The Supercontinent Cycle

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The supercontinent cycle

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Abstract | Supercontinents signify self-organization in plate tectonics. Over the past ~2 billion years, three major supercontinents have been identified, with increasing age: Pangaea, Rodinia and Columbia. In a prototypal form, a cyclic 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 tectonically segregated. In this Review, we discuss how the emergence of supercontinents provides a minimum age for the onset of the modern global plate tectonic network, whereas Archaean supercratons might reflect an earlier geodynamic and nascent tectonic regime. The assembly and breakup of Pangaea attests that the supercontinent cycle is intimately linked with whole-mantle convection. The supercontinent cycle is, consequently, interpreted as 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 remains controversial, resulting in contrasting models of supercontinent formation, which can be tested by quantitative geodynamic modelling and geochemical proxies. Specifically, which oceans close to create a supercontinent, and how such predictions are linked to mantle convection, are directions for future research.

Plate tectonics can be considered simply as a force balance between slab pull from subducting plates, ridge push during ocean spreading and basal drag from the convecting mantle. However, a description of the fundamental system does not provide an explanation of how plate tectonics occurs as a consequence of mantle convection[1,2]. Plate tectonics is a prime example of self-organization or emergence in a system[3,4], and supercontinents emerge as a result of collective, interrelated tectonic and convective processes.

The supercontinent cycle plays a major role in how Earth's interior and surface operate, interact and evolve with each other[5–10]. Hence, supercontinent kinematics are a critical boundary condition for constraining the evolution of Earth's surface[5,6,11–14]. Advances in palaeogeographic reconstructions and geodynamic modelling have allowed these approaches to now be coupled, providing a clearer picture of the supercontinent cycle, with exciting implications for understanding how tectonics has co-evolved with major changes in Earth's surface environment over the past few billion years.

The existence of the supercontinent Pangaea was first evidenced by the fit of continents (namely, Africa and South America), which led to the hypothesis of continental drift — Alfred Wegener's prototypical theory[15] that evolved into the theory of plate tectonics decades later[16–22]. Because plate tectonics has been operational for at least 2 billion years (Gyr)[23–26], if not longer[27–30], the likelihood of the existence of pre-Pangaea supercontinents is high. At least three supercontinents have been identified, with increasing age: Pangaea, Rodinia and Columbia (FIG. 1). It is, therefore, now appropriate to use the term supercontinent cycle, as three recurrences are the bare minimum such that one can reasonably talk about cyclicity.

The operational definition of a supercontinent employed here includes several aspects, which are not mutually exclusive, including large size, a mantle legacy and longevity. A supercontinent does not necessarily have to include all continents — even Pangaea did not include North and South China or other Cimmerian blocks (FIG. 1). The size criterion is typically considered either qualitatively to include most continents[31] or quantitatively to meet a threshold of 75% of available continental crust at any given time[32]. The second criterion (a mantle legacy) has been suggested to offer a more geodynamically meaningful solution, for example, a supercontinent must have been large enough to have been associated with long-wavelength mantle convection[33]. Another aspect of such a mantle legacy, however, is longevity, as a supercontinent must have existed for a sufficient amount of time (at least ~100 million years) for the effect on mantle flow to take hold.

Each supercontinent cycle has two main phases, assembly and breakup. It is, however, a common

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Key points

- The supercontinent cycle is an outcome of plate tectonics as a self-organizing system, where a supercontinent is both an effect and a cause of mantle convection, thus creating a feedback loop.
- 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.
- Both top-down (lithospheric) and bottom-up (mantle) tectonics control supercontinent dynamics, and it is critical to understand the coupling between them.

Large igneous provinces
Extremely large (>10^5 km^2 areal extent, >10^5 km^3 volume) magmatic events of intrusives (sills, dykes) and extrusives (lava flows, tephras) often attributed to mantle plumes.

Mantle plumes
Buoyant hot mantle material that rises from the core–mantle boundary, owing to basal heating of the mantle by the core.

Large low shear-wave velocity provinces
Two low-seismic velocity structures in the lower mantle covering one fifth of the core-mantle boundary and up to several hundred km tall.

True polar wander
Rotation of solid Earth (mantle and crust) about the liquid outer core to align Earth's maximum moment of inertia with the spin axis; also known as planetary reorientation.

Degree 1 mantle flow
One hemisphere of mantle upwelling and one hemisphere of mantle downwelling.

misconception to think of the supercontinent cycle as a binary process (that is, supercontinent or no supercontinent), because the assembly and breakup phases can temporally overlap. For example, the East African Rift[34] (continued breakup of Pangaea) and the continental collision of India with Eurasia[35] (assembly of the next supercontinent) both occur simultaneously in Cenozoic time. A supercontinent cycle is often considered to last 400–800 Myr (REF.[36]), where a statistical basis for such a ~600-Myr duration has been identified using time series analysis of hafnium isotopes of zircon[37], a geochemical proxy for the supercontinent cycle[38]. To be clear, the stable tenure period of a supercontinent (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 (REF.[39]) (FIG. 1).

In this Review, we describe the supercontinent cycle throughout Earth history. The geological evidence for the historical record of supercontinents is appraised, and the insights from geodynamic modelling as a potential explanation for the dynamics of supercontinent assembly and breakup are explored. From these discussions, we suggest that supercontinent cycles can be explained within a theory that connects plate tectonics and mantle dynamics. Finally, after identifying areas of continued uncertainty, future research directions that are required to develop a more robust model of supercontinent formation consistent with both data and theory are outlined.

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The supercontinent cycles

In this section, we discuss the evidence for historical supercontinents throughout Earth history, by exploring the geologic, tectonic and geophysical evidence that informs the geodynamics of each known supercontinent, and commonalities and differences among them. We also discuss how numerical modelling of mantle convection relates to such supercontinent dynamics. Finally, ancient Archaean time is surveyed, for which there is not yet a compelling case for a supercontinent, and the reasons for why it might not be plausible to expect one are discussed.

Pangaea. Pangaea was present from ca. 320 to 180 Ma (FIG. 1), and was the first supercontinent recognized by geologists. The history of Pangaea's existence and tectonic kinematics have been debated and refined for over a century[15,40–50]. As most of this history is well documented[41,45], the focus here is on how the understanding of the most recent supercontinent informs the linkages between its tectonic evolution (assembly and breakup) and mantle convection, that is, its geodynamics. Established linkages between Pangaea and the underlying convecting mantle include: large igneous provinces (LIPs) emplaced by mantle plumes sourced from the edges of large low shear-wave velocity provinces (LLSVPs) in the deep mantle[51–57]; net characteristics of plate motions during Pangaea tenure and breakup that reflect coupling with long-wavelength mantle convective patterns[58–62]; and repeated oscillatory true polar wander (TPW) events, whereby the spin axis approximately follows a great circle orthogonal to a stable axis controlled by supercontinent-reinforced long-wavelength mantle flow[45,56,60,63–71].

Currently, divergent views on the evolution of mantle convection exist. On Earth today, mantle convection is dominated by large-wavelength cells[72,73], yielding most power at harmonics degree 1 mantle flow and degree 2 mantle flow[74]. Recent plate motions associated with Pangaea and its breakup exhibit net characteristics that follow these longest wavelength patterns in mantle flow, although the relative dominance of degree 1 mantle flow versus degree 2 mantle flow might have fluctuated over time[58]. It has been speculated that mantle flow has always followed degree 2 structure in essentially its present form[51,53,54,56,75], but it has also been argued that such longevity is unlikely beyond 300 Ma and the structure seen today only relates to the most recent Pangaea supercontinent cycle[76].

Considering dynamic and evolving mantle convection patterns have enabled potential changes in mantle flow farther back in time to be modelled with incorporation of proxy plate motion reconstructions and subduction histories[73,77]. For example, by constraining numerical models of mantle convection with plate reconstructions as an upper boundary condition, some have argued that the Palaeozoic (before 300 Ma) was characterized by the dominance of degree 1 flow during the assembly of Pangaea[73]. Orthoversion theory[60] 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

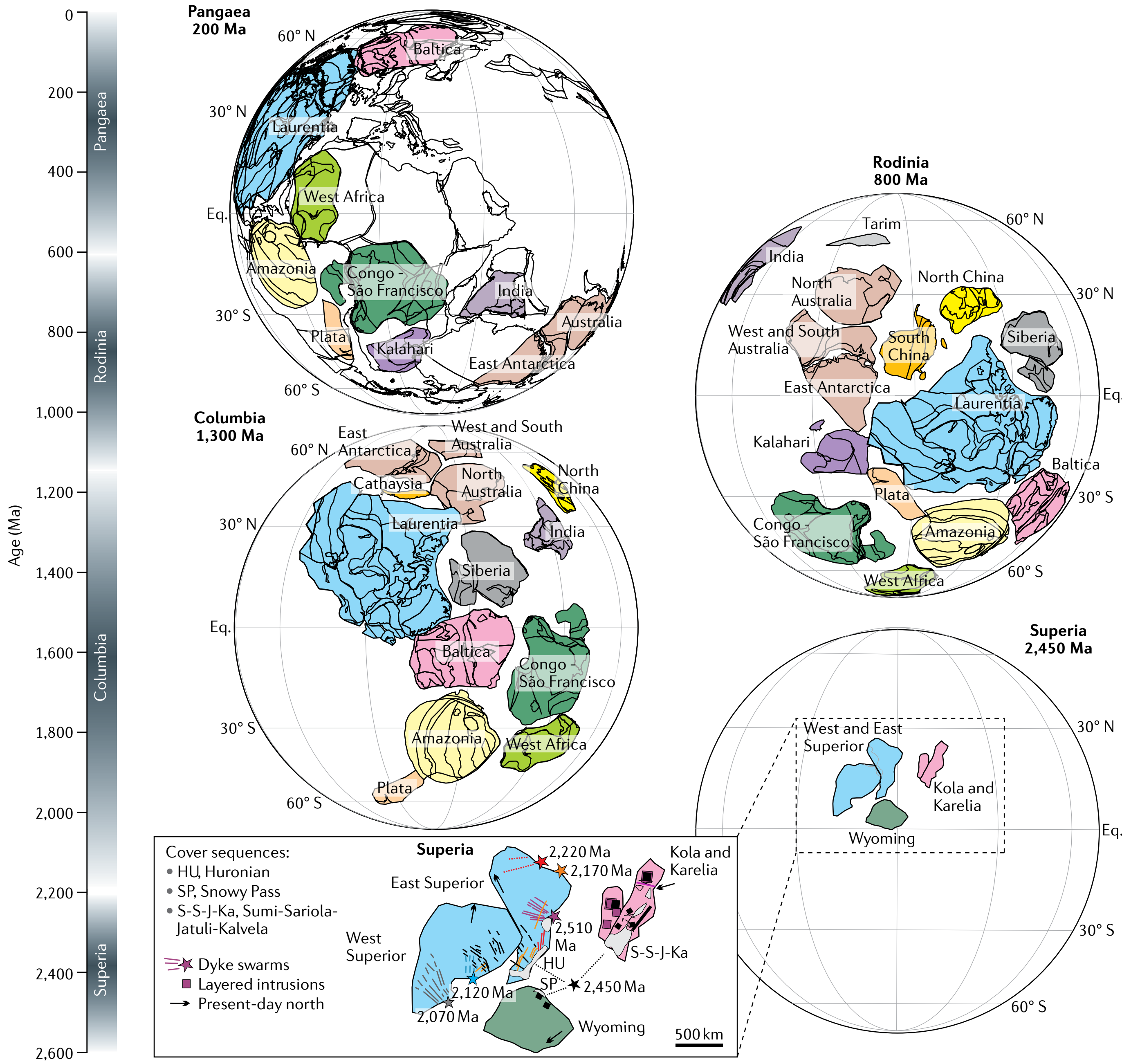


Fig. 1 | **Supercontinents through time.** Timeline of supercontinent cycles with palaeogeographic reconstructions at 200 Ma, 800 Ma, 1,300 Ma and 2,450 Ma. Pangaea, Rodinia and Columbia are supercontinents, whereas Superia is a hypothesized supercraton and might not have included all or even most cratons globally (that is, likely not an Archaean supercontinent). Inset shows Superia at a larger scale, with the geometry of coeval dyke swarms and layered intrusions (with ages) and cover sequences. Dashed lines project dykes and intrusions to plume centres (stars). Plata refers to Rio de la Plata Craton. Euler rotation parameters for palaeogeographic reconstructions are provided in Supplementary Table 1. Eq., equator.

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.

Orthoversion
Model of supercontinent formation by closure of orthogonal seas (Arctic and Caribbean seas and either the Indian Ocean or the Scotia Sea) ~90° away from the centre of the previous supercontinent.

can be spatially linked and palaeolongitude can, thus, be constrained. Orthoversion thus stipulates that Pangaea formed ~90° away from its predecessor, which is supported by palaeomagnetic data interpreted to constrain palaeolongitude[60].

The palaeogeography of supercontinent Pangaea ~20 Myr before breakup (ca. 200 Ma) is thought to be linked to the shape of present-day mantle structures based on their close spatial association[45,78] (FIG. 2). Furthermore, numerical modelling of the two main long-wavelength mantle convection patterns — degree 1 mantle flow and degree 2 mantle flow — shows that they are related to supercontinents[74,76]. For example, one hypothesis is that the supercontinent cycle causes an alternation between the dominance of degree 1 and degree 2 long convective wavelengths[74,76]. Initially, supercontinent assembly is dominated by degree 1 mantle flow, where continents would collect over the

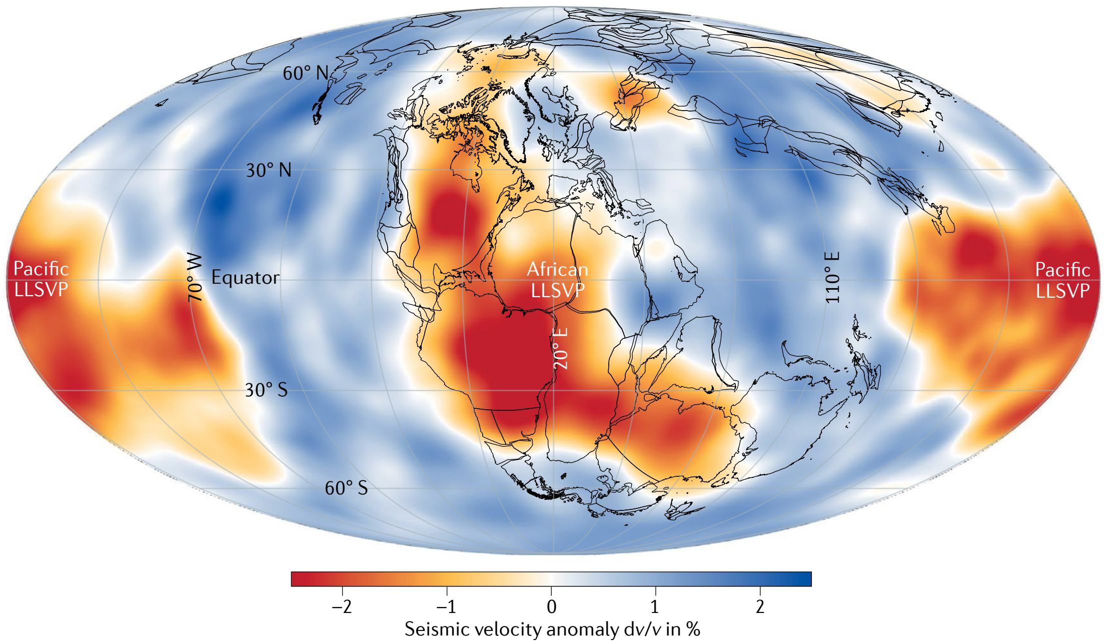


Fig. 2 | **Supercontinent Pangaea and mantle structure.** The modern lower mantle exhibits two large low shear-wave velocity provinces (LLSVPs, red), with higher velocities (blue) in between. This pattern is typical of long-wavelength degree 2 structure, which is suggested to have persisted since at least 200 Ma (REFS[47–53]). From that structure, whole-mantle convection is inferred with upwellings above LLSVPs that are separated by downwelling, which reflects subduction of oceanic lithosphere and with lower mantle flow towards LLSVPs, but with upper mantle flow predominantly away from LLSVPs. Central meridian is 020° E. Tomography is for 2,800 km depth. Plate reconstruction at 200 Ma from REFS[60,78] is in a true polar wander reference frame. Figure adapted with permission from REF.[78], China University of Geosciences (Beijing) and Peking University.

hemispheric superdownwelling. Several processes (the relative importance of which is debated[74,79,80]) combine to turn the region of downwelling beneath the supercontinent into one of upwelling. The supercontinent becomes encircled by subduction zones and geodynamic models indicate that return flow from subduction may be an important contributor to this transformation[74]. Mantle convection is, thus, transformed from degree 1 into degree 2, in which two antipodal regions of upwelling are bisected by a subduction girdle of downwelling[74,76].

Presently, whether the degree 2 mantle flow pattern inferred from data (FIG. 2) and modelling[74,76] is supercontinent-induced or whether it already existed is debated[75,81]. There are two competing end-member hypotheses about the origin of the mantle flow pattern and its relation to supercontinent formation. First is the stationary or quasi-stationary hypothesis[51,53,54,56,75] that the degree 2 pattern (as represented today by two antipodal LLSVPs under the African and Pacific plates) is relatively stable and long-lived, that is, degree 2 existed before supercontinent Pangaea formed or moved above one of current LLSVP locations. Second is the dynamic hypothesis[73,74,76,77,81–84], where degree 2 flow reflects coupling between the supercontinent cycle and convecting mantle, with a new LLSVP forming beneath the nascent supercontinent.

Subduction girdle
Circum-supercontinent subduction coupled with degree 2 mantle downwelling, for example, the present-day 'Ring of Fire' of circum-Pacific subduction zones.

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[74,83,85]. Rather, continents are expected to drift towards downwellings and dynamic topography lows[86,87] between the two LLSVPs, as observed in the dispersion of continents since the breakup of Pangaea[58–60]. 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 the coupling between supercontinents and the mantle is indirect (for example, TPW[60], LIP cyclicity[76,82] and geochemistry[81]) or involves back-calculating mantle structure with numerical modelling as influenced by plate tectonics reconstructions[73,77], both of which have large uncertainties.

Pangaea is, ultimately, the keystone that upholds the concept of what a supercontinent is and the detailed understanding of it provides the central principles on which the understanding of older supercontinents depends. But there are also aspects of Pangaea that are unique to this most recent supercontinent. Pangaea was where the dinosaurs roamed and provided the ecosystem in which the abundant fossil record of Phanerozoic flora and fauna evolved[88]. After Pangaea assembly, the concentration of atmospheric oxygen reached its zenith in Earth history because forests and vegetation flourished[89,90]. Burial and decay of vegetation-rich sediments then formed the vast Carboniferous coal deposits[89]. Finally, rifting processes during the breakup of Pangaea are associated with some of the largest oil and gas reserves on Earth, such as the Persian Gulf and Gulf of Mexico[91].

Rodinia and Columbia. Peaks in global isotopic ages[92–95] and other geologic occurrences[96,97] indicate the likelihood of at least two pre-Pangaean supercontinents:

Megacontinent
Geodynamic precursor to supercontinent formation that is large (~70% the size of its supercontinent) and early (assembly ~200 Myr before supercontinent amalgamation).

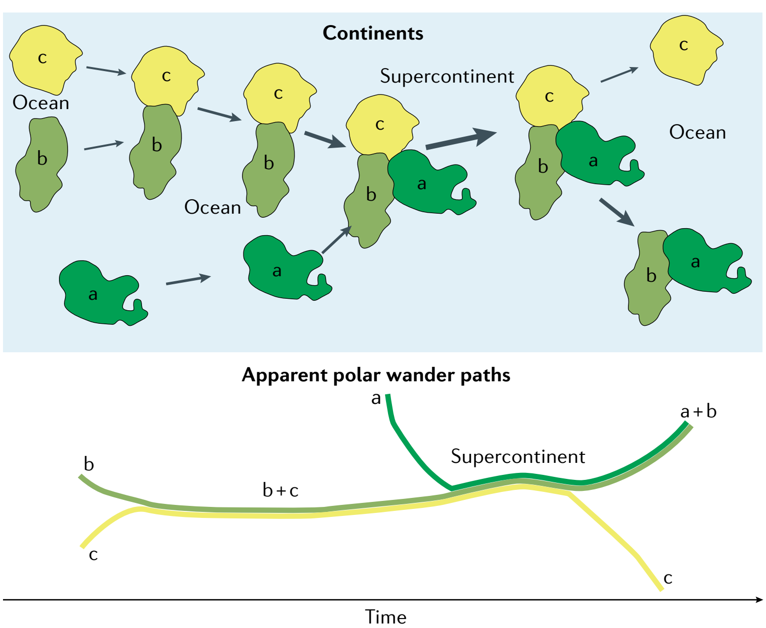
Rodinia at ca. 1 billion years ago (Ga) (REFS[98–104]) and Columbia at ca. 1.5 Ga (REFS[23,32,39,105–114]) (Columbia has also been referred to as Nuna, but a solution to the semantic standoff is that Nuna represents a precursor megacontinent building block of the larger supercontinent of Columbia, much like Gondwana was a precursor to Pangaea[115]). Palaeogeographic reconstructions in Precambrian time are inherently controversial, given the lack of constraints from seafloor spreading that make the first-order reconstruction of Pangaea comparatively straightforward[116]. Nonetheless, great strides have been taken to reconstruct pre-Pangaean supercontinents[10].

Box 1 | **Reconstructing supercontinents**

Diverse types of evidence are used to reconstruct Precambrian (pre-Pangaean) supercontinents[10,227], including palaeomagnetism, orogens of the same age and metamorphic style, the distribution of passive margins surrounding central blocks, geological piercing points (for example, the geometry of large radiating dyke swarms and associated magmatic barcodes), detrital zircon provenance and more. As 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[31,102,112,113,228]. Then, during supercontinent breakup, continents should share ages of rift-related magmatism prior to passive margin development[102,106,113].

Palaeomagnetism 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; see figure) of a continent with respect to the North Pole between two successive time steps. 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.

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 at any time; nonetheless, palaeolatitudes of evaporites[229] and large mafic dyke swarms[230] appear to suggest the validity of the geocentric axial dipole throughout Proterozoic time. Although palaeomagnetic poles are sufficiently available for APW path comparisons for supercontinents Rodinia and Columbia[100,106,107], 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. Figure adapted with permission from REF.[231], Geological Society of America.



The reconstructions of pre-Pangaean supercontinents depicted (FIG. 1) have not yet reached a level of consensus, as many uncertainties and debates remain[10,36]. For example, in supercontinent Columbia, it is debated whether Siberia had a tight fit[106,117,118] or a loose fit[119,120] with Laurentia. Although some aspects of the configuration are debated, there is generally first-order agreement on the existence of both pre-Pangaean supercontinents and their general timing of assembly and breakup (Columbia, ca. 2.2–1.2 Ga; Rodinia ca. 1.2–0.6 Ga; Pangaea, ca. 0.6 Ga to present), 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) path comparison (BOX 1) measured with palaeomagnetism assuming a geocentric axial dipole, 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 was geologically distinct from both Columbia and Pangaea[97,121,122], in that Rodinia is relatively poorly endowed in mineral deposits[123] and is also the only one of the three known supercontinents to have experienced low-latitude Snowball Earth glaciations[124–126]. The configuration of Rodinia is thought to have played a central role in the development of Snowball Earth. For example, the dominantly tropical to subtropical distribution of Rodinia's continents[127] likely facilitated global-scale glaciation by enhanced drawdown of CO_2, owing to increased continental weathering[103,126]. The late Neoproterozoic Cryogenian Period of Snowball Earth episodes (720–635.5 Ma) coincided with the rifting of Rodinia and increased glacial erosion[128] (with deep glacial incisions occurring in rift-related uplifted horsts[129]), processes that collectively influenced the geochemical carbonate-saturation state of the oceans[130]. The uniqueness of Rodinia might relate to a contrasting style of tectonic assembly with that of other supercontinents[97,121,122].

Columbia is Earth's oldest known supercontinent, as it assembled during ca. 2.0–1.6 Ga. The beginning of Columbia started with the formation of its core (the megacontinent of Nuna[106,115]) during the Thelon orogen 1,970 Ma (REF.[131]). During this orogenic event, the Rae Craton served as the upper plate in the collisions that formed Laurentia, which, in turn, formed part of the larger Nuna[132]. Progressive assembly of Columbia continued until the final suturing of Australia at ca. 1.6 Ga (REF.[133]), which was located along the periphery of Columbia[39,108]. The occurrence of voluminous, anorogenic granite–anorthosite complexes (granitoids crystallized from a magma with low water content and lacking tectonic fabrics) 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[134]. Such observations led to the speculation that this upwelling occurred beneath

Apparent polar wander
Palaeomagnetically measured motion of a continent relative to Earth's time-averaged magnetic pole, and results from a combination of both plate motion and true polar wander.

Palaeomagnetism
Study of rocks containing magnetic minerals that preserve the orientation of the magnetic field and constrain the position of the continent with respect to the North Pole at that age.

Geocentric axial dipole
Earth's magnetic field is dominated by a dipole at the surface that aligns with the spin axis when averaged over 1,000–10,000 years.

Geologic piercing points
Geologic correlations used to test palaeogeographic reconstructions, including orogenic sutures, conjugate rift margins, and magmatic intrusions and dyke swarms.

Magmatic barcodes
Record of short-lived magmatic events on a continent or a craton that can be compared with those of different fragments to test ancient palaeogeographic reconstructions.

Supercratons
Assembly of Archaean cratons, where the landmasses were likely in small and segregated clusters, which form an alternative hypothesis to an Archaean supercontinent.

the Palaeoproterozoic–Mesoproterozoic supercontinent Columbia, providing evidence for Earth's first true supercontinent[134]. It should also be noted that Columbia is the most endowed supercontinent in terms of mineral deposits[123]; however, the reasons for this abundance remain unclear.

Evidence of plate tectonics coupling with mantle convection can be deduced from the geologic record for pre-Pangaean supercontinents, albeit less directly than comparison with present-day mantle seismic structure (FIG. 2). Like Pangaea, both Proterozoic supercontinents exhibit a close association with mantle-related anomalies, for example rifts and LIPs sourced from mantle plumes[39,102,103,106,117,135,136] and intervals of TPW, whereby the spin axis approximately follows a great circle orthogonal to an axis central to each supercontinent[60,64,65,137–141], both controlled by the sub-supercontinent mantle upwelling.

Unknown Archaean. The history of crustal growth during Earth's early evolution is hotly debated[142–144], although most models propose that a majority of Earth's continental crust formed prior to the assembly of Columbia[145]. 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[146]), crustal assembly into a truly large supercontinent might 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)[105]. 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[147]. 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, in other words, constrained by palaeomagnetic poles of only one age[148,149]. Even though single-pole comparisons effectively compare palaeolatitude, they are completely unconstrained in the relative palaeolongitude of component blocks. For example, 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, owing to the general paucity of palaeomagnetic data from most cratons.

Thus, interpretations of late Archaean palaeogeography have relied on geologic means of correlation, using approaches such as comparing magmatic barcodes[150,151] (BOX 1). As an alternative to an Archaean supercontinent, the existence of smaller and segregated supercratons has been proposed, in which clusters of cratons occurred without them ever becoming connected[152]. The appeal of the supercratons hypothesis is that it can explain the long-known diachroneity of late Archaean cratonization[153,154]. Reconstructions based primarily on emplacement ages of radiating dyke swarms[155], correlative rift basin successions[155,156] and at least one instance of matching APW paths of two cratons[157] are consistent with the idea of a supercraton called Superia surrounding the Superior Craton. There is also at least one instance of an APW path comparison between cratons suggesting that Yilgarn and other cratons were most likely not a part of Superia, which is inconsistent with a single Archaean supercontinent and supportive of the existence of another supercraton geographically distant from Superia[158].

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, such as small sizes and/or short durations of continental clusters[80] and/or the lack of a global subduction girdle that could have been the primary driver for the formation of LLSVPs[76,102]. 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)[159], but its existence has been called into question on palaeomagnetic grounds[160]. Without contiguity with other cratons (if any), the relatively small size of continental area would have likely been insufficient to steer mantle convection towards dominance of the very large scales, such as degree 1 and degree 2 flow.

As currently reconstructed[155,158], the Superia supercraton is estimated to have been about the size of modern-day Antarctica, and, so, is much smaller than any of the three established supercontinents[74,80] (FIG. 1). Superia might have been larger than Antarctica[152], but it is thought that Superior was the predominant craton of Superia, surrounded by multiple potential neighbours (for example, Wyoming, Karelia and Kola, Hearne). Palaeogeographic reconstructions can ultimately distinguish between the supercontinent and supercratons hypotheses for Archaean–Proterozoic time, but our present understanding suggests that Archaean supercratons[152] were likely not large enough to have been the products of a dominant degree 1 or degree 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[152]. Thus, the difference between the scale of mantle convection patterns beneath supercontinents and supercratons — if there is a difference in convective length scales — is arguably reflected in the different surface area sizes of their rifted blocks[152,161]. According to inference, Archaean mantle convective cells associated with supercratons might have only been <40% of the size of their Proterozoic–Phanerozoic successors associated with supercontinents.

Smaller Archaean convective cells can account for the episodic, intermittent nature of Archaean subduction[162,163]. It is therefore possible that Archaean mantle convection was exclusively characterized by higher harmonics and/or random mantle flow. More randomized Archaean convection could provide a viable 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.

Supercontinent dynamics

Building on the general palaeogeographic evidence for the existence of multiple supercontinents over the last ~2 Gyr, we explore how the kinematics of the supercontinent cycle can be explained by the coupling between plate tectonics and mantle convection. Numerical modelling sheds light on these geodynamic processes (FIG. 3), as well as the role of mantle convection in top-down versus bottom-up tectonics (BOX 2).

Mantle flow. Despite its theoretical plausibility and a wealth of empirical evidence, the coupling between mantle convection and plate tectonics remains controversial[1]. Both evidence and modelling suggest that supercontinents are both an effect and a cause of mantle convection[60,74]. 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, owing to return flow[74,76,102]. According to this model, 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.

A genetic relationship between large-scale mantle flow and the dynamics of the supercontinent cycle is commonly assumed[64,74,76,86,164], although deciphering the evolution of such convective models throughout Earth history has remained elusive. Numerical simulations of mantle convection[74], particularly those including the influence of continents[164,165], starting with random flow (FIG. 3a), arrive at degree 1 structures, as smaller downwellings (or upwellings) gradually merge together until only one of each remain (superdownwelling and superupwelling, respectively) 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[74,76,86], although subduction zone initiation elsewhere can modify such a degree 1 planform[166].

Supercontinent amalgamation could facilitate the transition from degree 1 to degree 2 convective mantle flow through converting the superdownwelling into a superupwelling[74], but the processes involved are debated. One contributing factor is that the downwelling might stop when subduction terminates between converging continental blocks and the corresponding slabs sink to the base of the mantle[83]. Another contributing factor is the establishment of subduction around the supercontinent periphery, causing upwelling via mantle return flow[74]. The end result is the establishment of a second superupwelling antipodal to the first superupwelling bisected by a girdle of downwelling, producing

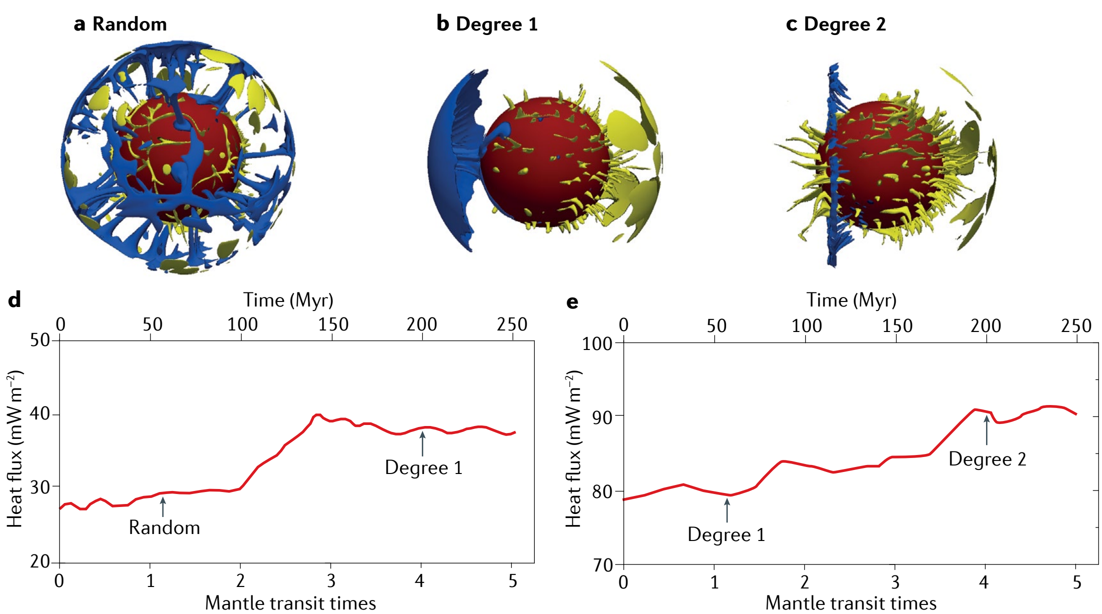


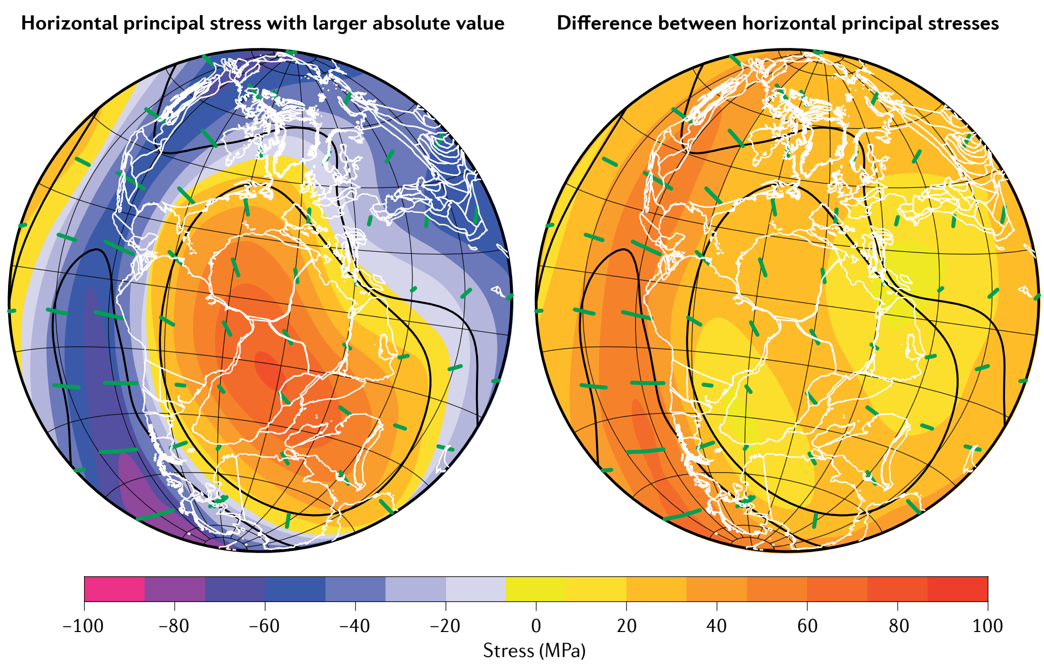
Fig. 3 | **Numerical modelling of long-wavelength mantle convection.** Supercontinent-induced long-wavelength mantle convection influences core–mantle heat flux. Modes of mantle convection associated with supercontinent geodynamics. **a** | Random flow pattern, perhaps representative of the Archaean, before the supercontinent cycle began. **b** | Degree 1 flow that promotes supercontinent assembly over the superdownwelling. **c** | Degree 2 mantle flow during supercontinent breakup with antipodal upwelling zones (yellow) bisected by a girdle of downwelling. Earth's core is red, mantle downwelling is blue (associated with tectonic subduction) and mantle upwelling is yellow (associated with tectonic rifting). **d** | Core–mantle boundary heat flow simulation during a transition from random (panel **a**) to degree 1 mantle flow (panel **b**). **e** | Core–mantle boundary heat flow simulation during a transition from degree 1 mantle flow (panel **b**) to degree 2 mantle flow (panel **c**). In both panels **d** and **e**, heat flux is recorded after the initial mantle overturn. For panels **a**–**d**, simulations updated from those of REF.[74]. For panel **e**, simulations updated from REF.[225].

Box 2 | **Top-down versus 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[232]. With only bottom heating, Cartesian geometry, without secular cooling and with 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 represents only about a quarter of the heat released from the mantle, indicating the importance of internal heating and secular cooling[233]. Both primordial fossil heat and the decay of radiogenic elements contribute to the heat flow out of the mantle. The average mantle temperature is higher than it would be if there was no internal heating and secular cooling, so, with these additional heat sources, the temperature drop is larger across the upper thermal boundary of the mantle and smaller across the lower thermal boundary, respectively, than without them. Temperature-dependent viscosity creates a stiff upper thermal boundary layer (in other words, 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) is dominated by strong downwellings (slabs) and relatively weak focussed upwellings (plumes)[232], plus a diffuse upward return flow to balance mass flux. The superposed stress contributions from top-down (related to flow caused by subducted slabs) and bottom-up (related to upwelling flow above the large low shear-wave velocity provinces) components are roughly equal and constructively add up (see figure). Short dark green lines indicate direction of maximum compressive stress. Long black lines separate regions with principal stresses both positive, with different signs and both negative. Stresses imposed on lithosphere from mantle flow[234], computed as in REF.[235], with palaeogeography at 140 Ma (REF.[45]). Grid lines indicate mantle reference frame, where North is up in the palaeomagnetic frame.



a subduction geometry similar to what is observed today along the 'Ring of Fire' surrounding the Pacific Ocean (FIGS 2,3c). In this scenario, there is a feedback between mantle convection and supercontinent formation, where mantle convection can 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[74,167,168] (FIG. 3d,e). Results are shown for two cases: the transition from smaller scale to predominantly degree 1 mantle convection, corresponding to the formation of the first supercontinent (FIG. 3d), and the transition from predominantly degree 1 to degree 2 convection after supercontinent formation (FIG. 3e). Interestingly, although estimates for the age of inner core nucleation range widely from 1.5 Ga (REF.[169]) to 600 Ma (REF.[170]), both these ages post-date the known occurrences of supercontinents. Both the onsets of a global-scale subduction network[23] and long-wavelength mantle convection were requirements for the supercontinent cycle. Both of these prerequisites would have accelerated planetary cooling, owing to cool slabs descending to the core–mantle boundary and through more efficient convection. Thus, secular cooling would have eventually led to formation of an inner core, although these two features of the supercontinent cycle (a global subduction network and efficient long-wavelength mantle convection) might have accelerated cooling of the core, promoting inner core nucleation a billion or so years before it might have occurred without supercontinents (FIG. 3).

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

Mechanisms of assembly and breakup. Both top-down and bottom-up geodynamic processes are important for supercontinent assembly and breakup, as well as how they are coupled. Forces acting on the plates themselves in combination with interaction with the convecting mantle facilitate continental convergence and divergence. Slab-pull force is the largest, but basal traction owing to coupling between the continental lithosphere and the convecting mantle is considerable and almost as large[58]. Although these two forces can be opposed to each other, more typically they are coupled to convective mantle downwelling[59] and, thus, reinforce one another. In geodynamic models, continents therefore tend to drift downhill, that is, towards dynamic topography lows, thus forming a supercontinent above a mantle downwelling[74,86]. 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 towards, and eventually collect above, downwellings. Supercontinent assembly is, thus, dependent on the wavelength of mantle flow. The longest wavelength, degree 1 mantle flow (FIG. 3b), is also favoured, owing to Earth's characteristic viscosity profile, which has a weak upper mantle inserted between the underlying strong lower mantle and the overlying rigid lithosphere[74,171]. Thus, the superdownwelling of degree 1 flow is often invoked to facilitate supercontinent assembly[73,74,76].

It has been proposed that a megacontinent[115] (for example, Gondwana) is a geodynamically important precursor to supercontinent amalgamation[172,173]. The ongoing assembly of Eurasia is considered as the fourth and most recent megacontinent associated with future supercontinent Amasia[60,174,175]. 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[58,176], close to where the Tethys sutures connect to the degree 2 circum-Pacific subduction girdle. In this context, the formation of Eurasia as a megacontinent occurs close to the degree 1 (or dipolar) locus of downwelling along the degree 2 girdle.

After the megacontinent forms, however, the intensity of local downwelling eventually diminishes, owing to both return flow from circum-megacontinent subduction and subcontinental insulation[74,177], thus, potentially generating plumes underneath the megacontinent and slab rollback along its periphery, as both observed in early Paleozoic Gondwana[173]. 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[115]. It is the eventual development of a degree 2 mantle upwelling beneath a young supercontinent that might explain why we do not seem to see supercontinents straddling the poles (FIG. 1), as TPW[64,71] would tend to shift the newly developed antipodal degree 2 upwellings to the equator[139] (FIG. 2), if the supercontinent did not already form there.

The dynamics of supercontinent breakup are arguably less well understood than for supercontinent assembly, not because of a lack of sources of stress but, rather, because there is little consensus on the relative importance of these stresses required for breakup. Various potential sources of extensional stress for supercontinent breakup, both top-down (slab-induced) and bottom-up (mantle-induced), can be compared (BOX 2).

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[178]. The continents have rifted away from Africa in the centre, which is still positioned over the African LLSVP. This observation suggests that plume push plays a major role in the initial rifting, consistent with modelling, although the plume-push force is transient[179]. Also, plumes can 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 by enhancing the continent's sensitivity to other stresses[180–183]. In some cases, plume-induced melts can facilitate rifting of even initially thick cratonic lithosphere through such thinning[181,183]. The emplacement of LIPs is either a cause or an initial manifestation of breakup, for example, the ca. 200-Ma Central Atlantic magmatic province ~20 Myr before seafloor spreading initiated.

The drifting of continents away from Africa is highly diachronous, with the Central Atlantic Ocean opening during the initial rifting of North America from Africa, which occurred ~40 Myr before the opening of the South Atlantic Ocean during the rifting of South America[178]. North America broke away (and, soon thereafter, South America as well) from elevated tensile stress beneath Africa (BOX 2), where mantle upwelling from the African LLSVP is located today and likely was then too[58] (FIG. 2).

Slab rollback has also been argued to be an important force in supercontinent breakup[184], but a sensitivity analysis conducted with numerical modelling suggests that it is arguably secondary to plume push[179,185]. Plume push is a larger but transient force that affects the supercontinent more centrally and broadly, whereas slab-rollback force is intermediate in strength but persistent and affects mostly the margin of the supercontinent[179]. Both slab-induced and mantle-induced stresses can combine to contribute to breakup of a supercontinent, where a model result (BOX 2) indicates that the associated top-down and bottom-up stresses are not only roughly equal in magnitude but also constructively interfere. Thus, both top-down and bottom-up stresses are important and also should not be thought of as mutually exclusive in their effects.

Models of supercontinent formation. Earth's present-day geography is in between supercontinent configurations and represents a temporal overlap between the assembly of the next supercontinent (recent collision between Asia and India ca. 40 Myr ago, 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. Introversion predicts

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

that the Atlantic Ocean will close. Extroversion predicts that the Pacific Ocean will close. Orthoversion predicts the smaller tracts of seafloor — the Arctic and Caribbean seas and either the Indian Ocean or Scotia Sea — orthogonal with respect to the centroid (located in Africa) of Pangaea will eventually close. We briefly discuss the assumptions behind each of these models and possible tests to distinguish between them using the historical record of supercontinents, geodynamic modelling 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, as it opened up during the breakup of Pangaea. Supercontinent assembly by the closure of the internal ocean, or introversion[7], is essentially where a supercontinent would converge inward on itself, possibly because of incomplete breakup[97] or dispersal, thus, amalgamating in a similar location to the previous supercontinent. The Pacific Ocean, on the other hand, was external to Pangaea and supercontinent assembly by extroversion[186–188] 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 compare introversion and extroversion is the inheritance or the regeneration, respectively, of the circum-supercontinent subduction girdle[97]. The presence of cycles in geochemical data and geologic occurrences that are as long as twice the duration of the supercontinent cycle have been used to argue for a longer period modulation[94], possibly because of alternation between supercontinents formed by introversion and extroversion[97,189].

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[60]. On present Earth, orthoversion would, thus, predict those seas located along the subduction girdle to close, instead of the Pacific or 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[83]. In combination with the antipodal geoid high, a prolate shape of the non-hydrostatic Earth develops, with the minimum inertia axis centred within the supercontinent. Mass anomalies in the mantle related to tectonics and convection induce TPW, which follows a great circle around this minimum inertia axis in order to align the spin axis with the maximum moment of inertia. Identification of TPW migrations about such a minimum moment of inertia axis has been proposed as a method for locating the centre of a supercontinent and appears to support the geodynamics of orthoversion as supercontinent centres shift ~90° in palaeolongitude from one supercontinent to the next[60].

Igneous geochemistry provides a clear test between introversion and extroversion with either Sm–Nd or Hf isotopic evidence[121,190]. Both of these isotopic systems can be used to fingerprint arc magmatic systems dominantly characterized by crustal reworking or mantle-derived magmatism[38,121]. 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[191]. Therefore, introversion would be consistent with evidence for increased crustal reworking owing to single-sided subduction and leading to internal collisional orogens. Alternatively, extroversion would produce increased juvenile, mantle-derived, magmas during double-sided subduction, leading to external collisional orogens[190].

Such contrasting geochemical and isotopic signatures correspond with the contrasting collisional styles of Rodinia and Gondwana (early stage in formation of Pangaea)[121]. It is argued by some researchers that the assembly of Rodinia was 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[121]. Other scientists, however, argue for an opposite scenario where Rodinia formed by introversion, based more on palaeogeographic considerations[97]. Isotopic predictions for orthoversion[60] are less clear, but would likely involve a mixture between the end-member predictions of introversion and extroversion[192].

Proxies and patterns

Although there continues to be considerable debate over their configurations, there is broad consensus on when individual continents assembled and rifted away from each supercontinent (FIG. 1). Irrespective of their configurations (FIG. 1), recurring supercontinent cycles of continental assembly and breakup through time are clearly evident in both geological and geochemical proxies[96]. Furthermore, the same proxies that provide a time series of supercontinent cycles also suggest secular shifts, indicating that the onset of supercontinents was an irreversible state change.

A supercontinent cycle time series. Geological proxies recording supercontinent cycles include the timing and locations of large igneous provinces[82], passive margins[193], orogens[194] and mineral deposits[97]. Igneous geochemistry offers additional insights into supercontinent dynamics by fingerprinting processes such as 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[38,92], as well as the MgO content of plume-derived basalts[195]. 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 considerably increase the volume of supracrustal reworking in the magmatic systems relative to mantle values[196], as has been argued for using Hf isotopes of zircon showing fluctuations between crustal reworking (supercontinent assembly) and mantle-derived magmatism (supercontinent breakup)[37,38].

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[197]. A global compilation[196] of oxygen isotopes in ~15,000 zircons through time includes analyses made by conventional laser fluorination and secondary ion mass spectrometry (Supplementary Data), and was tested here for statistically significant variability using change-point analysis following the technique of REF.[198]. This statistical technique[199] reveals only change points if the null hypothesis of no change (that is, one mean value) can be rejected. The change points are automatically assigned by the outcome of this statistical test. The change-point analysis on oxygen isotopes of zircon reveals 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 towards 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[37,38] and oxygen (FIG. 4) isotopes on well-dated zircons thus establishes a statistical basis for the supercontinent cycle.

A supercontinent state. It is debatable whether the supercontinent cycle existed before ca. 2 Ga. A global cycle of continental assembly and breakup of roughly ~600 Myr might have existed before 2 Ga, but large supercontinents might still have not formed — there is presently no compelling evidence that any pre-Columbia supercontinent existed. Secular change as the planet evolved is one of the possible reasons that supercontinents might not have formed until later in Earth history (BOX 3).

The same proxies used here for a supercontinent cycle time series also suggest that 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; these are oscillating signals in synchronicity with collisional assembly of supercontinents (a supercontinent cycle time series) and a single state shift as the planet evolved from one tectonic regime to another (a supercontinent state). A state shift — a shift from one state to another — can be caused by either a threshold or a sledgehammer effect[200]. An example of a sledgehammer effect is the sudden increase in river discharge because of flooding following a rainstorm. Incremental change that eventually exceeds a particular threshold value is more difficult to detect, but either type of state shift can cause the system to begin to operate within a range of variability outside that of its previous state.

The short-term variations in the $\delta^{18}O$ supercontinent cycle time series do not appear until ca. 2.4 Ga (FIG. 4), that is, immediately after the long-term shift into the modern supercontinent state, as evidenced by the geochemistry of both mafic and felsic rocks (BOX 3). Thus, geochemical proxies depict both supercontinent cycles (rhythms), as well as manifestations of secular change (trends)[195]. Secular change in the crust is thought to be manifest in the growth and emergence of the continents[144]. Evidence of both more crustal volume and more crustal volume above sea level should result in a notable increase (~1‰ $\delta^{18}O$) in supracrustal reworking in the magmatic systems associated with orogenesis[196]. 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 ca. 2.4 Ga is invariant and typified by mantle-like values (FIG. 4). The supercontinent state, thus, likely reflects secular evolution from ancient stagnant-lid and/or mobile-lid tectonics[26,201,202], with

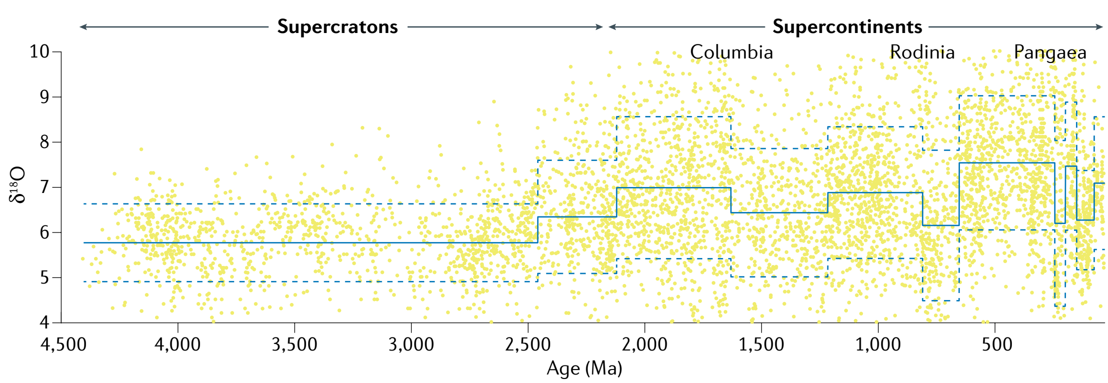


Fig. 4 | **Supercontinent time series.** Oxygen isotopes ($\delta^{18}O$) of zircon can be used as a geochemical proxy of the supercontinent cycle through time. Lower average isotopic values indicate more mantle-derived magmatism (for example, during tectonic rifting) and higher values indicate more crustal reworking (for example, during subduction). Note both higher overall values and cycles initiate in the $\delta^{18}O$ data after 2.5 billion years ago. Note cycles correspond to higher $\delta^{18}O$ during assembly and lower $\delta^{18}O$ during breakup phases of each of the three supercontinent cycles (Pangaea, Rodinia and Columbia). Average isotopic values (solid line) with 1σ uncertainties (dashed lines) were defined using a freely available statistical change-point analysis[199] and suggest a state shift to cyclic variations ca. 2.4 billion years ago (see also BOX 3). Plot has been truncated at 30 Ma because of the sampling of anomalous $\delta^{18}O$ values in neotectonic settings. Data from REF.[196], provided here in Supplementary Data.

Box 3 | Secular change and the supercontinent state

There is now broad consensus in Earth science that the planet has cooled over billions of years of mantle convective heat loss[236,237]. Mafic rocks, for example, exhibit a reduction in Ni content through time, which most likely resulted from less melting of olivine during mantle cooling (see figure). This secular change in the thermodynamics of the mantle is also thought to be broadly linked to the evolution of plate tectonics through time[26]. Felsic rocks, for example, exhibit an increase in the Eu* anomaly[238], which can be interpreted as an increasing subduction signature since 2.5 billion years ago (Ga) (see figure).

During the Archaean, most of the crust was comprised of tonalite–trondhjemite–granodiorite rocks, which could be formed by drip tectonics[239] (that is, delamination or episodic removal of the lithosphere into the convecting mantle) in the absence of plate tectonics[240]. Although early evidence of plate tectonics exists[241], it could have been relatively localized, and evidence of a global plate network is not found until arguably 2 Ga (REF.[23]). 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-lid or sluggish-lid convection[201] (that is, a single-plate regime or one in between tectonic and stagnant-lid end-members, respectively), so the proliferation of plate tectonics might have accelerated secular cooling. Furthermore, as plate tectonics became a global phenomenon and allowed for supercontinent formation[23], large supercontinents likely led to long-wavelength mantle convection. Long-wavelength mantle convection is convectively more efficient in transferring heat than smaller cells, with degree 2 flow representing a heat flow maximum[168], thus, further expediting planetary cooling. Secular trends in igneous rock geochemistry correlate with the transition from ancient supercratons to modern supercontinents (see figure). The three supercontinents since 2 Ga are, thus, arguably a manifestation of this secular change. The apparent sharpness of the state shift is likely affected by its temporal coincidence with the onset of cyclicity at the start of the supercontinent cycle.

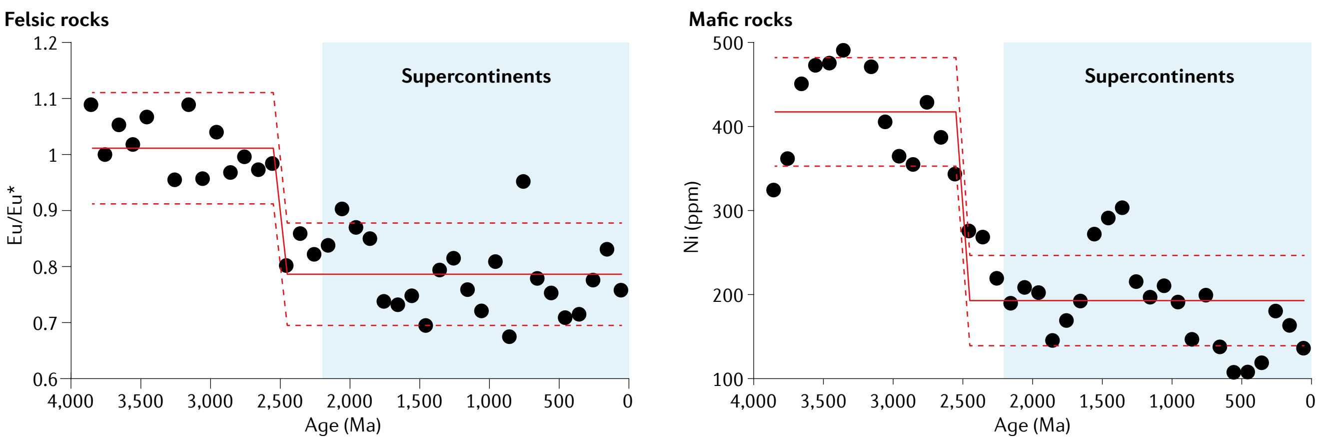


plate tectonics localized to ocean arcs, to the modern global plate tectonic network involving all continents[23,24].

Implications for Earth history

In addition to being an integral part of a linked plate tectonic and mantle convective theory, the supercontinent cycle likely influenced the course of Earth history. It has been hypothesized that a pronounced tectonomagmatic lull 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[203]. Assuming Columbia was Earth's first true supercontinent (FIG. 1), the onset of the supercontinent cycle (FIG. 4; BOX 3) was likely characterized by the appearance and dominance of long-wavelength mantle convection (for example, degree 1 and degree 2 structures; FIGS 2,3). 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 might have been inevitable and irreversible.

A Proterozoic onset (BOX 3) of long-wavelength mantle convection (FIG. 3) would carry implications for the earliest presence of thermochemical piles[204] 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[205]. The compositional origins of the LLSVPs could date as far back as Hadean magma ocean solidification, where crystallization caused the settling of dense particles at the base of the mantle[206]. 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), an outcome that requires the onset of whole-mantle convection in the form of degree 2 flow (FIG. 3b).

The present-day antipodal lower mantle structures appear to have been shaped by circum-supercontinent subduction, where the African LLSVP matches closely the location of supercontinent Pangaea at ca. 200 Ma, ~20 Myr before breakup[52,78] (FIG. 2). An onset of long-wavelength mantle convection associated with supercontinent Columbia might have, thus, organized the previously primordial global layer of dense particles into two antipodal LLSVPs, owing to the dominance of degree 2 mantle convection during supercontinent tenure and breakup (FIG. 3c). Alternatively, it has been 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[75].

It is also possible that compositional heterogeneities in the mantle that resulted from Hadean core–mantle differentiation, identified by short-lived ^{146}Sm–^{142}Nd

Continental freeboard
Mean height of the continental crust relative to mean sea level; also referred to as continental emergence when positive in sign.

isotope systematics[207], could 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 (REF.[208]) are now considered laboratory artifacts[209]. On the other hand, ^{182}W isotopic anomalies are found in young rocks[210] 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[211] or within silica-enriched domains in the lower mantle[212], then this isotopic system could be used to investigate the nature of primordial signatures, rather than the process of their homogenization since Hadean time[213]. A paucity of ^{142}Nd data between 2.7 and 0.8 Ga (REFS[214,215]) presently precludes testing whether the ^{142}Nd Hadean differentiation signature was ultimately obliterated by early Archaean convection and the birth of plate tectonics[29] or by early Proterozoic long-wavelength convection and the birth of the supercontinent cycle (FIG. 4; BOX 3).

Finally, the birth of supercontinents might have influenced Earth's surface evolution[5,6,11–14]. Following the Great Oxidation Event ca. 2.4–2.3 Ga (REF.[216]), the occurrence of repeated episodes of glaciation on some (but not all) cratons[158] and documented on supercraton Superia ca. 2.5–2.2 Ga (REF.[155]), indicates that some continental crust already had positive continental freeboard above sea level[198,217]. Nonetheless, there are as many cratons that do not have evidence for Early Proterozoic glaciation as those that do[158]. The conspicuous absence of such glaciations on many other cratons (for example, Dharwar, São Francisco, Slave, Yilgarn, Zimbabwe) suggests that elevated continental freeboard was arguably not a global phenomenon until the amalgamation of Columbia.

A compilation of burial rates of sedimentary units over the past 4 Gyr shows a state shift decrease between 2.5 and 2.0 Ga (REF.[218]). More continental freeboard came about because of 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 could have flooded the oceans with free ions that might have facilitated widespread biomineralization for the first time, as well as the oldest known eukaryotes[219]. The ca. 1,880 Ma Gunflint microfossils represent the oldest unambiguous example of such widespread biomineralization[220,221]. The oldest abundant aeolianite deposits known in the geologic record occur between 2.1 and 1.7 Ga and thus were deposited during Columbia assembly[222,223]. These deposits can be accounted for by an increase in continental freeboard because of supercontinent formation necessary to source wind-blown sediments.

Summary and future perspectives

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 (REF.[23]) and Earth has experienced three supercontinents[10] since then, in the order of Columbia, Rodinia and Pangaea. Palaeogeographic reconstructions of the three supercontinents over the past 2 Gyr have been refined (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[37,38,82,96,97]. Even though a ~600-Myr period is dominant[37,38], other cyclicities of both longer and shorter periods are present[19,37,94,97] and future research needs to address the degree to which the supercontinent cycle is not simply a single cycle but, potentially, a more complex[224] spectrum of interacting cyclicities. Such cyclic variations arguably have only occurred for the past 2 Gyr since the onset of the supercontinent cycle (FIG. 4), suggesting that modern supercontinents are a manifestation of secular change, such as planetary cooling and tectonic evolution (BOX 3). In addition to the onset of global subduction by 2 Ga (REF.[23]), 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 three supercontinent cycles, as well as results from numerical modelling[73,74,86,165,174,175,225], indicate that supercontinent formation is intimately linked with whole-mantle convection. For Pangaea, lower mantle seismic data indicate that 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[56,63]. Similarly large amplitude TPW has been suggested for the two Proterozoic supercontinents as well[60,64]. 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[51,53,54,56]. Earlier supercontinents also have pronounced LIP emplacement before and during breakup[39,102,106,135,136,226], suggesting that LLSVP-related mantle upwellings existed under these supercontinents as well[76,97].

Continued efforts to reconstruct the palaeogeography of Proterozoic supercontinents Rodinia and Columbia are ongoing and have become 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. Efforts to integrate palaeolongitude[60,78] and full-plate topologies[99] into Proterozoic reconstructions are now being developed and should offer a new means of refining ancient palaeogeography.

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. Although the possibility of an Archaean supercontinent has not been ruled out, no compelling evidence yet exists[158]. The hypothesis of multiple segregated supercratons can better explain the diachroneity of the geological histories of cratons[152] and is more consistent with geodynamic considerations for Archaean time. Acquiring more high-quality, well-dated palaeomagnetic poles across the Archaean–Proterozoic transition from multiple cratons offers the hope of definitively testing an Archean supercontinent versus the supercratons hypothesis.

Despite substantial progress on linking plate tectonic theory and mantle convection, our understanding of supercontinent cycle dynamics is arguably still in its infancy. Mechanisms for both the assembly and the 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 2). Despite a strong correlation, the dynamic link between the two antipodal LLSVPs in the lower mantle and the supercontinent cycles requires further investigation. Why the actual present-day LLSVPs are more elongated and irregular in shape (FIG. 2) than the nearly perfectly circular expressions of mantle upwellings in numerical models (FIG. 3) remains to be explored. The debate persists whether the sub-supercontinent LLSVP existed before Pangaea amalgamated or whether the LLSVP formed as a result of Pangaea assembly. Distinguishing between hypothetical models in which LLSVPs are considered fixed for up to 2 Gyr versus LLSVPs that respond to the supercontinent cycle is a frontier question.

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Author contributions
R.N.M. conceived the idea. N.Z. and B.S. conducted numerical modelling. J.S., Y.L. and Z.-X.L. made palaeogeographic reconstructions. C.J.S. conducted geochemical analyses. J.B.M. coordinated the presentation of the various sections. All authors contributed to the manuscript preparation, interpretation, discussion and writing, led by R.N.M.

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