis, has been proposed as a method for locating the centre of a supercontinent and appears to support the geodynamics of orthoversion[58].

Igneous geochemistry provides a clear test between introversion and extroversion with either Sm-Nd or Hf isotopic evidence[112,188]. Both of these isotopic systems can be used to fingerprint arc magmatic systems dominantly characterized by crustal reworking or mantle-derived magmatism. The Pacific subduction girdle would eventually develop into double-sided subduction with dominantly mantle-derived magmatism, whereas Tethyan subduction systems are characterized by single-sided subduction with dominantly crustal reworking[189]. Therefore, introversion would be consistent with evidence for increased crustal reworking due to single-sided subduction leading to the internal collisional orogens, whereas orogens by extroversion would produce increased juvenile, mantle-derived, magmas due to double-sided subduction leading to external collisional orogens[188]. Such contrasting geochemical and isotopic signatures correspond with the contrasting collisional styles of Rodinia and Gondwana (early stage in formation of Pangaea) and imply that "not all supercontinents are created equal"[112]. The assembly of Rodinia is characterized by melting juvenile crust and is more consistent with extroversion, whereas the assembly of Gondwana is characterized by the melting of old crust, more consistent with introversion[112]. Isotopic predictions for orthoversion[58] are less clear, but would likely involve a mixture between the end-member predictions of introversion and extroversion[190].

Implications for Earth history

In addition to being an integral part in a linked plate tectonic and mantle convective theory, the supercontinent cycle likely greatly influenced the course of Earth history. It has been hypothesized that a uniquely pronounced tectono-magnetic lull (TML) occurred ca. 2.3 Ga, in between the transition from supercratons and supercontinents (Fig. 4), and thus possibly serving as a trigger for the supercontinent cycle[191]. Assuming Columbia was Earth's first "true" supercontinent (Fig. 1), the era of supercontinents (Columbia, Rodinia, and Pangaea; Fig. 4; Box 2) was likely characterized by the appearance and dominance of long-wavelength mantle convection (e.g., degree-1 and degree-2 structures; Figs 2 and 3). In combination with secular changes including long-term planetary cooling and increased lithospheric viscosity contrast, the appearance of supercontinents in Proterozoic time and the increased convective wavelength of the mantle may have been inevitable and irreversible.

A Proterozoic onset (Box 2) of long-wavelength mantle convection (Fig. 3) would carry implications for the presence of thermochemical piles[192] on the core/mantle boundary—the most common explanations for the LLSVPs seismically observed today (Fig. 2), although other interpretations have been proposed to explain the same seismic structures[193]. The compositional origins of the LLSVPs may date as far back as Hadean magma ocean solidification, where crystallisation caused the settling of dense particles at the base of the mantle[194]. Such a model of a globally homogeneous layer, however, cannot explain why the mantle evolved to generate two LLSVPs that straddle the equator and are antipodal with respect to one other (Fig. 2), a outcome that requires whole mantle convection in the form of degree-2 flow (Fig. 3b). These lower mantle structures appear to be shaped by circum-supercontinent subduction, where the present-day African LLSVP matches closely the location of supercontinent Pangaea at breakup ca. 200 Ma[76] (Fig. 2). An onset of long-wavelength mantle convection associated with supercontinent Columbia may have thus organized the previously primordial global layer of dense particles into two antipodal LLSVPs due to the dominance of degree-2 mantle convection during supercontinent tenure and breakup (Fig. 4c). Alternatively, it can be argued that the two LLSVPs are not only compositionally ancient but so is their convective organization which, according to this viewpoint, pre-dates Earth's first supercontinent[73].

It is also possible that compositional heterogeneities in the mantle due to Hadean core/mantle differentiation, identified by short-lived ^{146}Sm-^{142}Nd isotope systematics[195], may have persisted until Proterozoic time, after which the mantle was sufficiently mixed to homogenize ^{142}Nd. Note that suggested ^{142}Nd isotopic anomalies as young as ca. 1.5 Ga[196] are now considered laboratory artifacts[197]. On the other hand, ^{182}W isotopic anomalies are found in young rocks[198] and so must be comparatively resistant to homogenization by mantle mixing. If regions of anomalous ^{182}W can remain isolated in deep pockets either near the core/mantle boundary[199] or within silica-enriched domains in the lower mantle[200], then this isotopic system could be used to investigate the nature of primordial signatures rather than the process of their homogenization since Hadean time[201]. A lack of ^{142}Nd data between 2.7 and 0.8 Ga[202] presently precludes testing whether the ^{142}Nd Hadean differentiation signature was ultimately obliterated by early Archaean convection and the birth of plate tectonics and the supercontinent cycle (Fig. 4; Box 3).

Finally, we consider what influence the birth of supercontinents may have had on surface evolution[1,2,7-10]. Following the Great Oxidation Event ca. 2.4-2.3 Ga[203], the occurrence of repeated episodes of glaciation on some (but not all) cratons, documented on supercraton Superia ca. 2.5-2.2 Ga[144] , indicates that some continental crust already had significant freeboard above sea level[158,204]. Nonetheless, there are as many cratons that do not have evidence for Early Proterozoic glaciation as those that do. The conspicuous absence of such glaciations on many other cratons (Dharwar, Sao Francisco, Slave, Yilgarn, Zimbabwe, etc.) suggests that elevated continental freeboard may not have become global in scale until the amalgamation of Columbia. Recent compilation of burial rates of sedimentary units over the past 4 Gyr shows a state shift decrease between 2.5 and 2.0 Ga[205], where more freeboard due to supercontinent formation, and the subsequent development of a subcontinental upwelling causing a dynamic topography high, could have decreased accommodation space resulting in slower burial rates. Increased weathering rates associated with elevated continental freeboard of the first large supercontinent may have flooded the oceans with free ions that may have facilitated widespread biomineralization for the first time as well as the oldest known eukaryotes[206], with the ca. 1880 Ma Gunflint microfossils representing the first unambiguous evidence[207,208]. The first abundances of eolianites in the geologic record between 2.1 and 1.7 Ga, also occurring during Columbia assembly, can similarly be accounted for by an increase in continental freeboard due to supercontinent formation necessary to source wind-blown sediments[209,210].

Conclusions

Summary

The study of supercontinents is interdisciplinary research that connects mantle convection with plate tectonic theory. Earth presently has a global plate tectonic network and the repeated assembly and breakup of supercontinents is an emergent phenomenon of such a self-organizing system. It is likely that the global plate network existed by at least 2 Ga[19] and Earth has experienced 3 supercontinents cycles[6] since then, in order: Columbia/Nuna, Rodinia, and Pangaea. Palaeogeographic reconstructions of the 3 supercontinents over the past 2 Gyr have been refined in recent decades (Fig. 1; Box 1), although they are still a work in progress. Independent of palaeogeography, geological and geochemical proxies corroborate the ~600 Myr duration of the supercontinent cycle[31,32,78,88,89]. Such cyclic variations arguably have only occurred for the past 2 Gyr since the onset of the supercontinent cycle (Fig. 4), which suggests that modern supercontinents are a manifestation of secular change, i.e., planetary cooling and tectonic evolution (Box 2). In addition to the onset of global subduction by 2 Ga[19], supercontinents associated with convectively efficient long-wavelength mantle convection (degree-1 and degree-2; Fig. 3) are thus consistent with increased secular cooling ever since.

Evidence from all 3 supercontinent cycles, as well as results from numerical modelling[71,72,82,163,172,173,211], indicate that supercontinent formation is intimately linked with whole mantle convection. For Pangaea, lower mantle seismic data indicate the supercontinent was positioned over a mantle upwelling above the African LLSVP (Fig. 2). A link between the LLSVP in the deep mantle and Pangaea at the surface is independently confirmed by oscillatory TPW that occurred about an axis controlled by the locations of antipodal LLSVPs[54,61], and similarly large amplitude TPW has been suggested for the two Proterozoic supercontinents as well[58,62]. Evidence for the stability of the LLSVP beneath Pangaea is further corroborated by the emplacement of LIPs from mantle plumes preferentially emanating from the edges of the African LLSVP[49,51,52,54]. Earlier supercontinents also have pronounced LIP emplacement prior to and during breakup[33,94,98,125,126,212], suggesting LLSVP-related mantle upwellings existed under these supercontinents as well[74,89].

Future perspectives

Continued efforts to reconstruct the palaeogeography of Proterozoic supercontinents Rodinia and Nuna/Columbia is ongoing and increasingly interdisciplinary. Acquiring more high quality palaeomagnetic data from poorly constrained continents and cratons is required; also other reconstruction constraints including geological piercing points, kinematic and provenance considerations, and geological correlations must be refined independently. Recent efforts to integrate palaeolongitude[58,76] and full-plate topologies[91] into Proterozoic reconstructions offer new means of refining ancient palaeogeography that are just now being developed.

Testing the antiquity of the supercontinent cycle and exploring the related implications for geodynamic and tectonic evolution through time are frontier questions that remain to be answered. While the possibility of an Archaean supercontinent has not been ruled out, no compelling evidence exists. The hypothesis of multiple segregated “supercratons” may better explain the diachroneity of the geological histories of cratons and be more consistent with geodynamic considerations for Archaean time.

Despite significant progress on linking plate tectonic theory and mantle convection, our understanding of the dynamics of the supercontinent cycle is arguably still in its infancy. Mechanisms for both assembly and breakup phases of the supercontinent cycle have been proposed, but the relative importance of them, particularly for breakup, are still being evaluated. It is nonetheless clear that both top-down and bottom-up tectonics and their feedbacks are important in supercontinent dynamics (Box 3). Despite a strong correlation, the dynamic link between the two antipodal LLSVPs in the lower mantle and the supercontinent cycles requires further investigation. Debate remains over whether the subsupercontinent LLSVP existed before Pangaea amalgamated, or whether the LLSVP formed as a result of Pangaea assembly. Distinguishing between models in which the LLSVPs are considered fixed for up to 2 Gyr, or respond to the supercontinent cycle, is a frontier question.

Key References

REF.[6]
Offers a review of the history of efforts to reconstruct pre-Pangaean supercontinents and shows the emerging consensus, and remaining uncertainties, of each of their reconstructions.

REF.[19]
Reports first global-scale evidence for subduction using seismic images from multiple continents arguing for the onset of the global plate tectonic network ca. 2 Gyr ago.

REF.[34]
Explores how geodynamic models, based on observations such as kinematics, stress, deformation, and rheology that link mantle convection and plate tectonics can take into account self-organization.

REF.[56]
Shows how plate tectonic motions during the past 250 Myr have been tightly coupled with degree-1 and -2 mantle flow due to basal tractions being nearly as strong as slab pull forces.

REF.[58]
Provides the first geodynamic model of supercontinent formation, orthoversion, where a new supercontinent will form along the degree-2 subduction girdle ~90° away from its predecessor.

REF.[61]
Finds oscillatory total motions of all continents using apparent polar wander (APW) that can be interpreted as true polar wander (TPW) about a stable axis near the centre of supercontinent Pangaea.

REF.[72]
Provides numerical modeling to link major modes of mantle convection (degrees 1 and 2) to supercontinent formation and TPW, with degree 1 downwelling facilitating supercontinent formation and degree 2 convection then resulting from circum-supercontinent downwelling.

REF.[107]
Establishes a megacontinent (e.g., Gondwana) as a significant geodynamic precursor to the later assembly of a supercontinent (e.g., Pangaea).

REF.[141]

Proposes that small and segregated Archaean “supercratons” existed instead of one unified supercontinent based on highly diachronous tectonomagmatic events.

REF.[144]

Offers a combined geologic and palaeomagnetic reconstruction of supercraton Superia and its context in low-latitude glaciation and the Great Oxidation Event (GOE).

REF.[191]

Finds widespread and diverse evidence for a tectonomagmatic lull ca. 2.3 Gyr ago that have played a critical role in triggering initiation of the subsequent modern age of supercontinents.

Competing interests.

The authors have no competing interests.

Key points

- The supercontinent cycle is an outcome of plate tectonics as a self-organizing system.
- According to palaeogeography, three supercontinent cycles of assembly and breakup have occurred over the past 2 billion years (Gyr).
- Before 2 Gyr ago, the occurrence of an older supercontinent is uncertain, and possibly only smaller and separated landmasses existed.
- Geochemical proxies indicate secular change suggesting tectonic evolution from non-cyclic to cyclic changes occurring ca. 2 Gyr ago with the appearance of supercontinents.
- For a better understanding of supercontinent dynamics, it is necessary to connect mantle convection and plate tectonics into one theory.
- A supercontinent is both an effect and a cause of mantle convection (i.e., creating a feedback loop).
- Both top-down (lithospheric) and bottom-up (mantle) tectonics control supercontinent dynamics and it is critical to understand the coupling between them.

Glossary

Apparent polar wander (APW)

Palaeomagnetically measured motion of a continent relative to Earth’s time-averaged magnetic pole. APW results from a combination of both plate motion and true polar wander (TPW).

Degree 1 mantle flow

One hemisphere of mantle upwelling and one hemisphere of mantle downwelling.

Degree 2 mantle flow

Two antipodal mantle upwellings bisected by a meridional girdle of mantle downwelling as the most likely degree 2 configuration for Earth's mantle.

Extroversion

Model of supercontinent formation by closure of the external (Pacific-like) ocean.

Geocentric axial dipole (GAD)

The hypothesis that Earth's magnetic field is dominated by the dipole component at the surface. Palaeomagnetism utilizes this hypothesis when a sufficient number of samples are collected covering 1-10 thousand years.

Geodynamics

The study of dynamics of Earth, including how mantle convection relates to plate tectonics.

Introversion

Model of supercontinent formation by closure of the internal (Atlantic -like) ocean

Large igneous provinces (LIPs)

Extremely large (>10^5 km^2 areal extent, >10^5 km^3 volume) accumulations of igneous rocks, including intrusives (sills, dikes) and extrusives (lava flows, tephra deposits). The formation of LIPs is often attributed to mantle plumes, in particular plumeheads.

Large low shear-wave velocity provinces (LLSVPs)

Seismically imaged structures in the lower mantle critical to our understanding of whole mantle convection and, according to some theories, intimately related to supercontinent assembly and breakup.

Magmatic barcodes

The overall record of short-lived magmatic events in a particular fragment of continental crust. Temporal, spatial and geometrical matching between different fragments provides a method for reconstructing ancient continents.

Mantle plumes

Buoyant hot mantle material that rises from the core-mantle boundary due to basal heating of the mantle by the core.

Orthoversion

Model of supercontinent formation by closure of orthogonal seas (e.g., Arctic, Caribbean, Scotia, and Tasman seas) ~90° away from the center of the previous supercontinent (e.g., Africa).

Palaeomagnetism

Study of Earth's past magnetic field, based on magnetic minerals (magnetite and hematite) that preserve its orientation when a rock formed, constraining the position of the continent with respect to the North Pole at that age.

Subduction girdle

Circum-supercontinent subduction coupled with degree 2 mantle downwelling, e.g., the present-day "ring of fire" of circum-Pacific subduction.

Supercratons

Assembly of Archaean cratons, but in small and segregated clusters as an alternative hypothesis to an Archaean supercontinent.

True polar wander (TPW)

Wholesale rotation of solid Earth (mantle and crust) about the liquid outer core in order to align Earth's maximum moment of inertia with the spin axis (also known as planetary reorientation and observed on other planets and moons).

Tables

Supplementary only

Figures

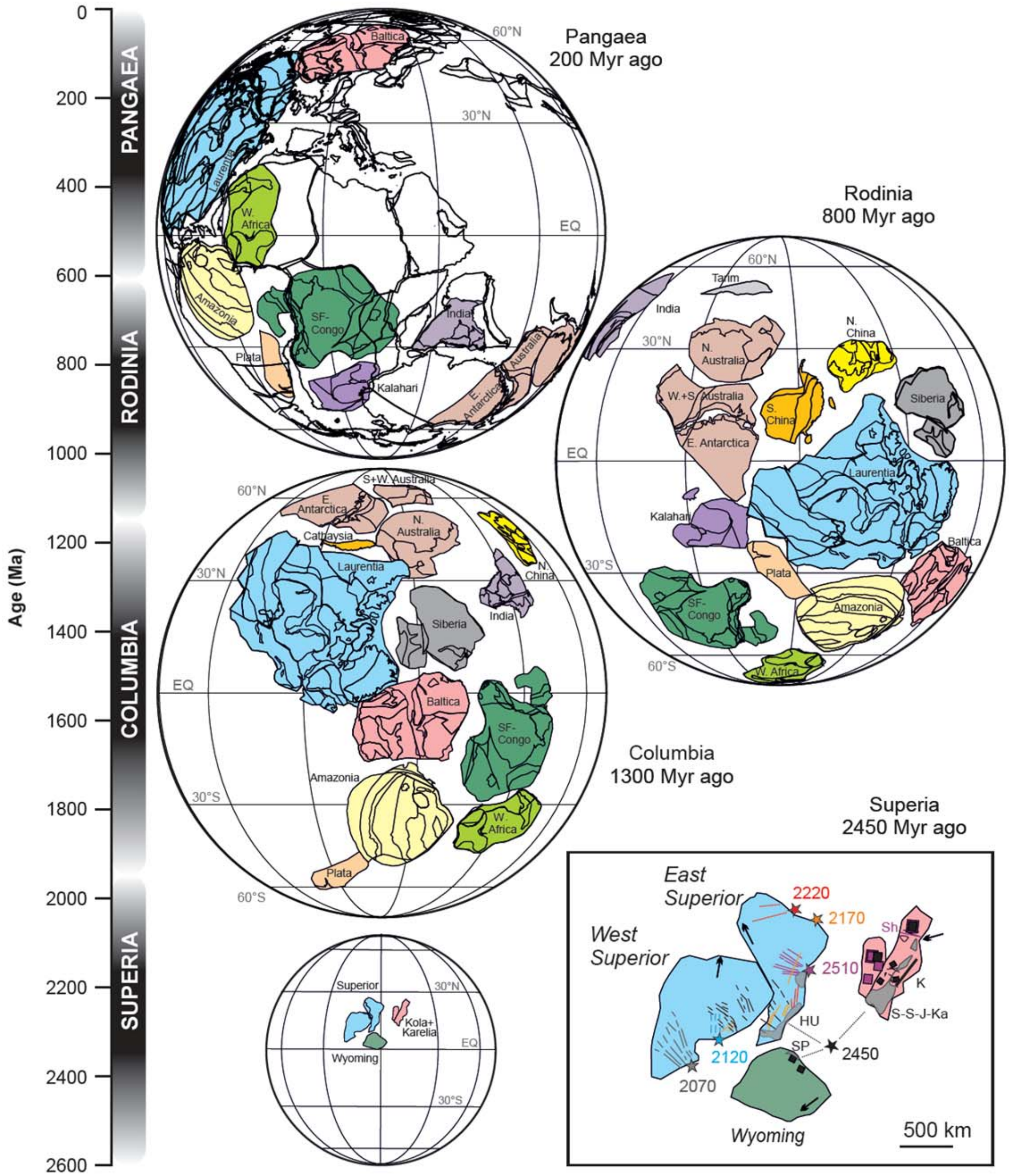


Fig. 1. | Supercontinents through time. Timeline of supercontinent cycles with palaeogeographic reconstructions at various ages. Superia is a hypothesized supercraton and may not have included all or even most cratons globally (*i.e.*, an Archaean supercontinent). Euler rotation parameters for palaeogeographic reconstructions are provided in Supplementary Table S1.

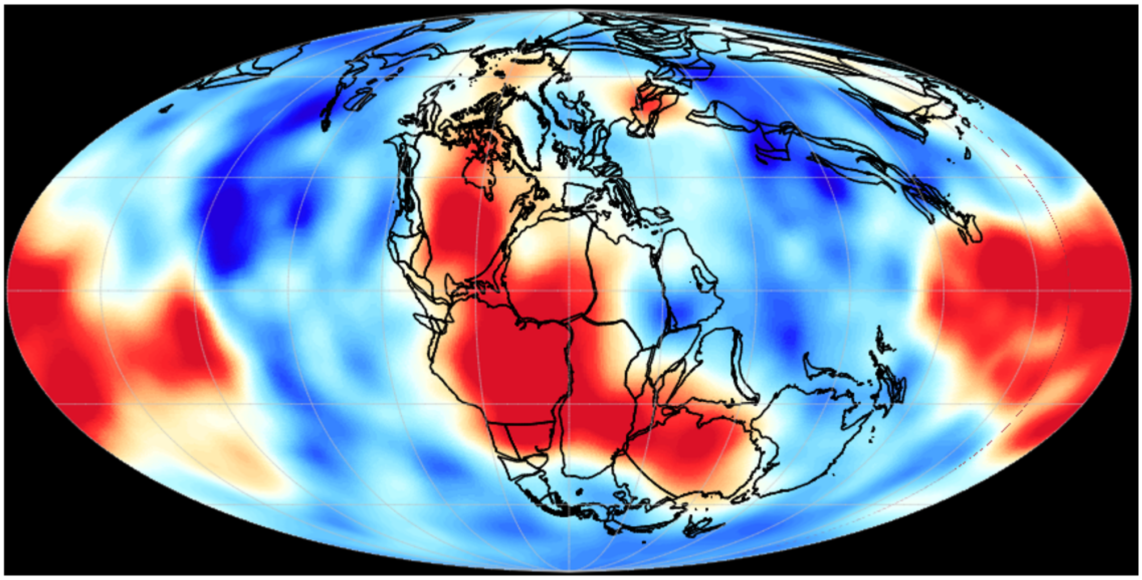


Fig. 2 | Supercontinent Pangaea and mantle structure The lower mantle exhibits two large low-velocity shear-wave provinces (LLSVPs, red) with higher velocities in between. This pattern is typical of long-wavelength degree-two structure, which is suggested to have persisted since at least 200 Ma[47-53]. From that structure, whole-mantle convection is inferred with upwellings above LLSVPs that are separated by downwelling that reflects subduction of oceanic lithosphere and with flow towards LLSVPs at the base of the mantle, but predominantly away from LLSVPs in the upper mantle. Modified from REFS[58,76] and similar to REFS[44,54]. Central meridian is 020˚E.

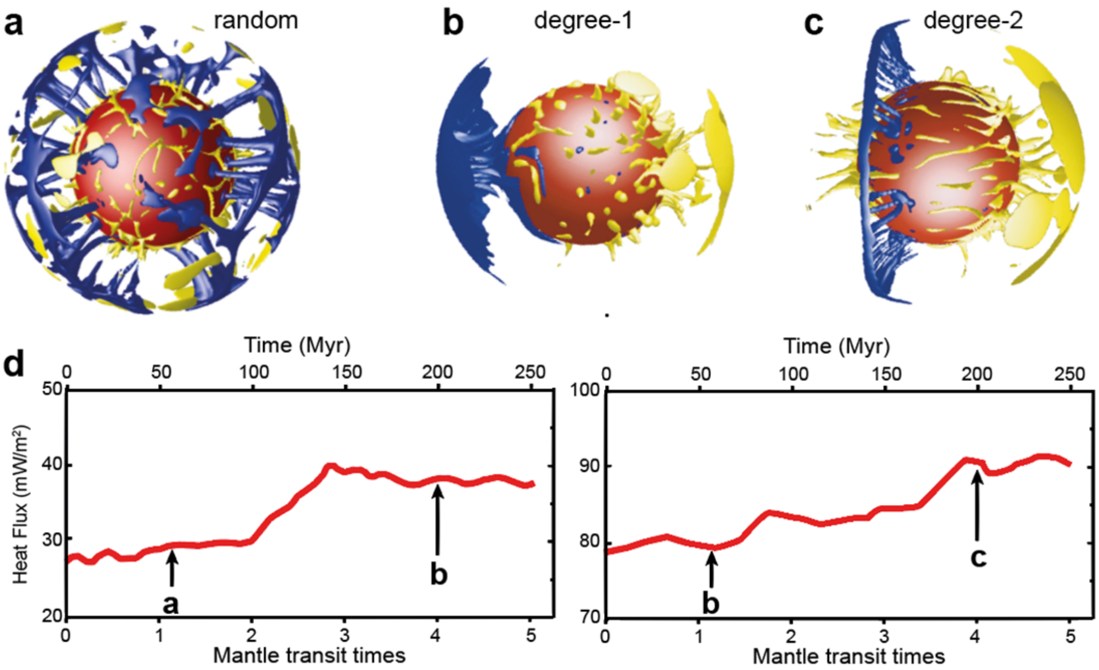


Fig. 3. | Numerical modelling of long-wavelength mantle convection. How supercontinent-induced long-wavelength mantle convection influences core-mantle heat flux (modified from REF.[72]). (**a**-**c**) Modes of mantle convection associated with supercontinent formation. Core is red, mantle downwelling is blue, and upwelling is yellow. (**a**) Random flow pattern, perhaps representative of the Archaean, before the supercontinent cycle began. (**b**) Degree-1 flow that promotes supercontinent assembly over the super-downwelling. (**c**) Degree-2 mantle flow during supercontinent breakup with antipodal upwelling zones (yellow) bisected by a girdle of downwelling. (**d**) Core/mantle boundary heat flow simulation during a transition from **a** random to **b** degree-1 mantle flow (left; modified from REF.[72]) and heat flow simulation during a transition from **b** degree-1 mantle flow to **c** degree-2 mantle flow (right; modified from REF.[211]). In both cases depicted, heat flux is recorded after the initial mantle overturn.

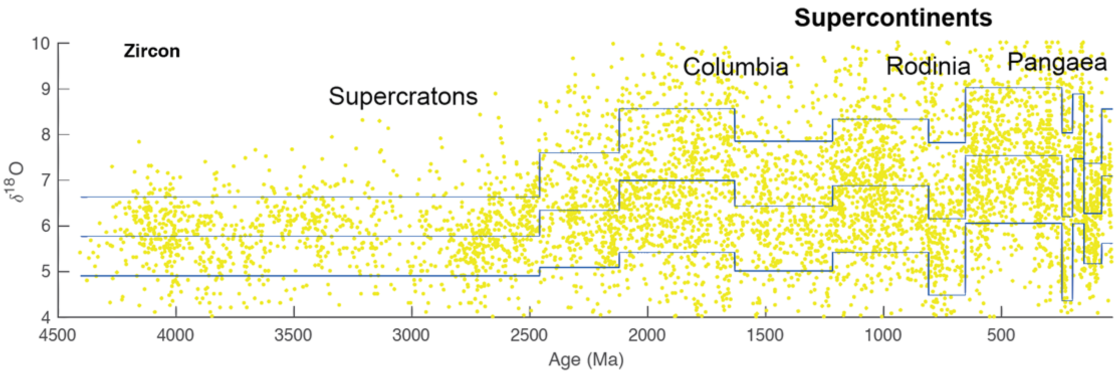


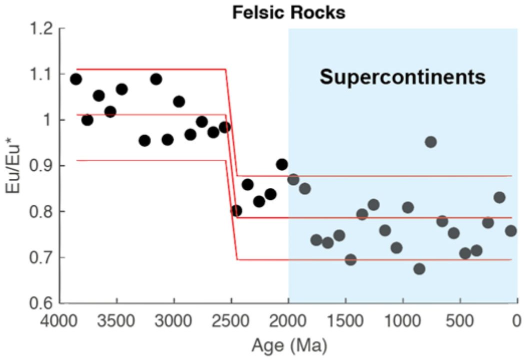
Fig. 4. | Supercontinent time series. Oxygen isotopes ($\delta^{18}O$) of zircon as a geochemical proxy of the supercontinent cycle through time. Lower values indicate more mantle-derived magmatism and higher values indicates more crustal reworking. Note both higher overall values and cycles initiate in the $\delta^{18}O$ data after 2.5 Gyr ago. Note cycles correspond to higher $\delta^{18}O$ during assembly and lower $\delta^{18}O$ during breakup phases of each of the 3 supercontinent cycles. Data are from REF.[156]. Average values were defined using a freely available statistical change-point analysis[159] and suggests a state shift to cyclic variations ca. 2.5 Ga (see also Box 2). Plot has been truncated at 30 Ma due to the sampling of anomalous $\delta^{18}O$ values in neotectonic settings.

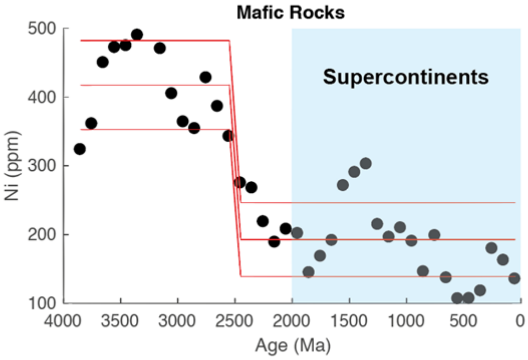
Boxes

Box 1| **How to reconstruct a supercontinent?** Diverse types of evidence are used to reconstruct Precambrian (pre-Pangaean) supercontinents[6] including: palaeomagnetism, orogens of the same age and metamorphic style, the distribution of passive margins surrounding central blocks, geological piercing points (e.g., the geometry of large radiating dyke swarms), detrital zircon provenance, and more. Since continents must collide during supercontinent assembly, identifying an orogenic suture with coeval collisional orogens on the margins of two continents provides the most obvious test that two continents were neighbours in a supercontinent[27,94,104,105,213]. Then, during supercontinent breakup, continents should share ages of rift-related magmatism prior to passive margin development[94,98,105]. Palaeomagnetism **[G]** is the most strictly quantitative method used and is therefore often considered a definitive test of any putative palaeogeographic reconstruction. Palaeomagnetism measures the apparent polar wander (APW) of a continent with respect to the North Pole. If continents were part of a supercontinent, then they should share the same APW path for the period of time that they were connected. During supercontinent assembly, APW paths should merge and during breakup, APW paths should diverge[214]. During the stable tenure of a supercontinent, APW paths of different continents can be superimposed to establish their relative configuration. This method would approximately work even if strong octupole and/or quadrupole components to the magnetic field existed as any time; nonetheless, palaeolatitudes of evaporites[215] and large mafic dyke swarms[216] appear to suggest the validity of the geocentric axial dipole back thought Proterozoic time depicted in Figure 1.

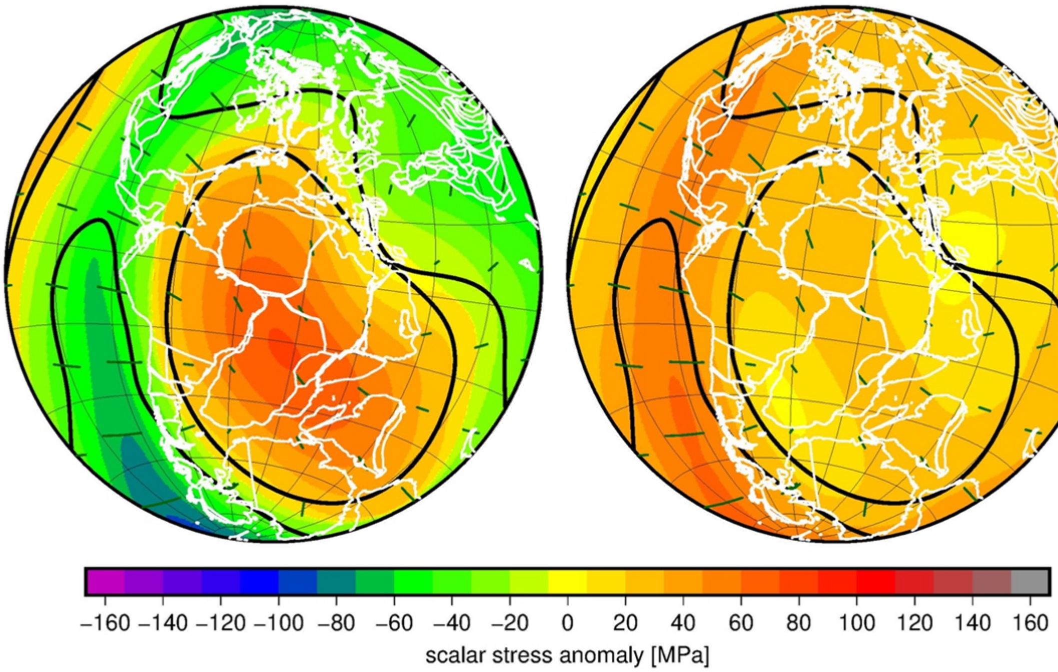
Although palaeomagnetic poles are sufficiently available for APW paths comparisons for supercontinents Rodinia and Columbia[92,98,99], too few poles are as yet available from Archaean cratons, thus palaeogeography across the Archaean-Proterozoic boundary relies predominantly on the geometry of coeval mafic dyke swarms (Fig. 1).

Box 2| **Secular change and the supercontinent state.** There is now broad consensus in the Earth sciences that the planet has cooled over billions of years of mantle convective heat loss[217,218]. Mafic rocks, for example, exhibit a reduction in Ni content through time, which is most likely due to less melting of olivine due to mantle cooling (below). This secular change in the thermodynamics of the mantle is also thought to broadly be linked to the evolution of plate tectonics through time[22]. Felsic rocks, for example, exhibit an increase in the Eu* anomaly, which can be interpreted as increasing subduction since 2.5 Ga (below). During the Archaean, most of the crust was comprised of tonalite–trondhjemite–granodiorite (TTG) rocks, which could be formed by drip tectonics[219] (i.e., delamination) in the absence of plate tectonics[220]. Although early evidence of plate tectonics exists[221], it could have been relatively localized, and evidence of a global plate network is not found until arguably 2 Ga[19]. Strikingly, but perhaps not surprisingly, the three relatively well-established supercontinents occur after the global plate network was established. Plate tectonics is convectively more efficient in cooling the mantle than stagnant- or sluggish-lid convection[160], so the proliferation of plate tectonics may have accelerated secular cooling. Furthermore, as plate tectonics becoming a global phenomenon allows for supercontinent formation[19], large supercontinents may lead to long-wavelength mantle convection (Fig. 2), which is convectively more efficient in transferring heat than smaller cells (Fig. 3; degree-2 flow representing a heat flow maximum[166]), thus further expediting planetary cooling. Secular trends in igneous rock geochemistry correlate with the transition from ancient supercratons to modern supercontinents. The 3 supercontinents since 2 Ga may thus be a manifestation of secular change.





Box 3 | **Top-down vs. bottom-up geodynamics.** Geodynamics is controlled by both "top-down" (lithospheric) and "bottom-up" (mantle) tectonics. Convection is necessarily mass-balanced (what goes down must be balanced by what comes up), but abundant evidence on Earth for convective asymmetry (either dominance of top-down or bottom-up tectonics) exists[222]. With only bottom heating, Cartesian geometry, and constant viscosity, Rayleigh-Bénard convection should be symmetric. However, complications including internal heating and temperature-dependent viscosity lead to convective asymmetry. Basal heating from the core only represents about a quarter of the heat released from the mantle, indicating the importance of internal heating and secular cooling[223]: both primordial "fossil" heat and the decay of radiogenic elements contribute to the heat flow out of the mantle. With internal heating and secular cooling, the average mantle temperature is higher than it would be without, making the temperature drop larger (smaller) across its upper (lower) thermal boundary than without. Temperature-dependent viscosity creates a stiff upper thermal boundary layer (i.e., the lithosphere is stiffer than the convecting mantle), reinforcing convective asymmetry. In plate tectonics, mantle downwellings primarily occur as subducting slabs. Analogue and numerical modelling indicate that the development of large-wavelength convection (as consistent with supercontinent formation; Figs. 2 and 3) is in fact dominated by strong downwellings (slabs) and relatively weak focussed upwellings (plumes)[222] plus a diffuse upward return flow to balance mass flux. We show the superposed stress contributions from top-down (i.e. related to flow caused by subducted slabs) and bottom-up (related to upwelling flow above the LLSVPs) components are roughly equal and add up. (Left) Absolute value of horizontal principal stress. (Right) Difference between the principal stresses. Dark green lines indicate direction of maximum compressive stress. Black lines separate regions with principal stresses both positive, with different sign, and both negative. Stresses imposed on lithosphere from mantle flow[224], computed as in REF.[225], with palaeogeography at 140 Ma[44].



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