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The role of megacontinents in the supercontinent cycle

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ABSTRACT

Supercontinent Pangea was preceded by the formation of Gondwana, a "megacontinent" about half the size of Pangea. There is much debate, however, over what role the assembly of the precursor megacontinent played in the Pangean supercontinent cycle. Here we demonstrate that the past three cycles of supercontinent amalgamation were each preceded by ~200 m.y. by the assembly of a megacontinent akin to Gondwana, and that the building of a megacontinent is a geodynamically important precursor to supercontinent amalgamation. The recent assembly of Eurasia is considered as a fourth megacontinent associated with future supercontinent Amasia. We use constraints from seismology of the deep mantle for Eurasia and paleogeography for Gondwana to develop a geodynamic model for megacontinent assembly and subsequent supercontinent amalgamation. As a supercontinent breaks up, a megacontinent assembles along the subduction girdle that encircled it, at a specific location where the downwelling is most intense. The megacontinent then migrates along the girdle where it collides with other continents to form a supercontinent. The geometry of this model is consistent with the kinematic transitions from Rodinia to Gondwana to Pangea.

INTRODUCTION

The supercontinent cycle of continental assembly and breakup has been linked to global-scale orogenesis, mantle convection patterns, and the evolution of climate, the environment, and life (Nance et al., 2014). Three supercontinents are proposed to have formed since 2 Ga: Pangea, Rodinia, and Columbia (Evans, 2013). Today, Earth is in between supercontinent configurations (Pangea in the past, Amasia in the future) (Mitchell et al., 2012), with supercontinent assembly beginning (e.g., Eurasia) while supercontinent breakup is ongoing (e.g., East Africa). Gondwana was a major and early-forming part of supercontinent Pangea (Fig. 1), but its role in the supercontinent cycle remains controversial. Some researchers emphasize the importance of large Gondwana, even referring to it as a supercontinent (Spencer et al., 2013), whereas others interpret Gondwana as only part of the larger Pangea (Doucet et al., 2019).

We present the concept of a "megacontinent" as a geodynamic precursor of supercontinent formation. If continents are rifted pieces of a supercontinent formed during the breakup phase, a megacontinent is viewed as an assembly of multiple continents geodynamically linked to the incipient amalgamation phase of the next supercontinent. The megacontinent becomes a large subset of the next supercontinent, which results from the amalgamation of a majority of continents into one contiguous, long-lived landmass (Evans, 2013). The new term fits in the continental hierarchy: supercontinent (e.g., Pangea) > megacontinent (e.g., Gondwana) > continent (e.g., Africa) > microcontinent (e.g., Japan). We provide evidence for the assembly of megacontinents as precursors to every supercontinent through time. We also offer a conceptual framework for the origin of megacontinents that refines models of the supercontinent cycle.

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MEGACONTINENTS OF EARTH HISTORY

Eurasia in Amasia

Eurasia is presently Earth's largest landmass (Figs. 2 and 3A), containing Siberia, the North China craton, the South China craton, the Tarim craton, India, and many small blocks bounded by multiple orogenic systems that collided with Baltica (and subsequently outboard additions) (Wan et al., 2019). Assembly of Eurasia started with the central Asian orogenic belt that welded Baltica and Siberia at ca. 250 Ma. This assembly overlaps with the tenure and breakup of Pangea and represents an early assembly phase of the proposed future supercontinent Amasia (Mitchell et al., 2012). Following Siberia's assimilation into Pangea, accretion along the eastern margin of Siberia of continental blocks and terranes occurred between 200 and 100 Ma (Torsvik et al., 2012; Wan et al., 2019). Much of Eurasia represents the reassembly of rifted fragments of Gondwana since the Devonian. The sense of plate motion has been meridional, translating rifted pieces of Gondwana from the Southern Hemisphere to assemble in Eurasia in the Northern Hemisphere. With the presently rapid northward migration of Australia and its imminent collision with Eurasia, assembly of the megacontinent is likely ongoing.

Gondwana in Pangea

Gondwana assembled in two sectors: West Gondwana, with the Brasiliano and Pan-African orogens; and East Gondwana, with the East African and Kuunga orogens. The amalgamation of Gondwana was initiated as early as ca. 750 Ma and was fully complete by ca. 520 Ma (Collins and Pisarevsky, 2005). Gondwana formed the southern portion of supercontinent Pangea (Fig. 1). The collision of Gondwana and Laurussia (Laurentia-Baltica-Avalonia) to finally form Pangea at ca. 350 Ma (Torsvik et al., 2012) thus implies that the assembly of megacontinent Gondwana predates amalgamation of supercontinent Pangea by ~170 m.y. (Fig. 2).

Umkondia in Rodinia

The Grenville orogen between eastern Laurentia and, most likely, Amazonia and other

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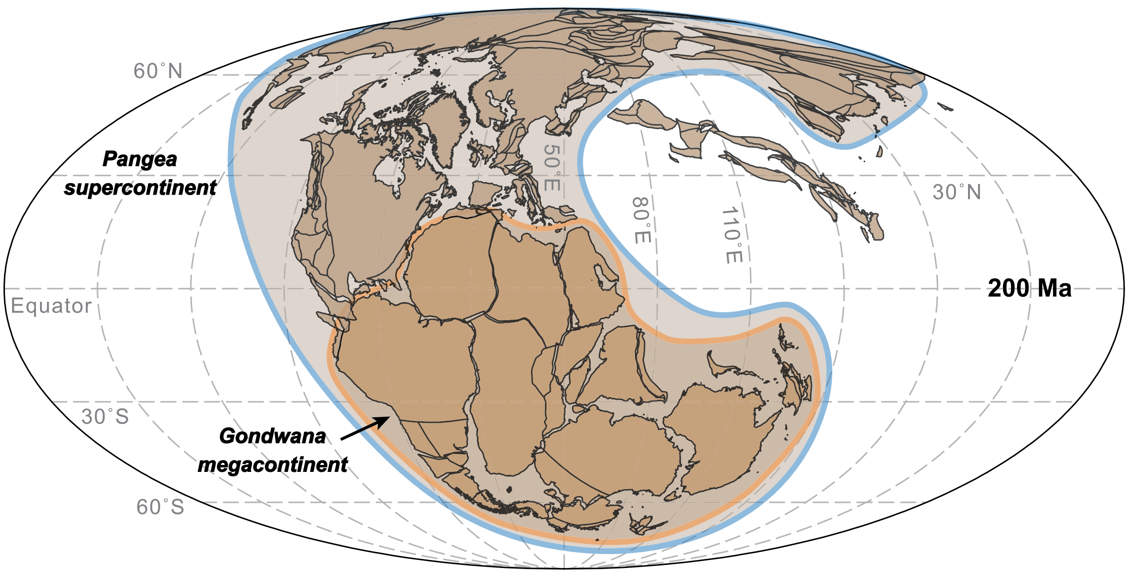

Figure 1. Paleogeographic reconstruction of Pangea before breakup, showing Gondwana megacontinent (orange) in Pangea supercontinent (blue)(Mitchell et al., 2012; Mitchell et al., 2020).

continents did not occur until ca. 1 Ga (Spencer et al., 2013), and Neoproterozoic supercontinent Rodinia was not finally assembled until ca. 900 Ma (Merdith et al., 2017). However, ~100 m.y. before the Grenville collision and ~200 m.y. before Rodinia amalgamation, several continents, including Amazonia, were part of a megacontinent "Umkondia", including the Congo–São Francisco, India, Kalahari, and West Africa cratons, that assembled before 1.1 Ga (Spencer et al., 2017; Choudhary et al., 2019). Thus, assembly of the Umkondia megacontinent began while the breakup of the previous supercontinent was ongoing (Evans and Mitchell, 2011). The case for Umkondia as a pre-Rodinian megacontinent is based on paleomagnetism, geochemistry, and geochronology of a coeval ca. 1.1 Ga large igneous province (Choudhary et al., 2019).

Nuna in Columbia

The existence of a Paleoproterozoic–Mesoproterozoic supercontinent Columbia (a.k.a. Nuna) has been proposed (Zhao et al., 2002; Kirscher et al., 2020). There is debate over its name, and legitimate cases for precedence can be made for either option (Meert, 2012; Evans, 2013). In a possible resolution to this semantic standoff, we refer to the supercontinent as Columbia and to its precursor megacontinent as Nuna because (1) "Columbia" was the name used for the first attempts at global-scale supercontinent reconstruction (Zhao et al., 2002), and (2) Hoffman (1997) used the term "Nuna" (an Inuit word for the lands bordering the northern oceans and seas of North America) to refer to the larger continent of Laurentia, which was suspected to be contiguous with Baltica. Peripheral constituents of supercontinent Columbia such as Australia were sutured by ca. 1.6 Ga, heralding final supercontinent amalgamation (Kirscher et al., 2020). The internal orogens of Laurentia indicate the assembly of the Nuna megacontinent by ca. 1.8 Ga via the Trans-Hudson orogen (Hoffman, 1997) and,

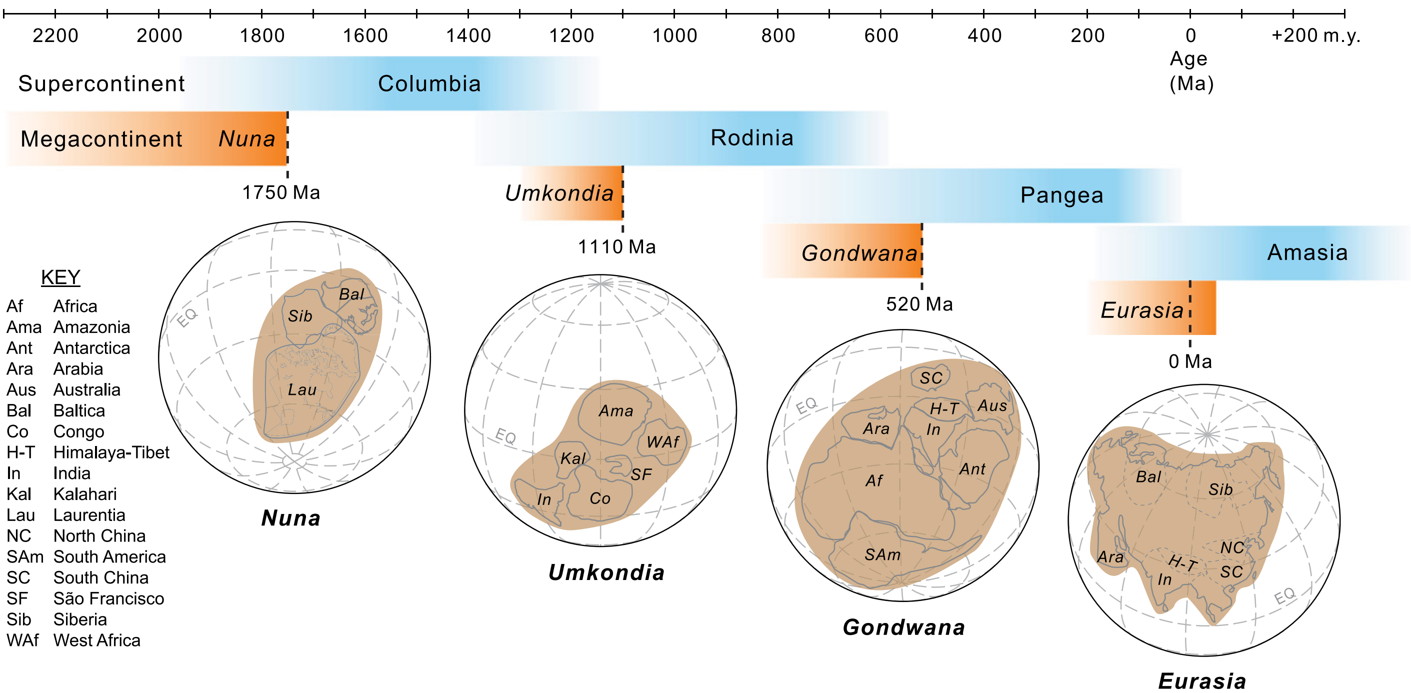

Figure 2. Megacontinents through time. (Top) Timeline of megacontinents and associated supercontinents. (Bottom) Megacontinent reconstructions at age of final assembly (Eurasia at present day). EQ—equator.

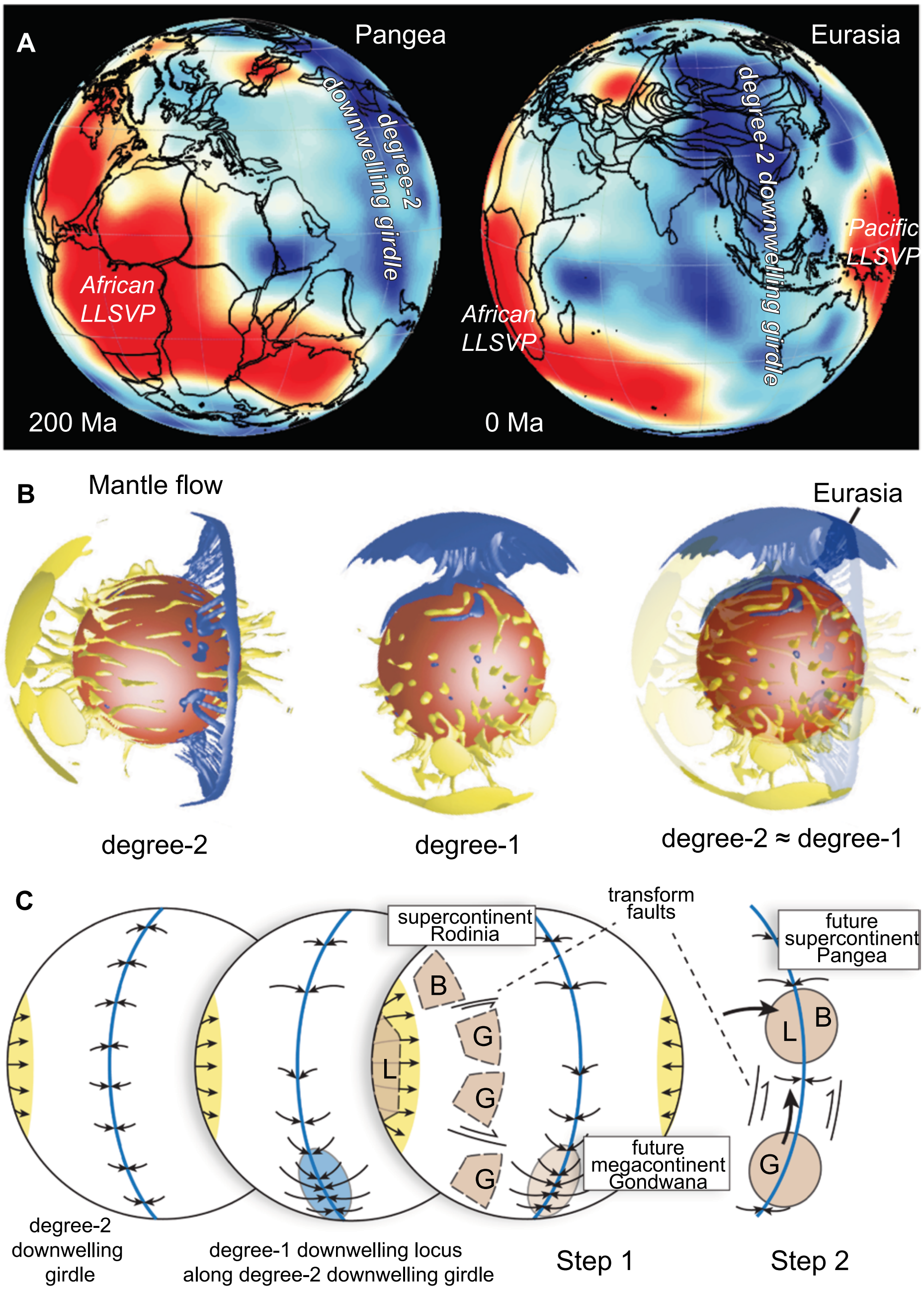

Figure 3. Megacontinent-supercontinent geodynamics. (A) Pangea before breakup, and an enlarging Eurasia since then. Seismic shear-wave velocity is from the *s5mean* model of Doubrovine et al. (2016) at 2800 km depth, where velocities are: red—slow; blue—fast; white—average. Large low-shear-velocity provinces (LLSVPs) of mantle upwelling and bisecting degree-2 downwelling girdle are labeled. (B) Two dominant modes (degree-1 and degree-2) of long-wavelength mantle convection (Zhong et al., 2007). Core is red, mantle downwelling is blue, and upwelling is yellow. When both flow modes are subequal (Conrad et al., 2013), their potential geometric superposition (right) allows a megacontinent to form above the degree-1 locus of downwelling along the degree-2 downwelling girdle. (C) How a megacontinent turns into a supercontinent. Focused degree-1 mantle downwelling occurs along the degree-2 girdle. Step 1 is formation of a megacontinent over the locus of downwelling (small arrows), and step 2 is formation of a supercontinent by convergence of continents (large bold arrows) to/along the downwelling girdle. L—Laurentia; B—Baltica; G—Gondwana.

based on paleomagnetism, Nuna also included Baltica and Siberia with Laurentia (Evans and Mitchell, 2011). Nuna was comparable in size to younger megacontinents, and its assembly predated that of supercontinent Columbia by ~200 m.y. (Fig. 2).

GEODYNAMIC SIGNIFICANCE OF MEGACONTINENTS

The existence of a megacontinent as a precursor to each supercontinent cycle can be identified through time, with the assembly of each megacontinent consistently predating amalgamation of its supercontinent by ~200 m.y. (Fig. 2). During this time interval, a large ocean closed, implying a large initial spatial separation between the megacontinent and the supercontinent. Megacontinent Gondwana, for example, assembled at high southerly latitudes as evidenced by glacial deposits and paleomagnetic data (Caputo and Crowell, 1985), whereas the amalgamation of supercontinent Pangea straddled the equator after the closure of the Rheic and Iapetus Oceans (Torsvik et al., 2012). We calculated megacontinent sizes using the areas of continent and/or craton geographic shape files (Pisarevsky et al., 2014; Torsvik et al., 2014) with GPlates software (https://www.gplates.org/), where Nuna, Umkondia, Gondwana, and Eurasia (including Australia in the future) represent ~6%, 5%, 16%, and 12% of Earth's surface, respectively (Fig. 2). Laurussia covers only <5% of Earth's surface, i.e., less than one-third the size of Gondwana, implying that each supercontinent likely has only one *bona fide* megacontinent. With Pangea covering ~23% of Earth's surface, a megacontinent like Gondwana, therefore, represents more than half (~70%) the size of its supercontinent.

There is a feedback between mantle convection and supercontinent formation. On one hand, continents are modeled to drift "downhill" toward geoidal lows, thus forming a supercontinent over a mantle downwelling (Gurnis, 1988; Zhong et al., 2007). On the other hand, there are several ways in which a supercontinent may promote mantle upwelling beneath it, including, but not limited to (1) thermal insulation due to the inefficiency of heat transfer of thick, stagnant continental lithosphere (Lenardic et al., 2011); (2) cold slab material no longer cooling the mantle beneath the supercontinent (Coltice et al., 2007; Lenardic et al., 2011); and (3) reorganization of mantle convective flow into a circum-supercontinent girdle of downwelling (e.g., the modern subduction "ring of fire") and coaxial supercontinent–superocean upwellings (Zhong et al., 2007; Li and Zhong, 2009). The two antipodal upwellings are each linked to equatorial large low-shear-velocity provinces (LLSVPs; the African and the Pacific) in the lower mantle and are a testament to the dominance of degree-2 mantle flow (two antipodal upwellings bisected by the girdle of downwelling) on modern Earth since at least 300 m.y. ago (Zhong et al., 2007; Torsvik et al., 2012). The shape and location of the African LLSVP closely correlates with the location of supercontinent Pangea before breakup (Mitchell et al., 2020) (Fig. 3A). It has been hypothesized (Li and Zhong, 2009) that the supercontinent cycle alternates between the dominance of degree-2 mantle flow during supercontinent tenure and breakup and degree-1 flow during supercontinent formation (one upwelling and one downwelling) (Fig. 3B). Patterns in global plate motions that are coupled to mantle flow through basal tractions indicate the predominance of degree-1 flow both before and after degree-2 flow predominated between 240 and 60 Ma (Conrad et al., 2013).

Although either degree-1 or degree-2 flow may predominate at any given time, both harmonics of mantle convection occur simultaneously (Fig. 3B). For example, where degree-1 and degree-2 flow planforms interfere, this superposition would focus a zone of most intense downwelling at the degree-1 locus of downwelling along the degree-2 girdle (Fig. 3C). In our model, the location of most intense downwelling along the girdle occurs where subduction is located at a 90° angle from the pole of rotation (hence, the greatest rate of subduction) of the lower (moving) plate. Such a situation occurs today as continents aggregate over mantle downwelling in the northern Indian Ocean and in south-central Asia (Replumaz et al., 2004; Conrad et al., 2013) along the degree-2 Pacific girdle. The formation of Eurasia as a megacontinent is located where mantle downwelling is most pronounced along the degree-2 girdle (Figs. 3A and 3B). The 47 Ma and present-day Euler poles for India and Australia, respectively, are both located in the Pacific LLSVP and 113° and 73° away from their respective continents (Fig. S1 in the Supplemental Material[1]), yielding an average of 93° that indicates meridional subduction along the degree-2 downwelling girdle. Thus, zones of most intense downwelling along the degree-2 girdle may reflect variable rates of subduction, as expressed by distance from the Euler pole of rotation in the subducting plate. In this scenario, the megacontinent (i.e., Gondwana) would assemble over a concentrated locus of downwelling along the girdle ~90° from the pole of rotation (Fig. 3C). As plate spin is negligible (Olson and Bercovici, 1991), all continents at a high angle to the pole of rotation would migrate toward the girdle with no net relative rotation between them, and the margins that collide would be the same ones that faced one another when they drifted apart, consistent with the Wilson cycle model (Wilson, 1966; Replumaz et al., 2004) and the observation of "strange attractors" (Meert, 2014).

As the megacontinent (Gondwana) forms, however, the intensity of local downwelling progressively diminishes due to return flow and subcontinental insulation (Coltice et al., 2007; Zhong et al., 2007), thus generating plumes along its margins, and potentially slab rollback (both observed in early Paleozoic Gondwana). The downwelling beneath the megacontinent diminishes so that it becomes less intense than elsewhere along the girdle. However, because it remains trapped along the girdle by the flanking LLSVPs, the megacontinent migrates along the girdle until it collides with the other continents that have finally migrated there (i.e., Laurussia), thus culminating in Pangea (Fig. 3C). The largely longitudinal motion of equatorial Laurussia throughout Paleozoic time that closed the Rheic and Iapetus Oceans was achieved by a subpolar Euler pole of rotation (Mitchell et al., 2012; Torsvik et al., 2012), implying that the next intense downwelling was located 90° from, and along the same great circle as, the downwelling associated with Gondwana assembly. Mantle convective modeling may be able to explore whether such an orthogonal migration of downwelling loci along the girdle is coincidental or a theoretical expectation. Given our hypothesized relationship of a megacontinent with the pole of rotation, having more than one megacontinent per cycle is unlikely. When the downwelling beneath Pangea evolved into an upwelling, forming or reinforcing the African LLSVP, degree-2 convection reached maximum dominance again during supercontinent breakup (Conrad et al., 2013). Following such a dispersal of the continents to their modern locations along the girdle, future migration along the girdle would close the Scotia, Caribbean, and Arctic oceans as envisioned in the amalgamation by orthoversion of future supercontinent Amasia (Mitchell et al., 2012).

If the assembly of megacontinents is geodynamically distinct from the amalgamation of supercontinents, then the two tectonic processes should generate contrasting proxy signals. The assembly of megacontinents is generally associated with negative ε_{Hf} values of zircon (Fig. 4), indicating their assembly was accompanied by the significant crustal reworking that characterizes Tethyan-style collisional orogens. By contrast, positive ε_{Hf} values reflect the reworking of juvenile crust, as is typical of collisions between continents flanked by circum-Pacific–style accretionary orogens (Spencer et al., 2013). Although megacontinents Nuna and Gondwana have pronounced ε_{Hf} troughs of crustal reworking, that of Umkondia is comparatively very muted. Strikingly, this exception is consistent with myriad geologic proxies that suggest the assembly of Rodinia was distinct from that of supercontinents before and after it (Liu et al., 2017). If each supercontinent was preceded by a megacontinent, it follows that the oldest supercontinent was preceded by an evolution from supercraton (Bleeker, 2003) to megacontinent and then to supercontinent (Fig. 4). The geodynamic driver of that process, possibly the final global linking of the modern plate tectonic network (Wan et al., 2020), may signal a significant reorganization of mantle convection at ca. 2 Ga.

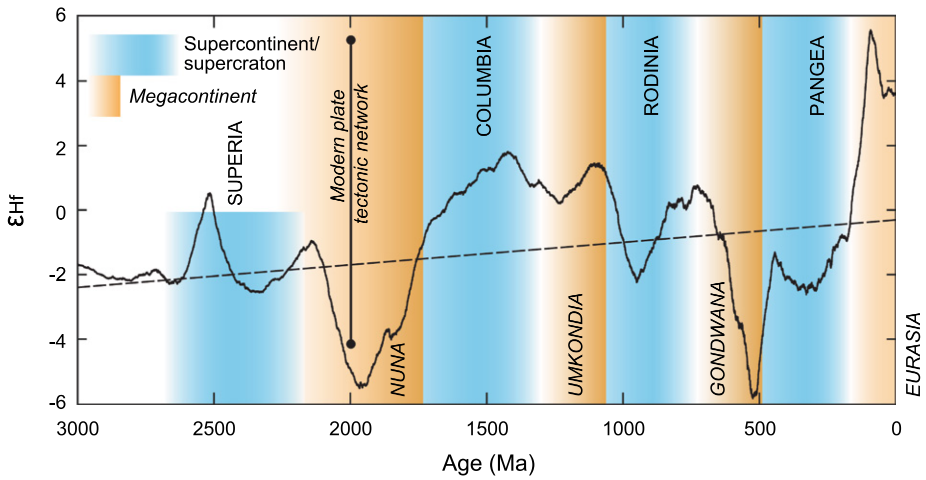

Figure 4. Correspondence between megacontinents and orogenic magmatism. Megacontinents are generally associated with increased crustal reworking. Hf isotopes of zircon (ε_{Hf}) are shown as a 2000-point moving average (Puetz and Condie, 2019). Dashed line is linear regression of the ε_{Hf} data. Archean supercratons (e.g., Superia) are thought to be segregated and small landmasses, unlike Proterozoic-Phanerozoic supercontinents, with the global plate network linking up between the supercratons–supercontinent transition (Wan et al., 2020).

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[1]Supplemental Material. Supplemental Figure S1 and references providing the distance of continents from their Euler poles of rotation in the assembly of Eurasia. Please visit https://doi.org/10.1130/GEOL.S.13232336 to access the supplemental material, and contact editing@geosociety.org with any questions.

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