The supercontinent cycle: A retrospective essay

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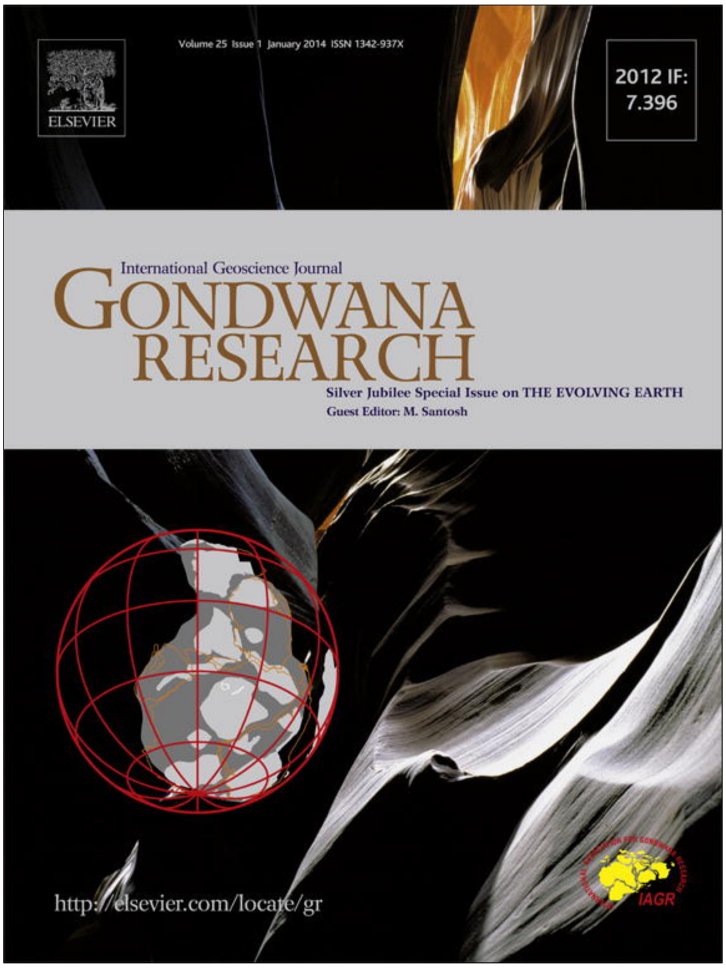

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The supercontinent cycle: A retrospective essay

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ABSTRACT

The recognition that Earth history has been punctuated by supercontinents, the assembly and breakup of which have profoundly influenced the evolution of the geosphere, hydrosphere, atmosphere and biosphere, is arguably the most important development in Earth Science since the advent of plate tectonics. But whereas the widespread recognition of the importance of supercontinents is quite recent, the concept of a supercontinent cycle is not new and advocacy of episodicity in tectonic processes predates plate tectonics. In order to give current deliberations on the supercontinent cycle some historical perspective, we trace the development of ideas concerning long-term episodicity in tectonic processes from early views on episodic orogeny and continental crust formation, such as those embodied in the chelogenic cycle, through the first realization that such episodicity was the manifestation of the cyclic assembly and breakup of supercontinents, to the surge in interest in supercontinent reconstructions. We then chronicle some of the key contributions that led to the cycle's widespread recognition and the rapidly expanding developments of the past ten years.

Contents

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1. Introduction

Over the past two decades, data from a wide variety of sources have led to the general realization that Wegener's Pangea, rather than being the Earth's only supercontinent (Fig. 1), is simply the most recent in a series of supercontinents that have punctuated Earth history for billions of years (e.g., Rogers and Santosh, 2002, 2003, 2004; Murphy and Nance, 2003, 2012; Santosh and Zhao, 2009; Condie, 2011; Yoshida and Santosh, 2011a; Huston et al., 2012; Mitchell et al., 2012). This history of episodic supercontinent assembly and breakup, which constitutes the supercontinent cycle, is now recognized as having profoundly influenced the course of the Earth's geologic, climatic, and biological evolution (e.g., Hoffman et al., 1998; Hoffman and Schrag, 2002; Lindsay and Brasier, 2002; Dewey, 2007; Condie et al., 2009, 2011; Goldfarb et al., 2010; Hawkesworth et al., 2010; Santosh, 2010a, 2010b, 2010c; Bradley, 2011; Hannisdal and Peters, 2011; Strand, 2012; Young, 2012, 2013a, 2013b; Melezhik et al., 2013). Its existence documents a fundamental aspect of the Earth's dynamic system (e.g., Condie, 2003, 2011; Evans, 2003; Zhong et al., 2007; Santosh et al., 2009a; Zhang et al., 2009) and its recognition is arguably the most important development in Earth Science since the introduction of plate tectonics over 40 years ago.

Sometimes overlooked in the pursuit of this exciting realization is the long history that led to its development. Although the widespread recognition of the importance of supercontinents in Earth history is quite recent, the concept of a supercontinent cycle is not new and the notion of episodicity in tectonic processes predates plate tectonics. In this paper, we attempt to give the rapidly expanding recognition of the episodic recurrence of supercontinents some historical perspective. We do so by tracing the history of the supercontinent cycle from its controversial introduction in the early 1980s, through its increasing application in the 1990s, to its widespread acceptance in the first decade of the 21st century.

2. Early ideas

2.1. Tectonic episodicity

Advocacy of long-term episodicity in tectonic processes is by no means new and was being expressed long before plate tectonics and an understanding of mantle dynamics provided the potential for its explanation. One of the most prescient of these early advocates was Umbgrove (1940, 1947) who argued for the existence of a ~250 m.y. "pulse" in Phanerozoic orogeny, magmatism, sea level and climate (Fig. 2). The notion of episodic orogenic activity was subsequently advocated in several early treatments of Precambrian fold belts (e.g., Holmes, 1951; Wilson et al., 1960; Burwash, 1969), and the idea that continental crust formation was likewise episodic was proposed by Holmes (1954) and further developed by Gastil (1960), who argued on the basis of age data that the geologic record of granite production was intermittent rather than continuous. Episodicity in tectonic processes is also inherent in the cratonic sequences documented by Sloss (1963), it was recognized in early radiometric age compilations (e.g., Voitkevich, 1958; Vinogradov and Tugarinov, 1962; Runcorn, 1962, 1965; Dearnly, 1966; Fig. 3), and it lay at the center of Sutton's (1963) argument for the existence of "chelogenic cycles", or global-scale shield-forming events. It was also inherent in Wilson's (1966) case for the repeated opening and closure of ocean basins now known as "Wilson cycles". However, unlike the well-known Wilson cycle, which pertains to individual oceans, Sutton's now-largely forgotten chelogenic cycle called for the episodic clustering of continents through changes in the pattern of subcontinental mantle convection. Rather than producing a supercontinent, however, the chelogenic cycle resulted in the periodic recurrence of two antipodal continental clusters, the assembly and disruption of which were responsible for the record of orogenic episodicity. The cycle was thought to occur because small subcontinental convection cells first resulted in continental clustering and orogeny in continental interiors, but then coalesced into larger cells that fostered continental breakup, orogenic quiescence, and the later regrouping of the disrupted continental masses into two new antipodal clusters. According to Sutton, the chelogenic cycle had a periodicity of 750–1250 m.y. and had been repeated at least four times during the geologic history of the Earth.

Following the introduction of plate tectonics, recognition of the process of ocean closure by subduction provided an explanation for orogenesis and crustal growth (e.g., Dewey, 1969), the episodic natures of which were confirmed by increasingly precise radiometric ages (e.g., Condie, 1976, 1982; Fig. 4) (see also Fig. 3), the pattern of Phanerozoic sedimentary cycling (Mackenzie and Pigott, 1981), and the distribution of ore-forming processes through time (Meyer, 1981, 1988). The concept

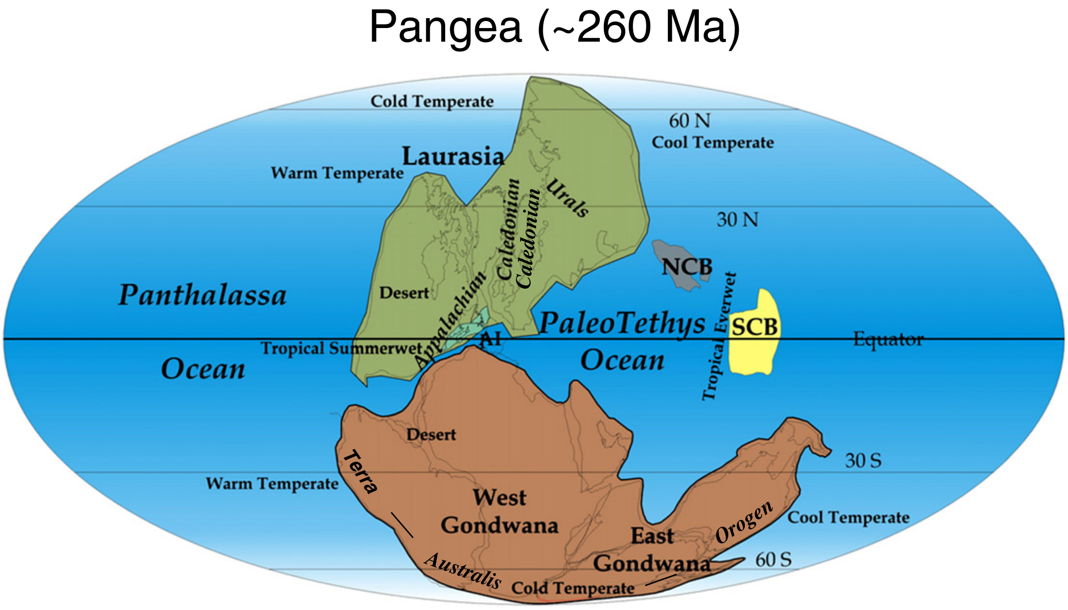


Fig. 1. The Late Paleozoic supercontinent Pangea at ca. 260 Ma, showing its two main components, Gondwana (south) and Laurasia (north), separated by the PaleoTethys ocean and surrounded by the Panthalassa. NCB = North China Block, SCB = South China Block, and AI = Armorica, Avalonia and Iberia. Modified from Meert (2012).

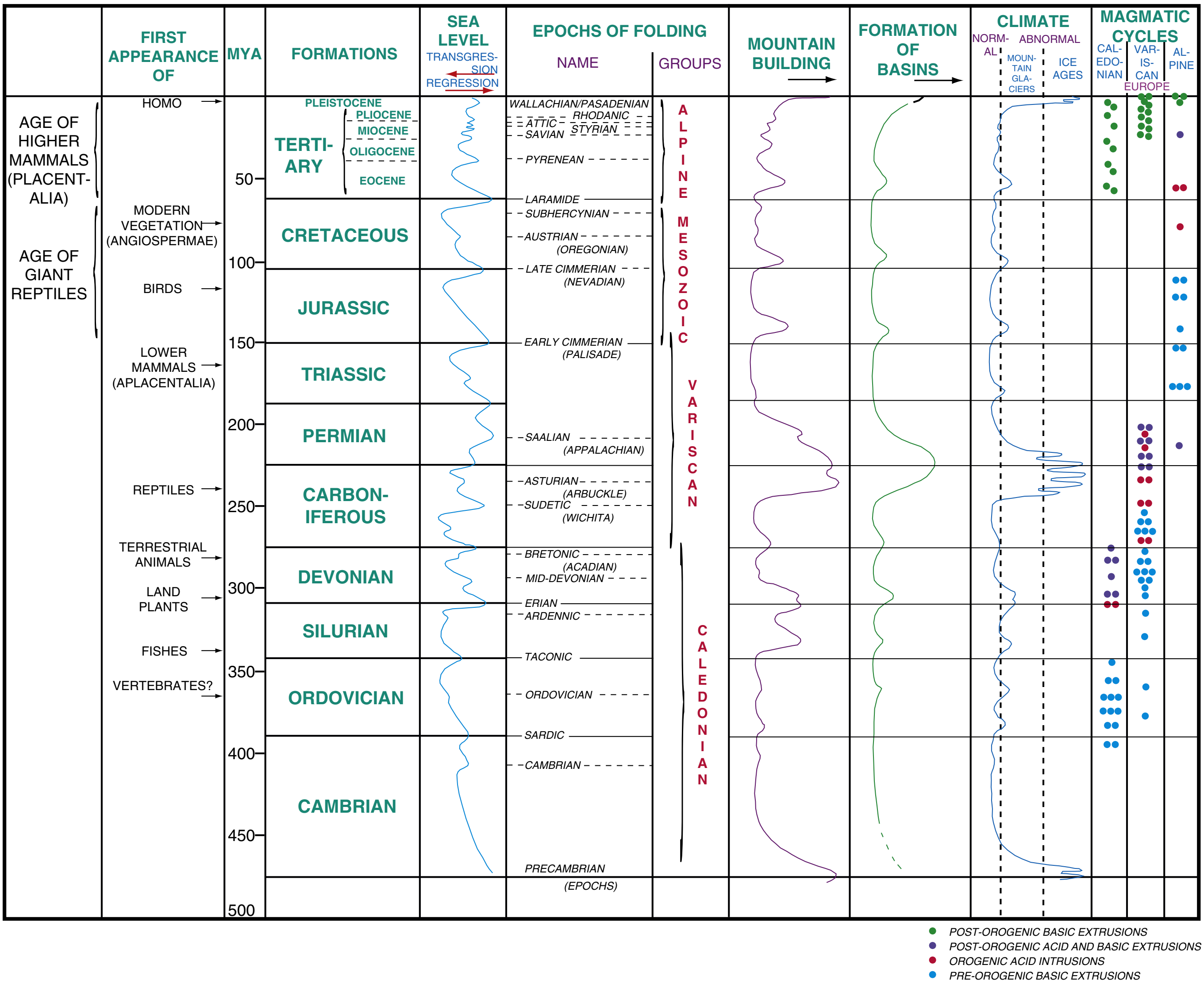


Fig. 2. Summary of Umbgrove's (1947) ~250 m.y. "pulses" in the Phanerozoic history of sea level, mountain building, basin formation, climate and magmatic activity.

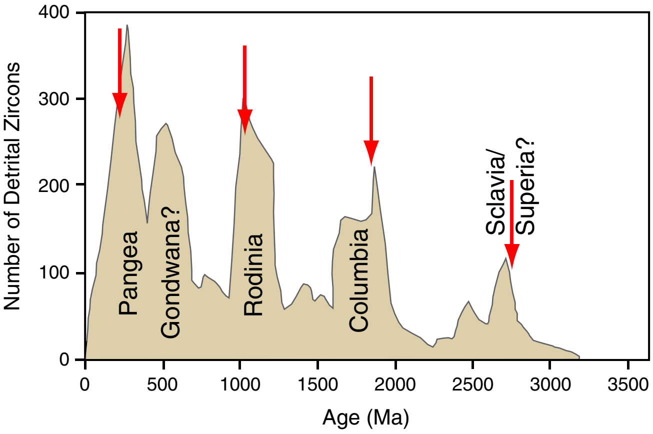


Fig. 3. Comparison of orogenic peaks (arrows) recognized in radiometric data by Runcorn (1962) with spectra of U–Pb detrital zircon crystallization ages reported by Hawkesworth et al. (2010) and proposed times of supercontinent assembly. Modified from Meert (2012).

of tectonic cycles was specifically advocated by Valentine and Moores (1970) and Hallam (1974) with regard to evolutionary biogenesis, and by Fischer (1981, 1984), who revived Umgove's (1947) model in a plate tectonic context by arguing for two ~300 m.y. supercycles in the Phanerozoic record of climate, sea level and granitoid magmatism (Fig. 5).

2.2. The supercontinent cycle

That this long-recognized history of episodicity in tectonic processes was the manifestation of a long-term cycle of supercontinent assembly and breakup was first proposed by Worsley et al. (1982, 1984). Since the assembly of supercontinents requires continents to collide, whereas supercontinent breakup requires them to rift, Worsley et al. (1982, 1984) argued that the existence of a supercontinent cycle would be manifest in the geologic record by episodic peaks in collisional orogenesis and rift-related mafic dike swarms. Using the available (largely Rb/Sr and K/Ar; see Fig. 4) geochonological data base, as summarized by Condie (1976, 1982), Windley (1977, 1984) and others, they suggested that such peaks could be recognized and that global episodes of orogenic activity lagged slightly by mafic

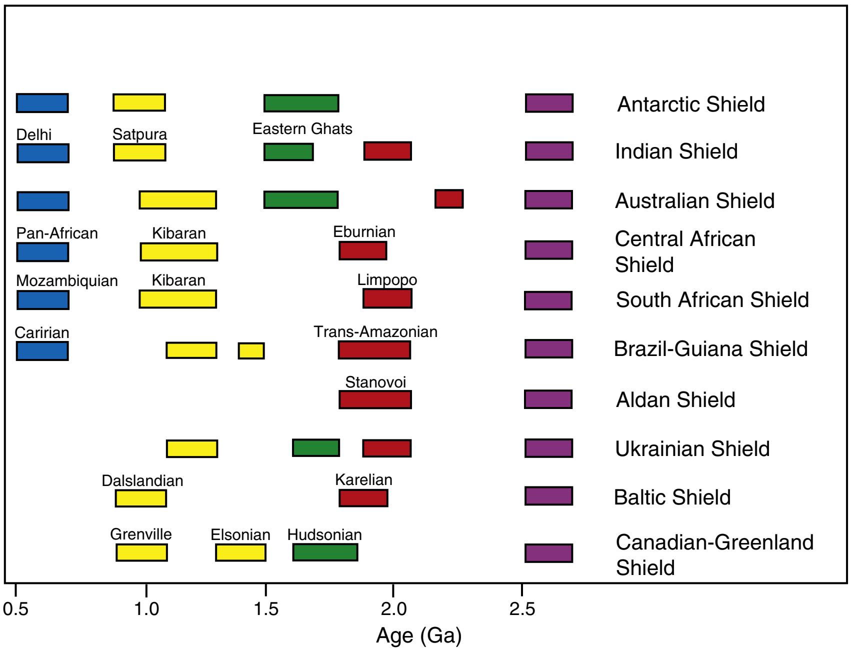


Fig. 4. Compilation of radiometric ages (largely Rb/Sr) for periods of major orogenesis in Earth history. These data were taken by Worsley et al. (1984) to document the episodic ("quasi-periodic") assembly of supercontinents. After Condie (1976, 1982).

dike swarms had punctuated Earth history at quasi-periodic intervals of ~500 m.y. for at least the past 2.0 billion years (Fig. 6). Based on these data, they predicted the existence of four, and later five (Worsley et al., 1985; see Fig. 8), pre-Pangean supercontinents at ca. 0.6, 1.1, 1.8–1.6, 2.0 and 2.6 Ga, four of which are now recognized as corresponding to the amalgamation of Pannotia (Gondwana), Rodinia, Columbia (or Nuna) and Kenorland (Superia and Sclavia).

For the Phanerozoic, Worsley et al. (1984) modeled the effect of such a supercontinent cycle on global sea level (Fig. 7) by assuming modern spreading rates and by applying Parsons and Sclater's (1971) age-versus-depth relation for oceanic lithosphere (modified to an ice-free world) to Berger and Winterer's (1974) calculations for the average age of the world's ocean floor as a function of the breakup of Pangea. They were able to broadly quantify the changes in global sea level (as defined by the average water depth at the world shelf break) that would be caused by the cycle's effect on ocean basin volume and continental area. Their calculations (like those of Heller and Angevine, 1985) suggested that the crustal

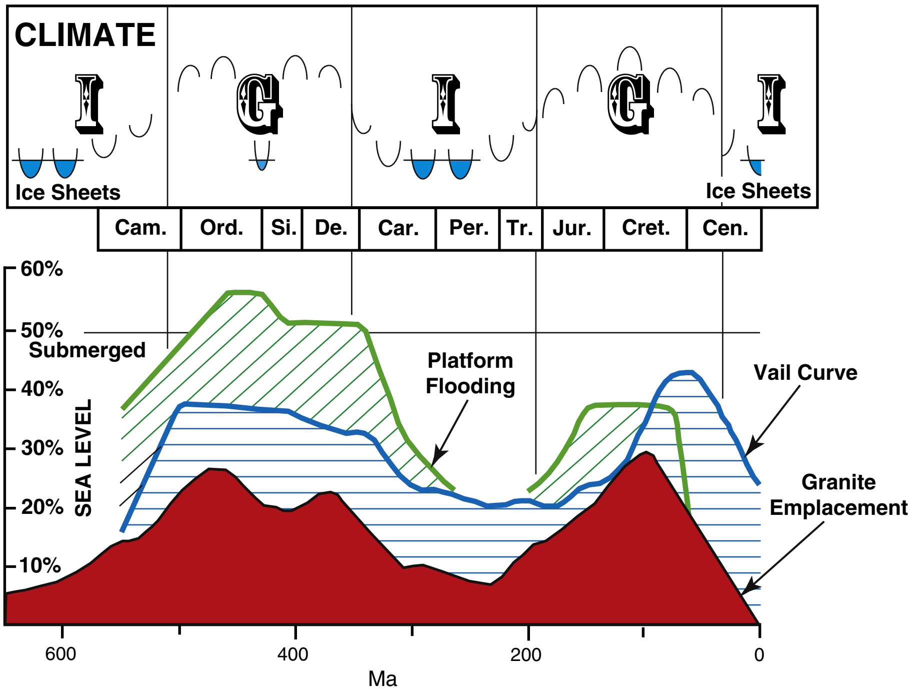


Fig. 5. Outline of the two ~300 m.y. supercycles of Fischer (1981, 1984) in the Phanerozoic record of climate, sea level and granitoid magmatism. After Vail et al. (1977) and Engel and Engel (1964).

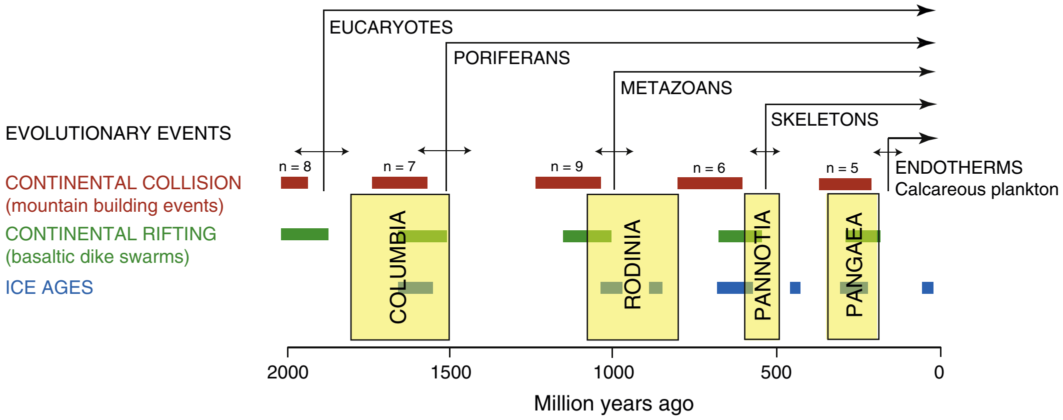


Fig. 6. Summary of episodic events in Earth History linked to the supercontinent cycle by Worsley et al. (1984, 1985). Yellow blocks show duration of supercontinents as presently known. Orogenic peaks (supercontinent assembly) from Condie (1976, 1982), lagging mafic dike swarms (supercontinent breakup) from Windley (1977), major evolutionary events from Cloud (1968a, 1968b, 1976)), and major glacial intervals from Frakes (1979) and Christie-Blick (1982).

extension and the creation of young ocean basins associated with supercontinent breakup would first cause sea level to rise rapidly, only to fall as the new oceans aged. During supercontinent assembly, on the other hand, subduction of old ocean floor combined with orogenic crustal shortening would cause sea level to rise again.

Drawing on the observation of Anderson (1982) that continental lithosphere, because of its thickness and radioisotope-enriched crust, should act as a thermal insulator to mantle heat flow, Worsley et al. (1984) further argued that supercontinents would become epeirogenically uplifted as heat accumulated beneath them, particularly if their size and peripheral subduction systems rendered them largely stationary. They suggested a minimum figure of 400 m for this thermal uplift based on available data (e.g., Hay and Southam, 1977; Harrison et al., 1981) for the present day ice-free shelf-break elevation of near-stationary Africa (200 m above sea level) relative to the global average (200 m below sea level). Modern estimates (e.g., Zhang et al., 2011) broadly support this figure.

Combining the independent effects of sea floor elevation on ocean basin volume and epeirogenic uplift on continental platform elevation, Worsley et al. (1982, 1984) showed that predicted water depths at the shelf break closely matched first-order Phanerozoic sea level change (Vail et al., 1977) to define a Phanerozoic supercontinent cycle of ~440 m.y. duration (Fig. 8). Subsequent changes to the geological time scale would reduce this figure by some 20 m.y. Later treatments (Hallam, 1992) and more sophisticated calculations using contemporary data (Cogné and Humler, 2008) broadly confirm these observations, a further implication of which is the assembly of a future supercontinent in about 150 m.y.

Worsley et al. (1985, 1986) and Nance et al. (1986, 1988) subsequently explored the supercontinent cycle's potential influence on the Earth's tectonic, biogeochemical and paleoceanographic record (Fig. 9). Subdividing the cycle into four phases – supercontinental stasis, fragmentation, maximum dispersal, and assembly – they suggested a variety of trends in tectonic activity, platform sedimentation, climate, life, and the stable isotope record that would be expected to accompany each phase.

Among these they argued that, during the lifespan of a supercontinent, tectonic activity would be dominated by epeirogenic uplift as

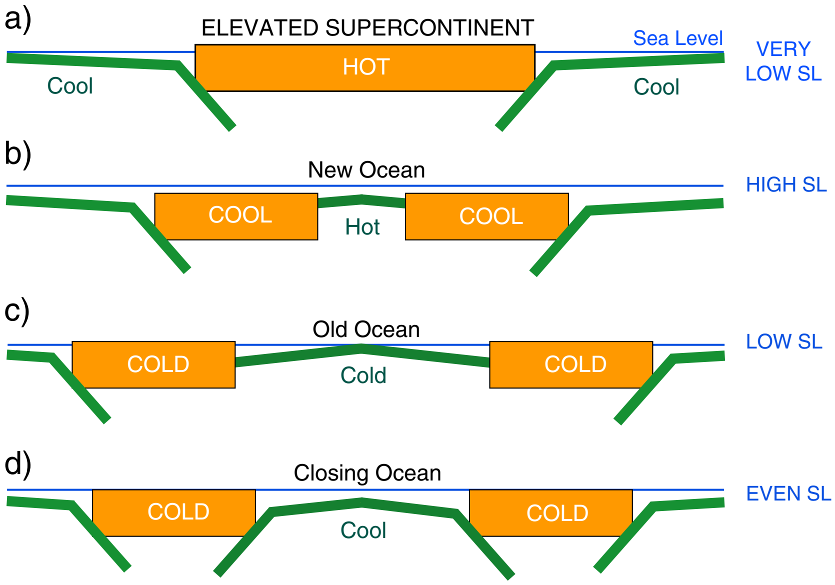


Fig. 7. Effect of the supercontinent cycle on sea level. (a) Supercontinents are epeirogenically elevated and so correspond to periods of low sea level. (b) When they break up, the resulting continental fragments cool and subside as they separate so that level rises. (c) In addition, new oceans are created at the expense of older ones. Since the new oceans are floored by young, hot, shallow crust, they cannot accommodate as much seawater as the older oceans they replace so that sea level continues rises. (d) But as these oceans get older and colder, they become deeper, causing sea levels to fall until the oceans start to close.

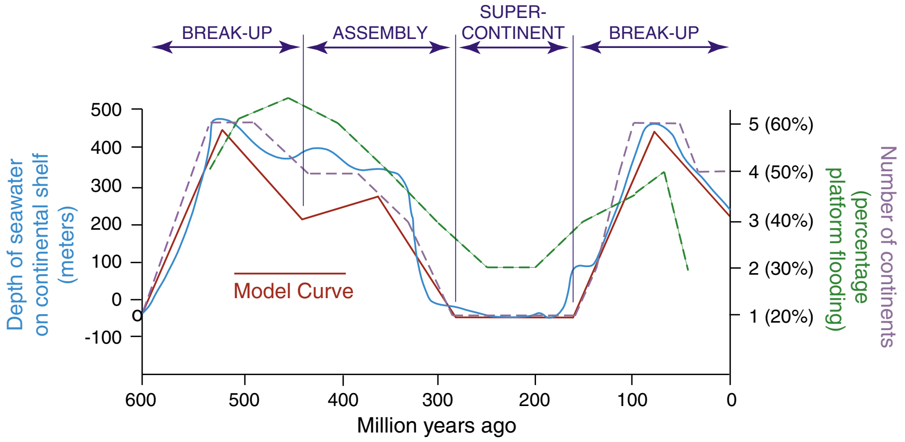


Fig. 8. Comparison of the calculated effect of the supercontinent cycle (rift, dispersal, assembly, Pangea) on sea level (Worsley et al., 1982, 1984) with first-order eustasy (Vail et al., 1977), the degree of platform flooding (Hallam, 1981) and the number of continents (Ziegler et al., 1979; Bambach et al., 1980; Barron et al., 1980) during the Phanerozoic. After Worsley et al. (1982, 1984).

trapped mantle heat accumulated beneath the largely stationary supercontinent, ultimately manifesting as hotspot activity contributory to fragmentation. Accretionary orogeny and the opening of back-arc basins might be expected along the margins of the Panthalassic (or "exterior"; Murphy and Nance, 2003) ocean, now at its largest size, and, with sea level at its lowest elevation, the production and preservation of terrestrial deposits should be enhanced while that of marine sediments is diminished. As a result, the sequestering of isotopically light carbon in non-marine and organic-rich sediments, and heavy sulfur in evaporites, could be expected to produce a record of low δ^{13}C and δ^{34}S in the reciprocal marine platform reservoir like that already documented for Pangea (e.g., Veizer et al., 1980; MacKenzie and Pigott, 1981). In addition, massive extinctions would be expected to accompany the loss of shallow marine habitat, and cold climates should develop (potentially leading to continental glaciation) as CO_2 is removed from the atmosphere by the weathering of large areas of subaerially exposed continental crust.

During supercontinent fragmentation, Worsley et al. (1985, 1986) and Nance et al. (1986) argued that younging of the world ocean floor through rifting and the opening of new ("interior"; Murphy and Nance, 2003) ocean basins, coupled with subsidence of the dispersing continental fragments, should raise sea level to a maximum elevation. At the same time, the incidence of collisional orogeny would be minimal (although accretionary orogeny might be expected on the exterior ocean margins), rapid biotic diversification and enhanced preservation of platform sediments with increasingly high values of δ^{13}C and δ^{34}S should accompany massive marine transgression, and warm, equable climates should develop as continental drowning allows atmospheric CO_2 levels to build.

According to their model, the world ocean floor is oldest at maximum continental dispersal (today's world), at which time they contend that sea level would be low once again and emergent polar continents could be glaciated. Finally, during supercontinent assembly, they argued that collisional orogenesis should increase to a maximum, global sea level should first rise and then fall as subduction consumes first the old and then the young floor of the interior oceans (opening and then closing back-basins along their margins), active margin sedimentation would increase, and atmospheric CO_2 levels should decline and cause global climates to deteriorate. Although data in support of these proposed influences were limited at the time, many have since been borne out by subsequent analyses of the contemporary database on secular trends in the geologic record (e.g., Veizer and MacKenzie, 2003; Condie, 2005; Bradley, 2011; Young, 2012, 2013a, 2013b; Eriksson et al., 2013).

With regard to a driving force for the supercontinent cycle, Worsley et al. (1984) suggested that one might be provided by the counteracting influences of the thermal insulating effect of continental lithosphere on terrestrial heat flow (Jordan, 1975; Anderson, 1982) and the cooling effect of age on the buoyancy of oceanic lithosphere (e.g., Hynes, 1982). They argued that, whereas the former might be expected to lead to the eventual breakup of supercontinents because of their size and likelihood of being near-stationary, the latter might be expected to result in the formation of supercontinents since it ensured that the new oceans created by supercontinent breakup would eventually close. This mechanism was subsequently modeled for supercontinent breakup and assembly by Gurnis (1988). However, in this model (and most subsequent numerical and kinematic treatments: e.g., Zhong and Gurnis, 1993; Duncan and Turcotte, 1994; Trubitsyn and Rykov, 1995), it is the Panthalassa-like exterior ocean that closes to reassemble a supercontinent, rather than the interior oceans postulated by Worsley et al. (1984).

This discrepancy highlights a fundamental uncertainty in our understanding of the process of supercontinent amalgamation that has yet to be resolved. Murphy and Nance (2003) subsequently introduced the terms "extroversion" (closure of the exterior ocean) and "introversion" (closure of the interior oceans) to refer to the two end-member paths by which supercontinents might assemble, and suggested that both may have been involved in the assembly of past supercontinents. To these, Mitchell et al. (2012) recently added a modified form of introversion they termed "orthoversion," in which a supercontinent forms at ninety degrees to its predecessor on the great circle of the precursor's encircling subduction system. However, as pointed out by Murphy and Nance (2008), a paradox exists between the outcome of geodynamic modeling, most of which results in extroversion, and the well-documented assembly of Pangea, which was the result of introversion and the closure of the interior Iapetus and Rheic oceans. Worsley et al. (1984) had based their argument on the history of Pangea.

2.3. Indications of pre-Pangean supercontinents

Worsley et al. (1982, 1984) were not the first to suggest that supercontinents had formed prior to Pangea. For example, the existence of a single supercontinent during much of the Proterozoic had been proposed on the basis of paleomagnetic data (Piper, 1974, 1982; Piper et al., 1976), although the evidence was disputed (McGlynn et al., 1975; Van der Voo and Meert, 1991), and a case had been made for the breakup of a Neoproterozoic supercontinent, also proposed on the basis of paleomagnetic data (Morel and Irving, 1978;

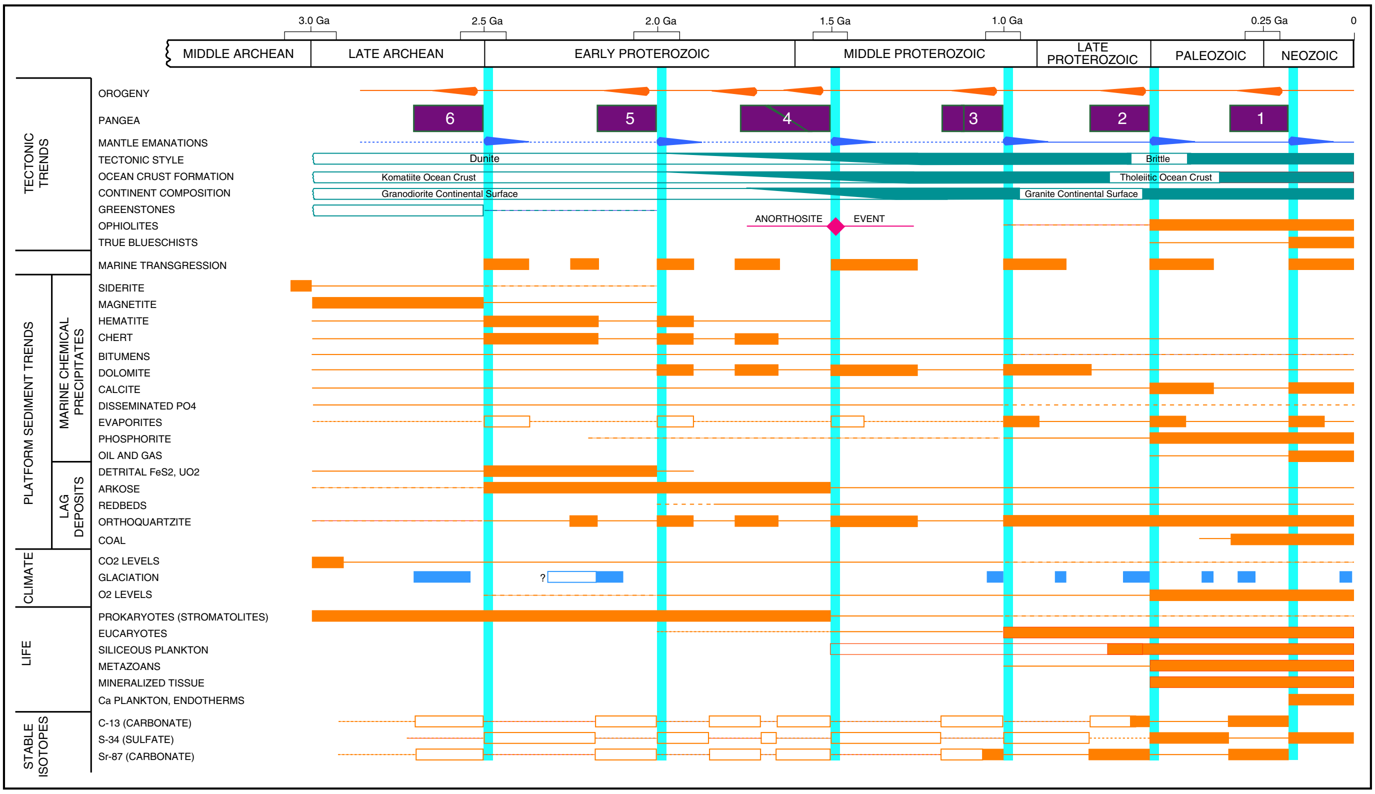
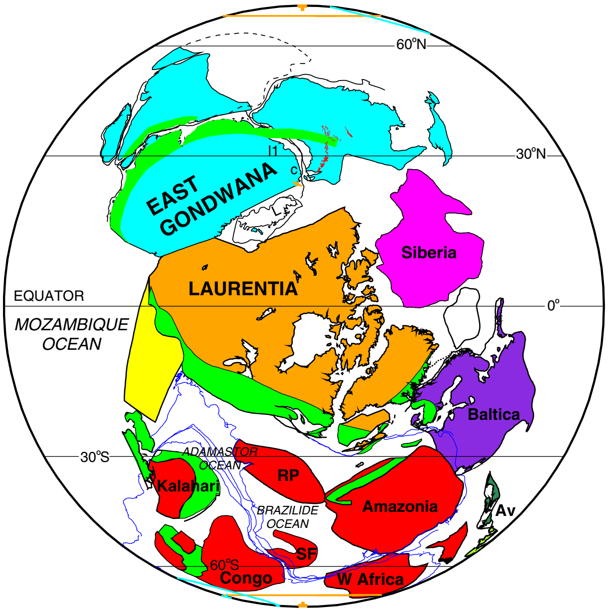


Fig. 9. Qualitative summary (Worsley et al., 1985; Nance et al., 1986) of late Archean to present tectonic, platform sedimentary, climatic, biotic and stable isotope trends tuned within allowable dating errors to a quasi-periodic, ~0.5 b.y. supercontinent cycle. Trends; abundant, intense or heavy shown by solid bars (documented) and stippled bars (speculative); common or moderate shown by solid and dashed lines (documented) and dotted lines (speculative).

a) Early to mid-Neoproterozoic



b) End Neoproterozoic (ca. 545 Ma)

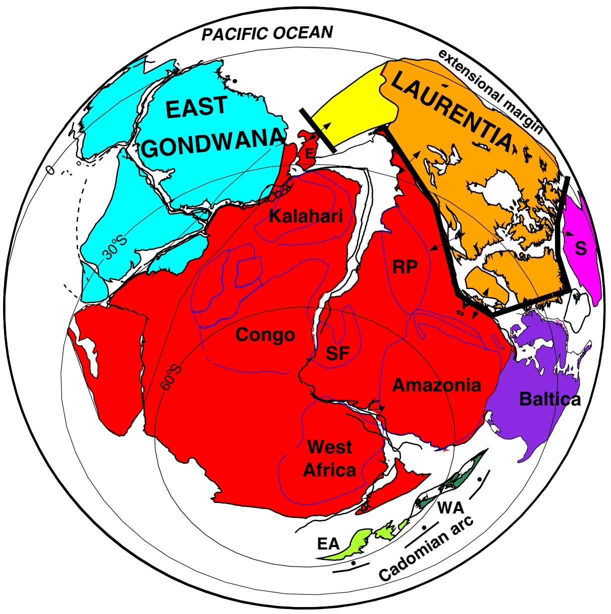


Fig. 10. Reconstructions of (a) Rodinia formed by amalgamation of older cratons in the global, ca. 1.0 Ga Grenvillian orogeny (green belts) at ca. 725 Ma, prior to separation of the Cordilleran margin of Laurentia from East Antarctic–Australia and the opening of the Pacific Ocean basin, and (b) Pannotia following the assembly of East Gondwana and West Gondwana (red), prior to the opening of the Iapetus Ocean with the separation of Laurentia from West Gondwana and Baltica (simplified from Dalziel, 1997). Abbreviations: Av = Avalonia, EA = East Avalonia, RP = Rio de la Plata craton, S = Siberia, SP = São Paulo craton, and WA = West Avalonia.

McWilliams, 1981), passive margin development (Bond et al., 1984) and the glacial record (Young, 1985), at the end of the Precambrian (e.g., Valentine and Moores, 1970; Sawkins, 1976; Lindsay et al., 1987). LePichon and Huchon (1984) had even paved the way for a supercontinent cycle based on the geoid, the present configuration of which shows little correlation to modern plate boundaries (suggesting it reflects lower mantle convection), but closely corresponds to the former position of Pangea (Anderson, 1982; Chase and Sprowl, 1983). LePichon and Huchon (1984) took this to imply separate but weakly coupled systems of lower and upper mantle convection, the effect of which led to hemispheric supercontinent configurations in which the best coupling is insured. Once assembled, however, they argued that the excessive heating of the upper mantle brought about by the insulating effect of the supercontinent would ultimately lead to continental dispersal and the process would repeat. Like Worsley et al. (1984), they estimated the duration of a complete cycle, from one supercontinent to the next, to be ~400–500 m.y.

But the proposition that supercontinent assembly and breakup had occurred episodically throughout the Proterozoic with profound consequences to the course of Earth history was a radical one and, while it found support in some quarters (e.g., Goodwin, 1985; Trurnit, 1988), it was generally given little credibility (e.g., Condie, 1989) and did not receive wide attention at the time of its publication.

3. Subsequent developments

By the end of the 1980s, the role of past supercontinents in Earth history was beginning to receive increased attention, and this interest would only heighten in the decade to follow. The concept of supercontinental episodicity was prominently re-introduced by Hoffman (1988, 1989) and Williams et al. (1991) in their reviews of the Precambrian evolution of Laurentia. At the same time, Cooper (1990) recognized tectonic cycles in southern Africa manifested in major episodes of continental volcanism, granitoid plutonism, orogeny, reciprocal terrestrial and marine sequences, platform carbonate sedimentation, glaciation and first-order eustasy, the recurrence of which suggested a periodicity of 320 ± 25 m.y. for at least the past 3.2 Ga.

In addition, the role of the supercontinent cycle was recognized in the geologic record of global climate change (Veevers, 1990), continental glaciation (Young, 1988, 1991), tectonic geomorphology (Summerfield, 1989) and metal deposits (Barley and Groves, 1992), and in the sedimentary record of rift–drift transition (Ilyin, 1990) and biological activity (McMenamin and McMenamin, 1990). The climatic effect of supercontinents was also explored by Worsley and Kidder (1991) who showed this to be dependent upon their configuration. Using end-member supercontinents with tropical ("ringworld") and meridional ("sliceworld") configurations, as well as a world with polar continents ("capword"), they showed that, of these, ringworlds would be coldest and capwords warmest because of their varying effect on atmospheric CO_2 levels.

3.1. Rodinia

Although the seeds had already been sown, interest in supercontinents was to surge with refinements of the proposal by Bell and Jefferson (1987) that the Pacific margin of North America was conjugate to that of Australia–Antarctica (Dalziel, 1991; Moores, 1991) prior to the breakout of Laurentia and the amalgamation of Gondwana (Pannotia) in the late Precambrian and early Paleozoic (Hartnady, 1991; Hoffman, 1991). The resulting debate focused attention on supercontinents before Pangea and, specifically, on the existence of a "Grenvillian" (ca. 1 Ga) supercontinent, previously named Rodinia (McMenamin and McMenamin, 1990; inset Fig. 11), and the configuration of a Late Neoproterozoic supercontinent, later named Pannotia (Stump, 1992; Powell, 1995), that may have briefly assembled (Dalziel, 1991, 1992) following the dispersal of Rodinia at 725 Ma (Powell et al., 1993; Fig. 10).

The Grenville belt of eastern North America, long recognized as a collisional orogen (Dewey and Burke, 1973), and its age-correlatives in the Amazon (Sunsas belt), Congo (Irumide and Kibaran belts) and Kalahari (Namaqua–Natal belt) cratons, were interpreted to reflect the amalgamation of Rodinia, whereas the Neoproterozoic passive margin sequences that surrounded Laurentia reflected its breakup and dispersal (Hoffman, 1991). The proposed southwestern U.S.–eastern Antarctica connection (or SWEAT hypothesis; Dalziel, 1991; Moores, 1991) launched a decade-long debate over the configuration of Rodinia,

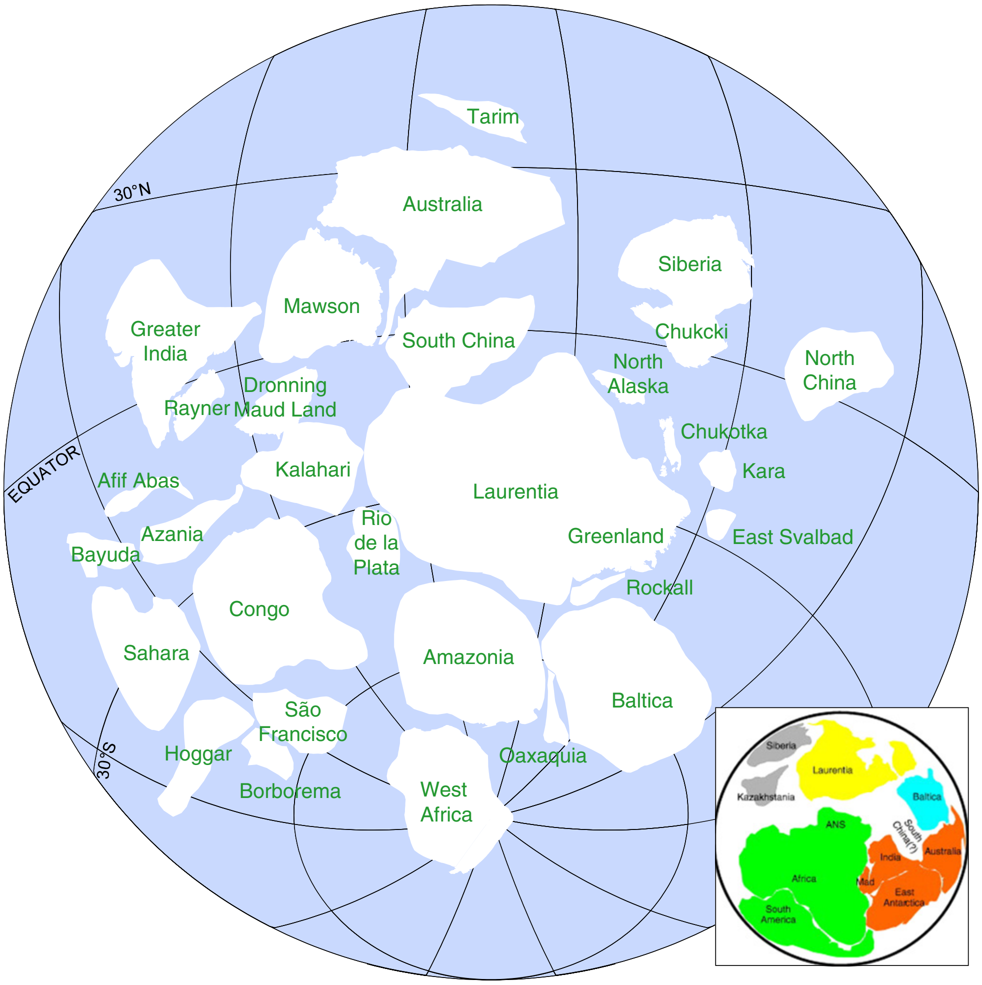


Fig. 11. "Concensus" Rodinia reconstruction of Li et al. (2008). Inset shows Rodinia as originally proposed by McMenamin and McMenamin (1990).

with other proposed configurations suggesting linkages between Australia and the western U.S. (or AUSWUS; Brookfield, 1993; Karlstrom et al., 1999; Burrett and Berry, 2000), Australia and Mexico (or AUSMEX; Pisarevsky et al., 2002; Wingate et al., 2002), and South China and the western U.S. (or the "missing link" hypothesis; Li et al., 1995, 1999). The debate ultimately led to a "consensus" configuration for Rodinia (Li et al., 2008; Fig. 11), although it is clear that several major aspects of the reconstruction remain to be resolved (e.g. Meert and Torsvik, 2003; Torsvik, 2003; Evans, 2009; Murphy et al., 2013).

3.2. Pannotia (Gondwana)

The existence of a late Neoproterozoic supercontinent has proven more controversial. But while it had long been known that orogenic events assigned to the global "Pan-African" episode had culminated in the formation of Gondwana (Clifford, 1968; Kröner, 1981, 2001; Cahen et al., 1984; Unrug, 1992; Meert and van der Voo, 1997), it was suggested that Gondwana may have been briefly united with Laurentia (Dalziel, 1991, 1992) to form the supercontinent Pannotia (Stump, 1992; Powell, 1995) prior to the opening of the Iapetus Ocean in the Late Neoproterozoic–Early Cambrian (Cawood et al., 2001). Recent syntheses suggesting West Gondwana (i.e. the cratons of South America and Africa) was amalgamated between 650 and 600 Ma (e.g. Pankhurst et al., 2008), and that East Gondwana was assembled in at least two stages, between 750 and 620 Ma (East African Orogen) and at 570–500 Ma (Kuunga orogen) (Meert, 2001; Collins and Pisarevsky, 2005), are equivocal on the existence of Pannotia. However, recent dating of granulites in the extension of the East African Orogen into Central Dronning Maud Land (Pant et al., 2013) places the suturing of East and West Gondwana at 640 Ma, which would allow Pannotia to have existed for 70 m.y. (cf., Cawood et al., 2001). Similarly, in reviewing contemporary data on the role of Antarctica in Neoproterozoic supercontinent reconstructions, Dalziel (2013) concludes that the evidence favors the existence of a short-lived end-Neoproterozoic supercontinent. Li et al. (2008) provide a sequence of reconstructions showing how the breakup of Rodinia may have led to the assembly of Gondwana and Pannotia (Fig. 12). Although parts of these reconstructions are controversial, they show in a general sense that Pannotia formed by preferential subduction of the oceanic lithosphere that surrounded Rodinia (the exterior ocean of Murphy and Nance, 2003).

As might be expected, the various continental collisions associated with the assembly of Gondwana/Pannotia produced Pan-African orogenic belts that came to occupy positions in the interior of the supercontinent once it had assembled (Murphy and Nance, 1991, 2003). However, over the same time interval, the Neoproterozoic Avalonian–Cadomian belt, located along the Amazonian–West African margin of Gondwana, was seen to be dominated by subduction-related orogenic activity that terminated in the development of a San Andreas-style transform system rather than in continent–continent collision (Murphy and Nance, 1989). As a result, the belt continued to face an open ocean into the Cambrian

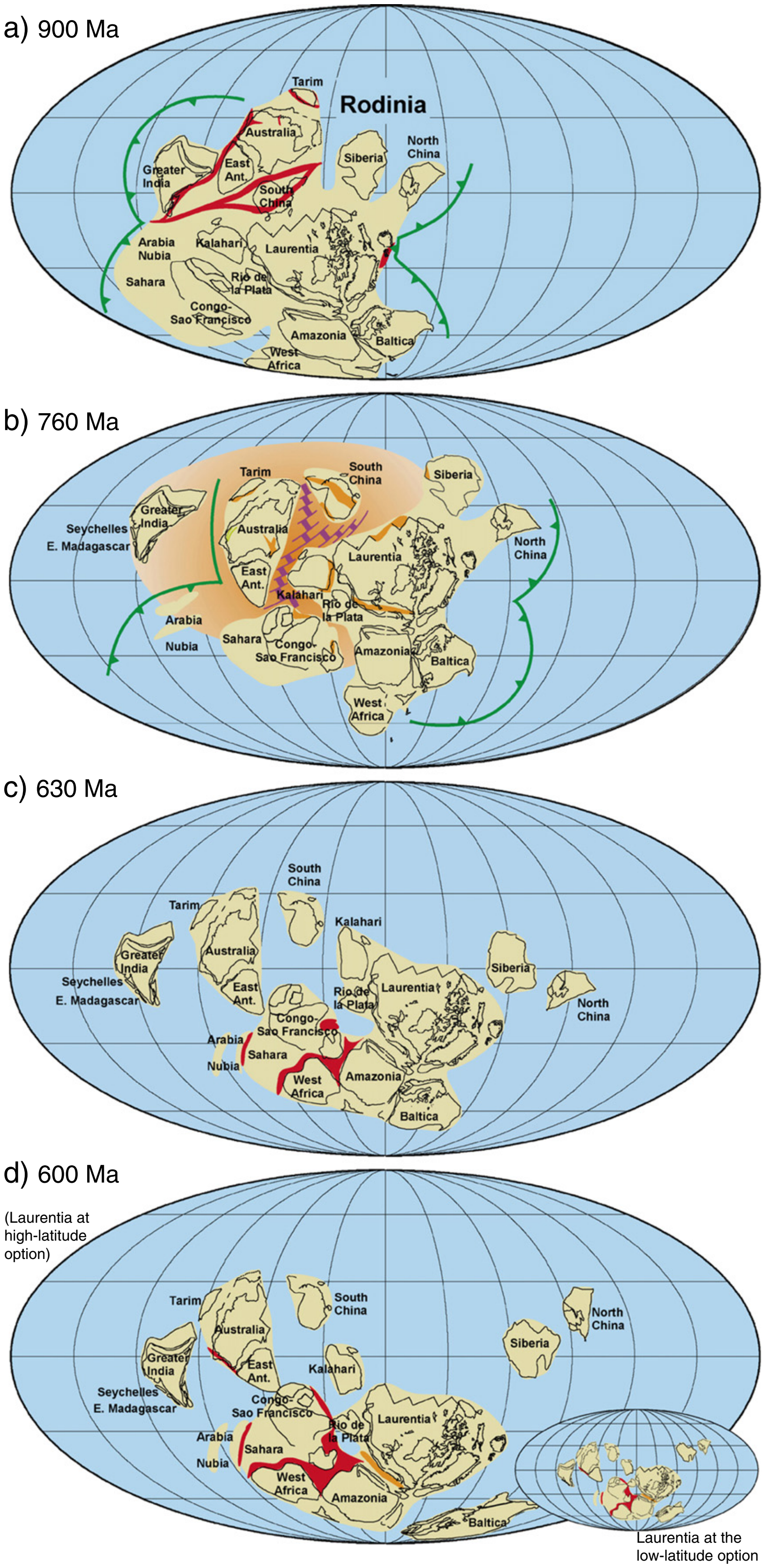


Fig. 12. Sequence of reconstructions from Li et al. (2008) showing how the breakup of Rodinia may have led to the assembly of Gondwana and Pannotia. (a) Rodinia at 900 Ma, (b) breakup of Rodinia at 760 Ma coincides with onset of widespread subduction in the peri-Rodinian (Mirovoi) ocean, (c) assembly of continents to form Pannotia (Gondwana + Laurentia) at 630 Ma, and (d) onset of subduction along margins of Gondwana at 600 Ma following amalgamation of Pannotia.

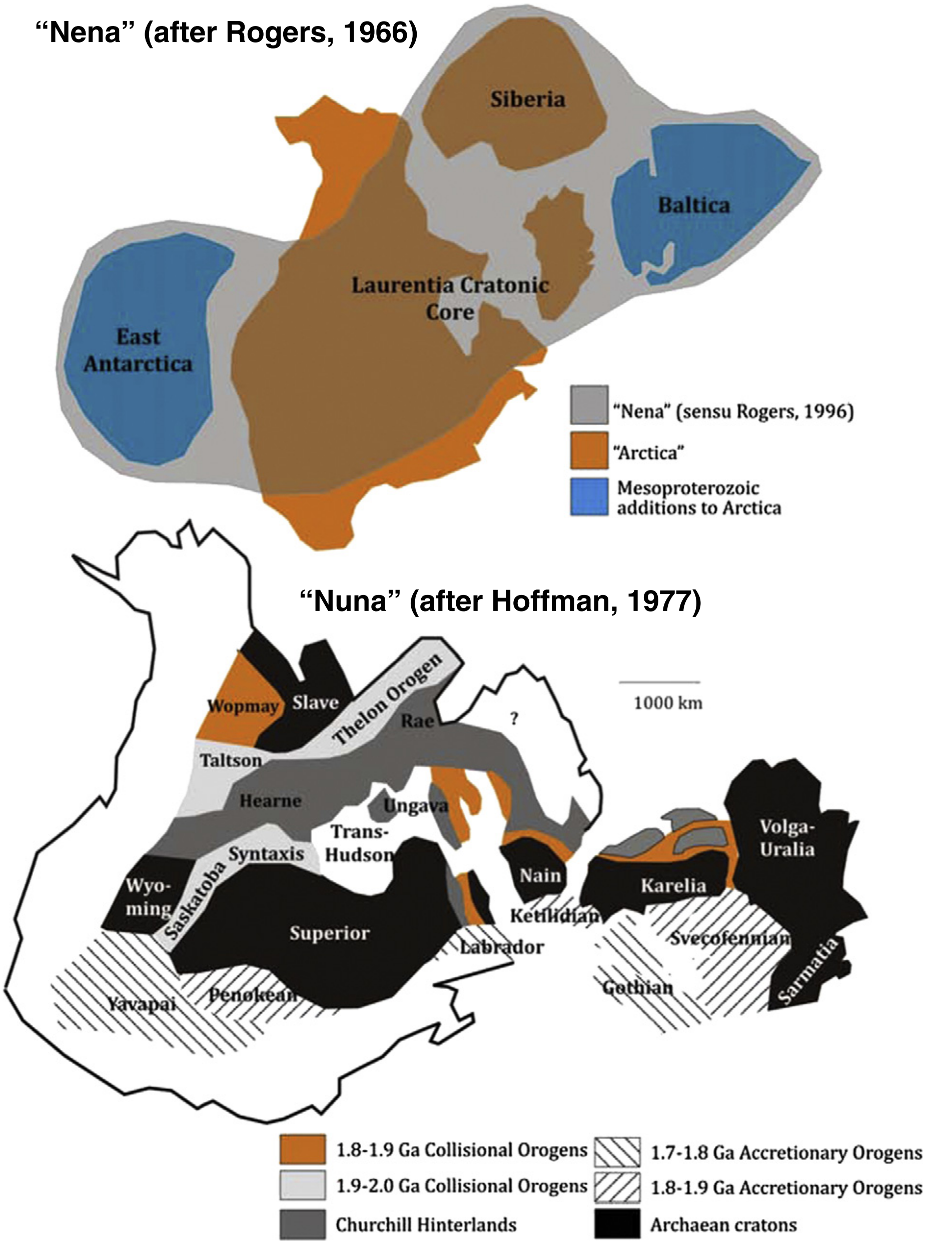


Fig. 13. Configuration of Nuna (Hoffman, 1997) and its precusor Nena (Rogers, 1997). Modified from Meert (2012).

(e.g. McKerrow and Scotese, 1990). This contrast in the style of Pan-African orogenesis led to the recognition that two fundamentally distinct types of orogen (cf., collisional and accretionary: Dewey, 1977; Windley, 1992) could be related to the supercontinent cycle: "interior" orogens that are formed by continental collision and become stranded in the interior of supercontinents, and "peripheral" orogens that are formed along the periphery of supercontinents and are dominated by accretionary tectonics (Murphy and Nance, 1991). The subsequent recognition of the accretionary Terra Australis orogen (see Fig. 1), extending from the eastern margin of Amazonia to eastern Australia (Cawood and Buchan, 2007), suggested that much of Gondwana/Pannotia was surrounded by peripheral orogens in the late Neoproterozoic (e.g., Murphy et al., 2009).

A wealth of later studies, which showed the amalgamation of Gondwana/Pannotia to have been accompanied by rapid continental growth, metazoan diversification, an explosion in biological activity, and dramatic climate swings (e.g., Hoffman et al., 1998; Knoll et al., 2004; Meert and Lieberman, 2008; Maloof et al., 2010), highlight the importance of an earth systems approach to the study of supercontinent cycles.

3.3. Pre-Rodinian supercontinents

Whereas the general configurations of Pannotia and Rodinia have been broadly constrained (e.g., Li et al., 2008; Meert and Lieberman, 2008), the reconstruction of older supercontinents is challenged by the fragmentary and incomplete nature of the Archean to Mesoproterozoic geologic record and the possibility that a different form of tectonics may have operated earlier in Earth history (e.g. Condie and Pease, 2008). Hence, the development of the concept of the supercontinent cycle prior to Rodinia has become intertwined with theoretical and geodynamic modeling.

There is now broad consensus that the large number and widespread distribution of continental collisions documented between 2.1 and 1.8 Ga record the amalgamation of yet another supercontinent.

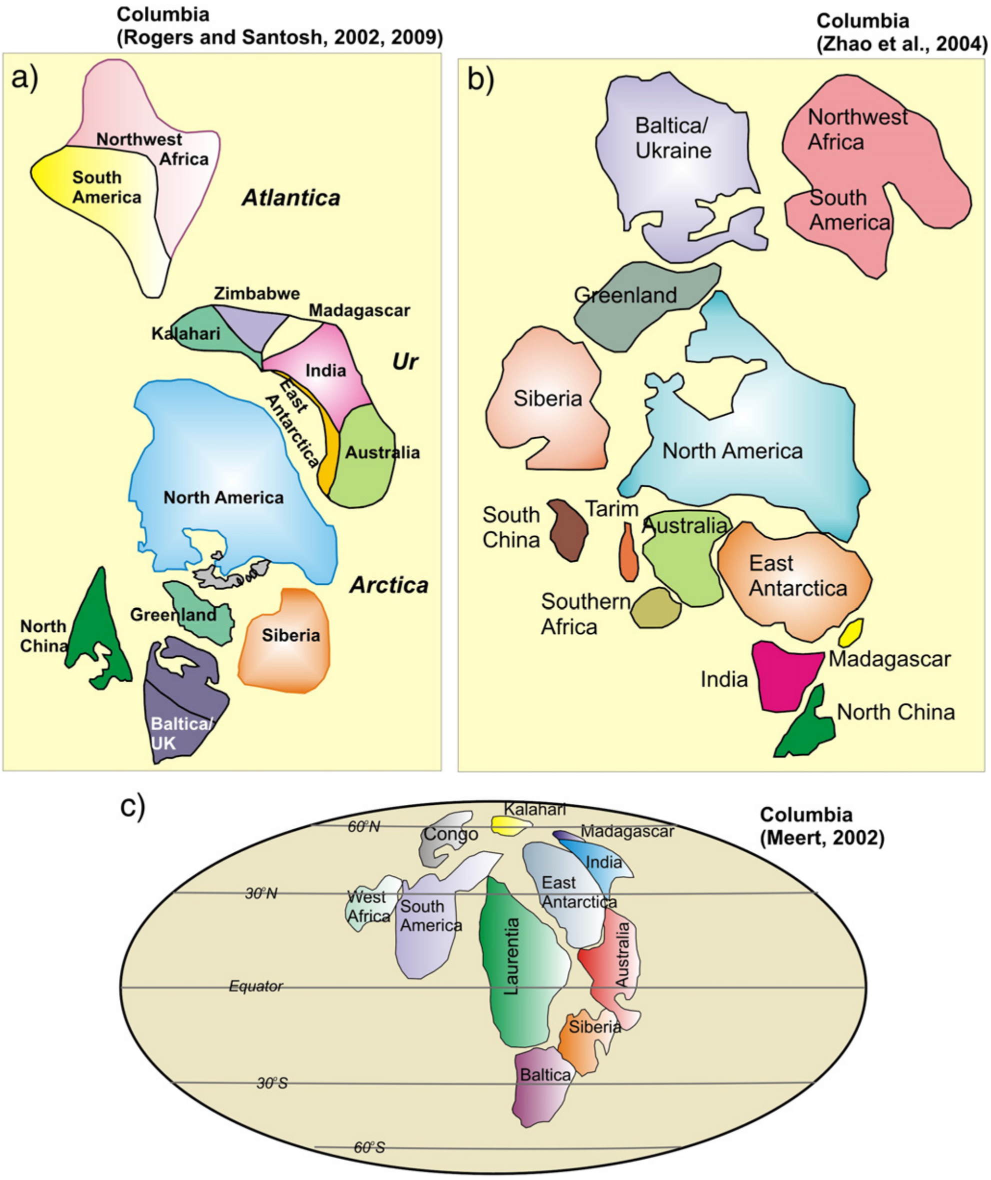


Fig. 14. Reconstructions of Columbia, (a) after Rogers and Santosh (2002, 2009) showing configurations of components Ur, Artica and Atlantica, (b) after Zhao et al. (2004), and (c) after Meert (2002).

First referred to as Nuna (Hoffman, 1988), this supercontinent is more widely known as Columbia (Rogers and Santosh, 2002; Sears and Price, 2002; Zhao et al., 2002), which, in its current usage, describes a larger continental configuration of which Nuna (previously Nena; Rogers, 1996) was part (Meert, 2012; Figs. 13 and 14). Many of the Paleoproterozoic orogenic belts along which the proposed supercontinent was sutured, such as the Wopmay and Trans-Hudson orogen of Laurentia (e.g. Hoffman, 1980; St-Onge et al., 2000, 2001; Corrigan et al., 2009) the Aravalli and Satpura orogens of India (Vijaya Rao and Reddy, 2002) and the Capricorn orogen of Western Australia (Occhipinti et al., 2004; Sheppard et al., 2004) were considered to resemble modern collisional orogens, with accretionary stages followed by collisional events taken to record supercontinent amalgamation. Likewise, contemporary sedimentary basins in South America were interpreted to chart a history of supercontinent assembly and amalgamation (Brito Neves, 2002).

More controversial are the proposals for even earlier supercontinents. It has been suggested that a supercontinent named Kenorland (or Superia and Sclavia; Bleeker, 2003) formed at ca. 2.7 Ga and broke up at 2.5 Ga (Williams et al., 1991; Heaman, 1997; Aspler and Chiarenzelli, 1998), and that another, named Vaalbara (from the Kaapvaal and Pilbara cratons), formed from proto-continents at 3.1 Ga and broke up at 2.8 Ga (Cheney, 1996; Zegers et al., 1998). In addition, Rogers (1996) gave the name Ur to a proposed continental assembly, comprising the Western Dharwar, Singhbhum, Kaapvaal and Pilbara cratons, that was argued to be the world's first at ~3 Ga. The implication of these hypotheses is that some form of plate tectonics existed in the Archean (e.g., Gerya, 2013), and a plethora of geochemical studies (e.g. Kerrich and Wyman, 1994; Kerrich and Polat, 2006; Polat et al., 2008) have yielded signatures interpreted to reflect subduction zone settings. Such models, however, are hotly disputed (e.g. Stern, 2008a, 2008b; Hamilton, 2011) since many of the features characteristic of modern plate tectonics, such as ophiolites, blueschists, lawsonite-bearing eclogites, ultrahigh pressure metamorphic rocks, paired metamorphic belts and passive margin development, are rare or absent in the Paleoproterozoic and Archean (Moores, 2002; Brown, 2006, 2008; Hynes, 2008). Indeed, according to some calculations, mantle temperatures in the early Archean were at least 200 °C hotter than today (e.g. Hynes, 2008). To some authors this implies an evolution from an Archean tectonic regime with either no (e.g. Hamilton, 2011) plate tectonics, or some modified form (e.g. Ernst, 2007) driven by asthenospheric convection ("proto-plate tectonics"), to modern plate tectonics driven by subduction, the latter only becoming dominant in the Neoproterozoic. However, Gerya (2013) suggests that whereas widespread development of modern-style collision may only have started during the Neoproterozoic (600–800 Ma), the widespread development of modern-style subduction began in the Mesoarchean–Neoarchean (3.2–2.5 Ga).

Despite these uncertainties, the case for the repeated assembly and breakup of supercontinents over a significant portion of Earth history was, by the turn of the century, gaining increasing momentum with applications to large igneous provinces (Yale and Carpenter, 1998; Dalziel et al., 2000), the evolution of the western margin of Australia (Wilde, 1999), massif-type anorthosites (Mukherjee and Das, 2002), and ophiolite emplacement (Vaughan and Scarrow, 2003). In addition, the period saw the first of what would become a series of special publications on supercontinent assembly and breakup (Rast and Rogers, 1997) and supercontinents in Earth history (Rogers and Santosh, 2002, 2003; Yoshida et al., 2002), which would set the stage for the developments seen in the past decade.

4. Modern views

The first decade of the 21st century witnessed a surge of interest in studies related to the origin, evolution and dispersal of supercontinents through Earth history. Advancements in analytical techniques and concepts in a number of fields including detrital zircon geochronology and Hf-isotopes, new data and refinements in paleomagnetism, and new approaches in geophysical techniques such as mantle tomography and numerical modeling, paved the way for innovative proposals and global models on supercontinents. The decade also saw new lines of thinking with regard to the relationship between supercontinent history and solid Earth tectonics, metallogeny, surface environment and life.

4.1. The Earth's earliest supercontinents

Of the hundreds of papers published on the supercontinent cycle in the past decade, several have focused on the Earth's earliest supercontinents. From a global synthesis of information on the formation of cratons and orogenic belts, Rogers and Santosh (2002, 2003, 2004) traced the history of various supercontinents starting with the oldest assemblies of Ur (ca. 3.0 Ga cratons of Southern Africa and Western Australia), 'Arctica' (ca. 2.5 Ga cratons of Greenland, Fennoscandia, Laurentia and Siberia) and 'Atlantica' (ca. 2.0 Ga cratons of Western Africa and South America), which they suggested remained coherent until the breakup of Pangea (Fig. 14a). They also introduced the concept of 'maximum close packing', and concluded that nearly all of the Earth's continental blocks had assembled into single closely packed assemblies at least three times during the Proterozoic. Piper (2010a) subsequently used the paleomagnetic record from the oldest (2.9–2.0 Ga) cratonic assemblies to proposed a mid-Archean supercontinent, 'Protopangaea', the outer domains of which were composed of the core elements of Ur and Arctica. The hemispherical crescent-shaped form of the supercontinent, which resembles that of Pangea and a postulated Meso-Neoproterozoic (ca. 1.3–0.6 Ga) supercontinent, "Paleopangaea" (Piper, 2000, 2007, 2010b), was interpreted to have resulted from whole mantle convection systems driving the continental crust towards regions of minimum gravitational potential (Fig. 15).

Prior to their global synthesis, Rogers and Santosh (2002) defined what may have been the Earth's first coherent supercontinent, which they termed "Columbia" (see Fig. 14a). Possibly containing nearly all of the Earth's continental blocks at some time between 1.9 Ga and 1.5 Ga, Columbia was proposed to have formed when eastern India, Australia and attached parts of Antarctica were sutured to western North America — the eastern margin of North America, the southern margin of Baltica/North China, and the western margin of the Amazon shield forming a continuous zone of continental outbuilding. Fragmentation of Columbia began at ca. 1.6 Ga and continued until

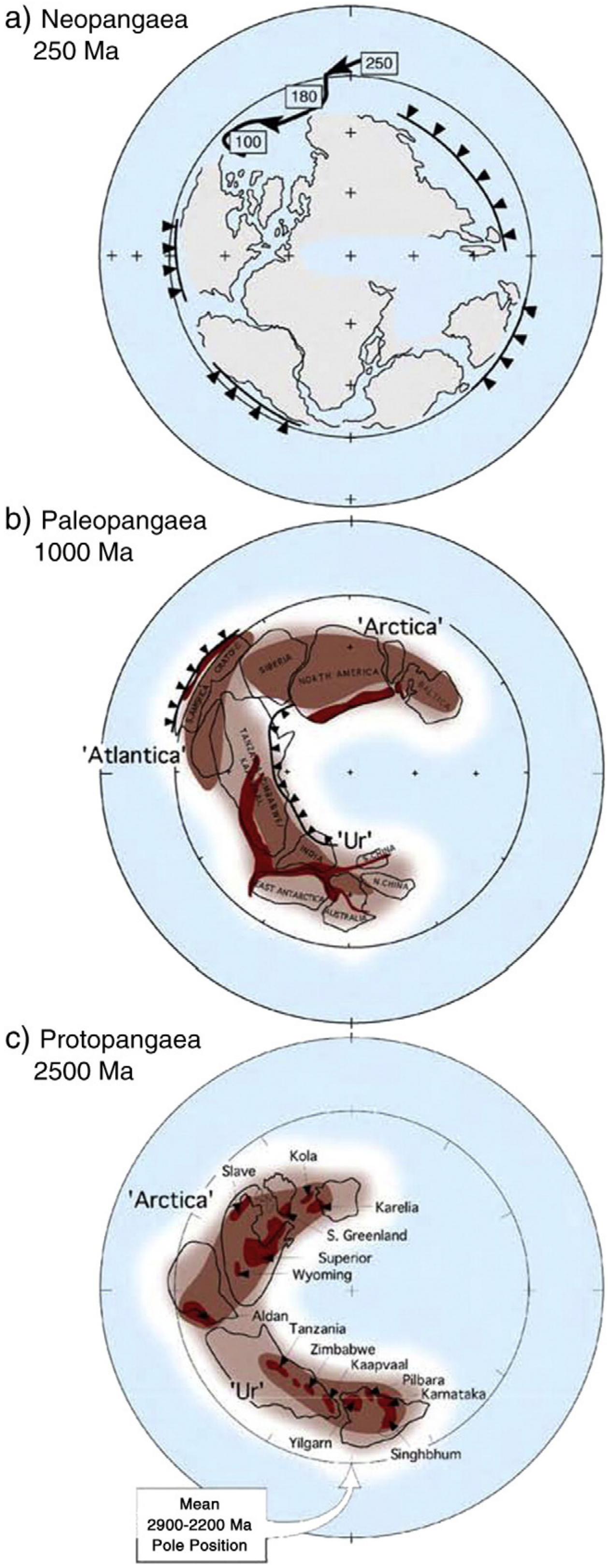


Fig. 15. Equal area projections of (a) Pangea (Neopangea), (b) Palaeopangaea, and (c) Protopangea illustrating their comparable symmetrical and hemispheric form. From Piper (2010b).

about 1.4 Ga, with the component blocks re-uniting in the Neoproterozoic supercontinent Rodinia. In a parallel proposal, Zhao et al. (2002) reviewed the lithostratigraphic, tectonothermal, geochronological and paleomagnetic data from 2.1 to 1.8 Ga collisional orogens and related cratonic blocks around the world and likewise identified a Paleo-Mesoproterozoic supercontinent. The Archean to Paleoproterozoic cratonic blocks in Columbia were welded by 2.1–1.8 Ga collisional belts, whereas its final breakup witnessed the widespread emplacement of 1.6–1.2 Ga anorogenic anorthosite–mangerite–charnockite–granite (AMCG) suites, 1.4–1.2 Ga mafic dike swarms, and the intrusion of kimberlite–lamproite–carbonatite suites. Zhao et al. (2004, 2006) later reviewed the history of Columbia, arguing that the supercontinent underwent long-lived (1.8–1.3 Ga), subduction-related accretionary growth at key continental margins following its final assembly. Similarly, Mertanen and Pesonen (2012) argued that Columbia ("Nuna" according to these authors) started to form at about 1.8 Ga, but did not fully assemble until ca. 1.53 Ga and only began to break up during several rifting episodes after 1.2 Ga.

The assembly and breakup of Columbia were further evaluated by Hou et al. (2008) based on the geometry of giant radiating dike swarms and orogenic belts. They proposed a revised configuration for the supercontinent, in which North China, India and Laurentia were united prior to breakup. Based on data on magmatism, paleomagnetism and dike swarms, Hou et al. (2008) further proposed that Laurentia, West Australia and East Antarctica were relatively stable from 1.85 Ga to 1.20 Ga, and that these continents constituted the core of Columbia in the late Paleoproterozoic. Goldberg (2010) also used dike swarms as indicators of major extensional events in the Columbia supercontinent. Six large fanning dike swarms identified from aeromagnetic data were found to span two major periods in the evolution of Columbia: (i) 1.9–1.7 Ga during and immediately following maximum packing of Columbia; and (ii) 1.3–1.2 Ga during the period of its final breakup. Goldberg (2010) linked the dike swarms to the loci of hotspot magmatism and showed that some were associated with failed or aborted rifts related to Columbia breakup.

Support for the existence of Columbia has come from studies of various continental blocks. Cordani et al. (2009), for example, examined the Proterozoic accretionary belts that form most of the Amazonian Craton, or are marginal to its southeastern border, and concluded that Amazonia was part of the Columbia assembly together with Laurentia, North China and Baltica, linked by Paleo- to Mesoproterozoic mobile belts. From a synthesis of paleomagnetic data, they further suggested that Laurentia and Amazonia, incorporated into the Rodinia configuration, remained united until at least 600 Ma, and that their separation marks the final breakup of Rodinia with the opening of the Iapetus ocean.

From a synthesis of geologic and geophysical data for one of the better-studied fragments of Columbia, the North China Craton, Santosh (2010a) proposed a double-sided subduction history that promoted rapid amalgamation of continental fragments within the craton and their incorporation into Columbia. Eriksson et al. (2011a, 2011b) examined the antiquity of the supercontinental cycle based on the history of one of the Earth's oldest cratons, Kaapvaal, where rocks ranging in age from ca. 3.1 to 2.05 Ga are preserved. They suggested that, in this region, definable supercontinent assembly could be traced from the collision of Kaapvaal with the Zimbabwe Craton at ca. 2.0 Ga.

Evans and Mitchell (2011) integrated tectonostratigraphic records and paleomagnetic data from Siberia, Laurentia, and Baltica to propose a quantitative reconstruction of the core of the Columbia ('Nuna' according to these authors) at 1.9–1.3 Ga. In their model, the present southern and eastern margins of Siberia were juxtaposed against the Arctic margin of Laurentia and the Uralian margin of Baltica, respectively (Fig. 16). Consistent tectonostratigraphic records in Siberia, Laurentia and Baltica collectively trace the history of assembly and breakup of the supercontinent and its late Mesoproterozoic transition to Rodinia. Based on a global synthesis and new paleomagnetic data from North China, Zhang et al. (2012) concluded that Nuna likely existed between ca. 1780 Ma and ca. 1400 Ma. Recently, Rogers (2012) posed a speculative question as to whether the formation of Columbia was related to the steady decline in the percentage of ^{235}U in terrestrial uranium that made natural fission impossible after about 1.8 Ga. The oldest widespread orogenic systems, which are those that assembled Columbia at ca. 2.0–1.8 Ga, may have been possible only after fission stopped contributing to the Earth's heat flow.

Despite widespread support for its existence, controversy has surrounded the definition of Columbia and what constitutes a supercontinent. Meert (2012) recently examined this question and, using Pangea as a model, suggested that any supercontinent should include ~75% of the preserved continental crust relevant to the time of maximum packing. Rodinia, for example, reached maximum packing at about 1.0 Ga and therefore should include 75% of all continental crust older than 1.0 Ga. Meert (2012) also examined the history of the terms Nuna and Columbia, and suggested that Columbia should be used to refer to the Paleo-Mesoproterozoic supercontinent since Nuna, as originally defined (Hoffman, 1997), is but one of several core elements within the Columbia configuration.

4.2. Neoproterozoic supercontinents

The most studied supercontinent in recent years has been the Neoproterozoic supercontinent Rodinia (Figs. 10a and 11), although aspects of its assembly, evolution and breakup remain highly controversial. The making and breaking of Rodinia came into focus with Meert and Torsvik's (2003) argument that the timing of Rodinia breakup as proposed in the 1990s were at odds with paleomagnetic data. Based on an evaluation of the various models for the relationships between the 'external' Rodinian cratons (e.g., Baltica, Siberia and Amazonia) to Laurentia, the notion of true polar wander, the lack of reliable paleomagnetic data, and the enigmatic interpretations of the geologic data, they concluded that while the existence of Rodinia was acknowledged, its exact disposition at any one time remained vague. Li et al. (2004) reported new geochronological and paleomagnetic data from mafic dikes in South China and suggested that Rodinia probably extended from the equator to the polar region at ca. 800 Ma, but underwent a rapid, ca. 90° rotation around a pole near Greenland that brought the entire supercontinent to a low-latitude position by ca. 750 Ma. They linked this episode of true polar wander to the initiation of a mantle superplume at its polar end.

In a detailed synthesis, Li et al. (2008) addressed the history of Rodinia on the basis of paleomagnetic constraints and geological correlations of basement provinces, orogenic histories, sedimentary provenance, the development of continental rifts and passive margins, and the record of mantle plume events. They concluded that the supercontinent assembled through worldwide orogenic events between 1300 Ma and 900 Ma, and incorporated most of the continental blocks on the globe existing at that time (Fig. 11). As with its assembly, the breakup of Rodinia occurred diachronously, starting along the western margin of Laurentia at ca. 750 Ma. Rifting between Amazonia and the southeastern margin of Laurentia also started at the same time, but breakup occurred only at 600 Ma.

In a marked departure from the consensus model of Rodinia, Evans (2009) re-evaluated its 'long-lived and all-inclusive' configuration from a paleomagnetic perspective. The late Neoproterozoic transition from Rodinia to Gondwana (Pannotia) involved rifting events that are recorded on many cratons in the interval ca. 800–700 Ma and collisional events between ca. 650 and 500 Ma. According to Evans (2009), the pattern of supercontinental transition involved large-scale dextral motion of West Africa and Amazonia, and sinistral motion plus rotation of Kalahari, Australia,

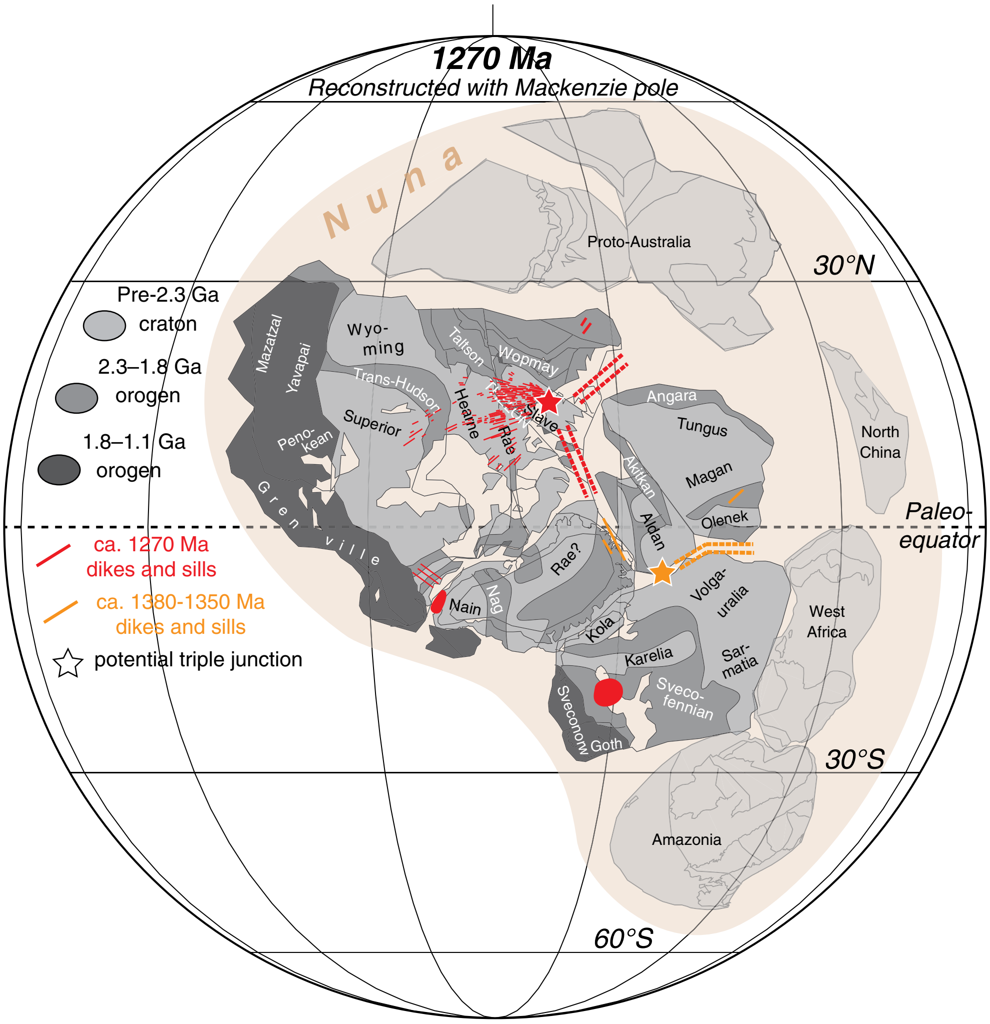


Fig. 16. Tectonic assemblage map of Nuna (Columbia), reconstructed to time of initial mid-Mesoproterozoic breakup. Simplified from Evans and Mitchell (2011).

India and South China, in a combination of introverted and extroverted styles of motion.

The late Neoproterozoic–Cambrian supercontinent Pannotia (Gondwana) (see Figs. 10b and 12c, d) has also received wide attention in the past few years with new information coming from petrological, geochemical and geochronological studies leading to different tectonic models — see Collins and Pisarevsky (2005) and the preface to a special issue on Western Gondwana (Tohver et al., 2012) for details. From these studies, it is clear that the birth of Gondwana involved the closure of a series of oceans between the converging crustal blocks during the mid- to late Neoproterozoic, with Pacific-type subduction along a number of convergent margins progressively yielding to collisional orogeny accompanied by magmatic, metasomatic and metamorphic processes characteristic of subduction–accretion–collision settings (e.g., Collins and Pisarevsky, 2005; Pankhurst et al., 2008; Santosh et al., 2009b; Casquet et al., 2011).

4.3. Mechanisms of assembly, dispersal and re-assembly of continental fragments

Several studies over the past decade have been directed at the mechanisms of supercontinent assembly and breakup. Cawood and Buchan (2007), for example, evaluated the assembly processes of Gondwana and Pangea and showed that the timing of collisional orogenesis between the amalgamating continental fragments was synchronous with subduction initiation and contractional orogenesis within accretionary orogens located along the margins of these supercontinents. Temporal relations across supercontinents between interior collisional and marginal accretionary orogenies supports Murphy and Nance's (2003) conjecture of a linked history between interior and exterior processes perhaps related to global plate kinematic adjustments (see also Collins, 2003).

Murphy and Nance (2008, 2012) and Murphy et al. (2009) subsequently presented new concepts for evaluating the assembly and breakup history of supercontinents. From the geologic and isotopic record, they elaborated on their earlier proposition that supercontinents form by two end-member mechanisms — introversion (where the interior ocean floor is preferentially subducted) and extroversion (in which exterior ocean floor is preferentially subducted) — by suggesting that the top-down geodynamics widely employed to account for the breakup and dispersal of a supercontinent at ca. 600–540 Ma may have been overpowered by bottom-up geodynamics during the amalgamation of Pangea. It was also speculated that superplumes, driven by slab avalanche events, occasionally overwhelm top-down geodynamics, imposing a geoid high over a pre-existing geoid low causing dispersing continents to reverse their directions to produce an introverted supercontinent.

Santosh et al. (2009a) identified two major types of subduction zones on the globe: the Circum-Pacific and the Tethyan, and proposed that the process of formation of supercontinents is controlled by super-downwelling that develops through double-sided subduction as seen in the present day Western Pacific. They also suggested that the tectosphere (sub-continental mantle lithosphere), which functions as the buoyant keel beneath ancient continents, plays a crucial role in the supercontinental cycle, including continental fragmentation, dispersion and amalgamation.

4.4. Rate and mechanisms of crustal growth and destruction

One of the most widely pursued topics in recent research on supercontinents is the rate of production of continental crust through modeling of mantle dynamics and statistical interpretation of isotopic age data, mainly from zircon geochronology (e.g., Hawkesworth et al., 2010). Condie (2004) correlated increased production rates of juvenile crust with the formation of supercontinents and the occurrence of superplume events. According to this view, catastrophic superplume events triggered by slab avalanches from the 660 km discontinuity in the mantle are considered to be responsible for episodic crustal growth, whereas superplume events caused by shielding of the mantle from subduction by supercontinents, are considered to be responsible for relatively mafic additions to the continents that may lead to supercontinent breakup (Murphy and Nance, 2012 and references therein). The Central Asian Orogenic Belt is a Phanerozoic example of large-scale continental crustal growth, for which Hong et al. (2004) proposed a temporal and spatial correlation of juvenile crustal growth with the Pangea supercontinental cycle.

Global continental growth history was also addressed by Rino et al. (2004, 2008) through U–Pb analyses of a large population of magmatic and detrital zircon grains collected from river sands at the mouths of major rivers across most of the world's continents. The continental growth curve produced by these data suggest continuous growth of continental crust since the Archean with an abrupt increase during the Late Archean and early Proterozoic, and major peaks at 2.7, 2.0–2.2, 1.7–1.9, 1.0–1.2 and 0.5–0.8 Ga. The data further suggest that the Neoproterozoic Grenvillian and Pan African orogenies contributed most significantly to the formation of the continental crust, from which they concluded that the Neoproterozoic was one of the most active periods of crust formation in Earth history.

In another study, Stern (2008a, 2008b) evaluated Neoproterozoic crustal growth and concluded that the processes involved were similar to those of the modern Earth and took place mostly at convergent margin settings, and that crustal growth and reworking took place within the context of the supercontinent cycle from the breakup of Rodinia, beginning at ca. 830 Ma, until the formation of Greater Gondwana or Pannotia at ca. 600 Ma. Safonova et al. (2010) dated detrital zircons from sands of major Russian rivers to evaluate major episodes of granitic magmatism in the Eurasian continent. Their results confirm: (i) the episodic nature of continent formation, (ii) a global Neoarchean magmatic event possibly associated with the formation of the supercontinent Kenorland, (iii) a global episode of crust formation at 2.0–1.8 Ga associated with the formation of the supercontinent Columbia, (iv) the breakup of Columbia at 1.3–1.2 Ga, and (v) a major period of Phanerozoic crustal growth in Central Asia.

Condie et al. (2009), Condie and Aster (2010) and Condie et al. (2011) addressed crustal growth from the global data-set of zircon ages and isotopic characteristics of granitoid magmatism and juvenile crust production, and identified several igneous spikes in major cratons or continents, ranging in age from 3.3 to 1.1 Ga. They concluded that single, short-lived mantle plume events at 2.7 and 1.9 Ga cannot fully account for the prolonged and episodic granitoid magmatism of the Precambrian. The age peaks of detrital zircons from modern river sediments across the globe extend vertically into both positive and negative $\varepsilon_{Hf}(T)$ space and correlate well with supercontinent formation, reflecting the preservation of both juvenile and reworked continental crust during continental collisions. The data suggest that, while some new continental growth may occur during continental collisions, supercontinent assembly does not require an increase in production rate of continental crust. However, five major age clusters are closely tied to supercontinent formation at 2700, 1870, 1000, 600 and 300 Ma, and minima in the age spectra at 2200–2100, 1300–1200, 750–650, and ≤200 Ma correspond to supercontinentality or breakup. The resulting histogram of continental preservation rate shows that about one-third of the extant continental crust formed during the Archean, a further 20% formed during the Paleoproterozoic, and only 14% formed during the last 400 My. Major age clusters are thought to largely reflect preservation of juvenile crust in orogens during supercontinent assembly.

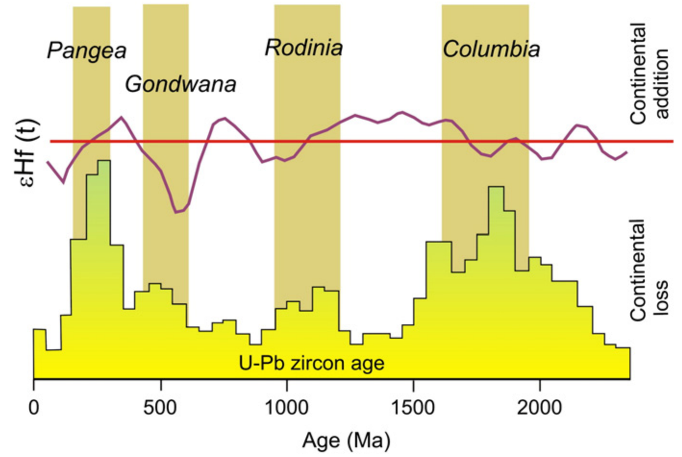


Fig. 17. Compilation of global zircon Hf data plotted as U–Pb zircon age versus ε_{Hf}(initial), and histogram of zircon U–Pb ages. Periods of named supercontinent assembly are shown by broad bars. Positive and negative excursions of the $\varepsilon_{Hf}(t)$ curve reflect increased continental addition and continental loss, respectively. Overlap between U–Pb maxima, supercontinent formation and negative ε_{Hf} excursions, indicate a link between the supercontinent cycle and changes in continental crust growth rate, whereby decreased growth rate occurs during supercontinent amalgamation, along with a possible increase in preservation of crust during these periods. Modified from Roberts (2012).

Hawkesworth et al. (2010) also used zircon data (see Fig. 3) to evaluate the generation and evolution of the continental crust and concluded that peaks in crystallization ages, while marking the times of supercontinent formation, may reflect an increased preservation potential for magmas formed at such times rather than enhanced crust generation. They consequently conclude that the present volume of continental crust was established 2–3 Ga ago. Similarly, Cawood et al. (2013) concluded that the episodic continental record is more likely to be a consequence of secondary processes, in which plate tectonics resulted in a biased preservational record, than a primary feature that reflects processes of generation.

Lancaster et al. (2011) employed U–Pb, O and Hf isotope data in detrital zircons from the Scottish Highlands to evaluate crustal evolution and likewise obtained zircon crystallization ages that are consistent with preservation due to continental collision and supercontinent stabilization. They identified a link between the distribution of U–Pb crystallization ages and model Hf ages indicating typical residence times of ca. 600 Ma between the formation of new crust and its reworking in later magmatic events. The continua defined by Hf model ages within each crystallization event suggest that the generation of new continental crust is a continuous process.

In a marked departure from all of these studies, Roberts (2012) used the distribution of data within $\varepsilon_{Hf}(t)$-time space of a global zircon database to demonstrate increased continental loss during supercontinent amalgamation (Fig. 17). Marked increases in continental loss at 1.0–0.9 Ga and 0.6–0.55 Ga correlate with the amalgamation of Rodinia and Gondwana (Pannotia), respectively, whereas periods of increased continental crust growth rate at 1.7–1.2 Ga, 0.85–0.75 Ga and 0.45–0.35 Ga respectively follow the formation of Columbia, Rodinia and Gondwana (Pannotia). Pangea assembly by introversion corresponds

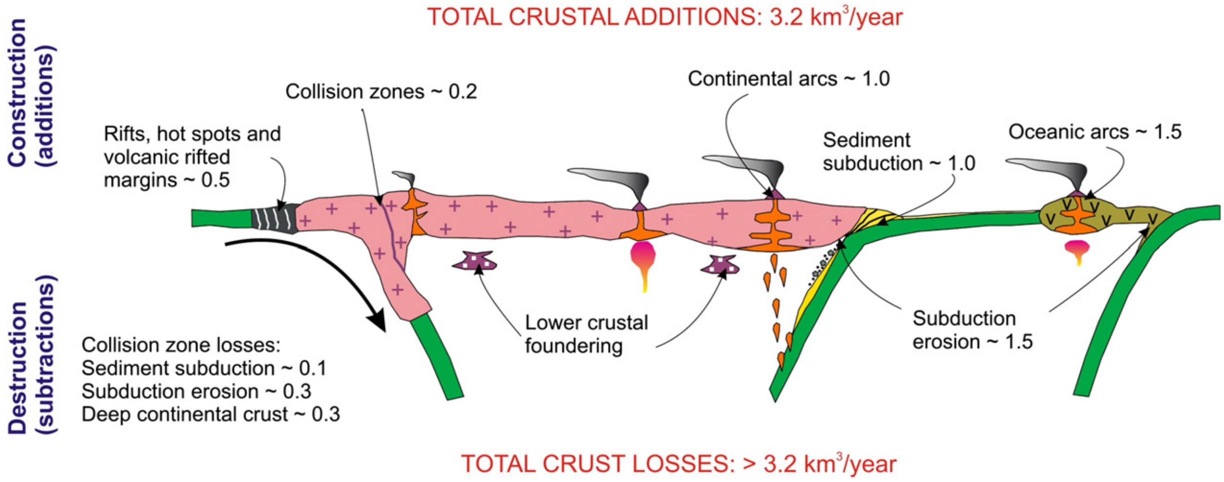


Fig. 18. Global rates of crustal growth and destruction losses. Redrawn with slight modification from Stern (2011).

to continental addition in exterior orogens concurrent with continental loss in the interior orogens.

Support for increased continental loss during supercontinent amalgamation comes from analysis of the destruction of continental crust at convergent margins, which has emerged as a focal theme of several recent studies (e.g., Scholl and von Huene, 2007, 2009). The return or recycling of continental crust in subduction zones includes the processes of sediment subduction, subduction erosion, and the detachment and sinking of deeply underthrust sectors of continental and intra-oceanic crust. Subduction erosion (cf. Keppie et al., 2009) results from a combination of erosion and structural collapse of the forearc wedge into the trench and abrasion and hydrofracturing above the subduction channel (Stern, 2011). Most crust and sediments subducted in this way are neither underplated below the forearc wedge nor incorporated in arc magmas, but rather, are transported deeper into the mantle. Stern (2011) estimates that the total rate of return of continental crust into the deeper mantle is currently equal to, or greater than, estimates of the rate at which it is being replaced by arc and plume magmatic activity, such that currently the continental crust is probably slowly shrinking (Fig. 18). Nevertheless, he concludes that the relative rates of crustal growth and destruction are dictated by the supercontinent cycle, crustal destruction being higher during times of supercontinent amalgamation, whereas crustal growth is likely to be more rapid during times of supercontinent breakup.

4.5. Supercontinents, surface environment and life

Although the formation and disruption of supercontinents have long been understood to have significantly impacted surface environments, biogeochemical cycles and life, several recent studies have reexamined this relationship, spearheaded by the introduction of the "Snowball Earth" hypothesis as an explanation for the climatic extremes of the Neoproterozoic (e.g., Kirschvinck, 1992; Hoffman et al., 1998; Hoffman and Schrag, 2002), and its potential link to supercontinent breakup (e.g., Hoffman, 1999; Donnadieu et al., 2004) and the emergence of complex metazoa (e.g., Lindsay and Brasier, 2002; Narbonne and Gehling, 2003). According to the "Snowball Earth" hypothesis, climatic deterioration initiated by a (preferably equatorial) supercontinent, once positively reinforced by the increasing planetary albedo of an ice- and snow-covered Earth, leads to runaway cooling and an entirely ice-covered planet. These "deep freeze" conditions prevail until rising volcanically sourced atmospheric CO_2 levels trigger a rapid switch to hot-house conditions, giving rise to the warm-water "cap" carbonates (recording negative $\delta^{13}C$ excursions) that directly overlie many Proterozoic glacial deposits (e.g., Kaufman et al., 1997; Hoffman et al., 1998).

Maruyama and Santosh (2008) presented a synopsis of events in the late Proterozoic (from 1000 to 542 Ma), during which time the Earth experienced two "Snowball Earth" glaciations – the Sturtian (715–680 Ma) and Marinoan (680–635 Ma) – following which large multi-cellular animals of the Ediacara fauna flourished as a prelude to the Phanerozoic world. The evolution of modern life in the Cambrian is proposed to have occurred once a geochemical bridge was in place in the form of elevated oxygen and nutrient levels in lakes that developed within continental rifts where hydrothermal systems in the granitic basement created the chemical environment for the birth of modern animals. With cosmic radiation exerting a significant control on mutation, Maruyama and Santosh (2008) also presented arguments linking events in the Neoproterozoic biosphere from the galactic to genome level. Stern (2008a, 2008b) likewise concluded that the intensity of Cryogenian and Ediacaran tectonic and magmatic processes, and their broad coincidence with the development of Neoproterozoic glaciations and metazoa, suggest that climate change and increasing biological complexity was strongly affected by the solid Earth system.

As reviewed by Santosh (2010b), the breakup of supercontinents and the development of hydrothermal systems in rifts enriched in nutrients serve as the primary building blocks of the skeleton and bone of early modern life forms. The assembly of supercontinents also had significant impact on evolution, including the formation of vast mountain belts such as those associated with the assembly of Gondwana (Pannotia), which may have provided an effective source of rich nutrients to equatorial waters, thus aiding in the rapid increase in biodiversity at the end of the Neoproterozoic. There is also a likely relationship between superplumes, supercontinent breakup and mass extinction. Upwelling plumes that break supercontinents apart generate large igneous provinces that may, in turn, affect climate by producing large-scale volcanism and plume-induced "winters" with catastrophic effects on the atmosphere and life.

The Paleoproterozoic era was also marked by profound changes in the Earth's evolution, including major climatic shifts that have been linked to "Snowball Earth" conditions (e.g., Kirschvink et al., 2000; Kopp et al., 2005). Reddy and Evans (2009) suggest that these changes may be linked to the formation of the first supercontinent cycle from the amalgamation and dispersal of a possible Neoarchean supercontinent to the formation of Nuna (Columbia) at 1.9–1.8 Ga. Likewise, Rogers and Santosh (2009) proposed that the assembly of Columbia at about 1.85–1.90 Ga coincided with several events that affected the surface environment and life on Earth, including a rapid increase in the concentration of oxygen in the atmosphere and oceans and the evolution of eukaryotes.

The stepwise increase in the concentration of oxygen in the Earth's atmosphere has also been correlated with the amalgamation of Earth's landmasses into supercontinents. Campbell and Allen (2008), for example, argued that the continent–continent collisions associated with the formation of supercontinents produce vast mountain systems, the rapid erosion of which releases large amounts of nutrients such as iron and phosphorus into the oceans, leading to an explosion of algae and cyanobacteria that abruptly raises the production of O_2 through enhanced photosynthesis. At the same time, the increased sedimentation during these periods promotes the burial of organic carbon and pyrite, thereby preventing their reaction with free oxygen to produce sustained increases in atmospheric oxygen. At the end of the Neoproterozoic, this intimate coupling between nutrient surplus and oxidation paved the way for the rise of metazoan life (Planavsky et al., 2010).

Eyles (2008) also evaluated the tectonic influences on long-term climate change by reviewing the relationship between periods of major glaciation over the past 3 Ga and phases of supercontinent breakup and assembly. His analysis showed a preferred relationship between glacial episodes and supercontinental rift systems that reflects either a causal link or an increased preservation potential. Young's (2012, 2013a, 2013b) syntheses likewise confirm earlier findings of a link between episodes of widespread glaciation in Earth history and periods of supercontinentality, and reaffirms the idea that such ice ages were likely initiated by increased weathering of high-standing supercontinents, especially at low latitudes, and the consequent global cooling caused by the resulting drawdown of atmospheric CO_2 (e.g., Goddéris et al., 2007).

Changes in Phanerozoic surface environments have long been linked to continental tectonics (e.g., Valentine and Moores, 1970; Fischer, 1981; 1984) and this linkage has only been confirmed by more recent studies (e.g., Bradley, 2011). The assembly and breakup of Pangea profoundly influenced Phanerozoic sea level and these changes show marked correlation with phytoplankton evolution, ocean chemistry, and the loci of carbonate, organic carbon, and siliciclastic sediment burial (Miller et al., 2005). Likewise, the Phanerozoic records of seawater chemistry and continental flooding with respect to the diversity of marine animals indicate a covariation between sedimentation and fossil biodiversity that can be linked to interacting Earth systems (Hannisdal and Peters, 2011). The link between biodiversity and environmental records reflects complex biotic responses to changing ocean redox conditions and long-term sea-level fluctuations driven by plate tectonics.

4.6. Supercontinents and metallogeny

Recent studies of the distribution of ore deposits through time (e.g., Teixeira et al., 2007; Lund, 2008; Bradley, 2011; Hazen et al., 2012; Huston et al., 2012; X.-F. Zhao et al., 2013) reaffirm their close relationship to phases of the supercontinent cycle advocated by Barley and Groves (1992), and to the evolution from plume-dominated to modern-style plate tectonics in a cooling Earth (Groves et al., 2005; Groves and Bierlein, 2007; see also Gerya, 2013). According to these authors, paleoplacer uranium, banded iron formation (BIF) and BIF-associated manganese carbonates that formed in the early Precambrian are notably absent in younger basins. This suggests a progressive oxidation of the atmosphere with consequent long-term changes in the hydrosphere and biosphere, the latter also influencing the temporal distribution and peak development of deposits such as the Mississippi Valley type, hosted in biogenic sedimentary rocks. Tectonic processes and environmental changes in an evolving Earth affect the temporal patterns of several major ore deposits, including orogenic gold, porphyry and epithermal deposits, volcanic hosted massive sulfides, paleoplacer gold, iron oxide–copper–gold (IOCG) deposits, platinum group elements, diamond and probably massive sulfide SEDEX deposits. The distinct temporal pattern of ore deposits identified at a global scale demonstrates the interplay between the evolving global tectonic regime, episodic mantle plume events, overall changes in global heat flow, atmospheric and oceanic redox states, and even singular impact and glaciation events (Goldfarb et al., 2010).

Some workers consider large-scale strike-slip translation of major cratons to be an effective reassembly mechanism in supercontinent cycles, in addition to rifting, spreading and collision (e.g., Yakubchuk, 2008). These cycles govern changes from the dominantly extension- to collision- and plume-related mineral deposit types in the internal orogens of the continental hemisphere to the subduction- to collision-related mineral deposit types that remain persistent through the metallogenic cycles at the oceanic/continental hemisphere transition zone, migrating oceanward in time.

4.7. Extreme metamorphism and fluid regimes

Specific cases of magmatic imprints associated with the supercontinent cycle, such as the mid-Proterozoic rapakivi granites, have also been described (Vigneresse, 2005). The age distribution of metamorphic belts that record extreme (UHT, H/UHP) conditions of metamorphism shows that such metamorphism occurs at times that correspond to the amalgamation of continental lithosphere into supercratons or supercontinents (Brown, 2006, 2007). Examples of the formation of UHT metamorphic rocks have been documented for the assembly of Columbia (e.g., Santosh et al., 2012 and references therein) and Pannotia/Gondwana (e.g., Collins et al., 2007). HP and UHT granulites typically occur within paired elongate belts. The active periods of their formation are punctuated by longer periods of stability, and each period culminated with the formation of a supercontinent, the amalgamation of which coincided with low- to medium-pressure/(U)HT granulite metamorphism immediately before continental breakup (Touret and Huizenga, 2012). Large quantities of mantle-derived CO_2 is presumed to have been stored in the lower crust at the final stage of supercontinent amalgamation, and released into the hydrosphere and atmosphere during breakup (Fig. 19). Hence, Touret and Huizenga (2012) consider fluid-assisted granulite metamorphism to be an important mechanism for transferring deep mantle fluids towards the Earth's surface, with possible consequences for the sudden end of Neoproterozoic glaciations and the Cambrian explosion.

4.8. The generation and role of mantle plumes in the assembly and breakup of supercontinents

The assembly of supercontinents involves subduction of large volumes of oceanic lithosphere, which impacts mantle flow fields, generates lower mantle chemical heterogeneities (see Tackley, 2012), creates upwelling plumes, and contributes to continental breakup and voluminous volcanism. A large number of recent studies have followed Condie's (1998, 1999, 2003, 2004) lead in addressing mantle dynamics in relation to the assembly and breakup of supercontinents (e.g., Meert and Tamrat, 2004; Maruyama et al., 2007; Phillips and Bunge, 2007; Vaughan and Storey, 2007; Zhong et al., 2007; Coltice et al., 2009; Li and Zhong, 2009; O'Neill et al., 2009; Senshu et al., 2009; Heron and Lowman, 2011; Murphy and Nance, 2012).

Maruyama et al. (2007) integrated the geological history of the Western Pacific region with mantle tomography and proposed a link between subducted cold slab graveyards produced in the deep mantle below supercontinents, and superplumes that drive supercontinent breakup. They suggested that such slab graveyards transform with time into large-scale upwellings as a result of heating from the core, and that the present-day Pacific superplume is located at the center of the Rodinian slab graveyard. The Western Pacific Triangular Zone

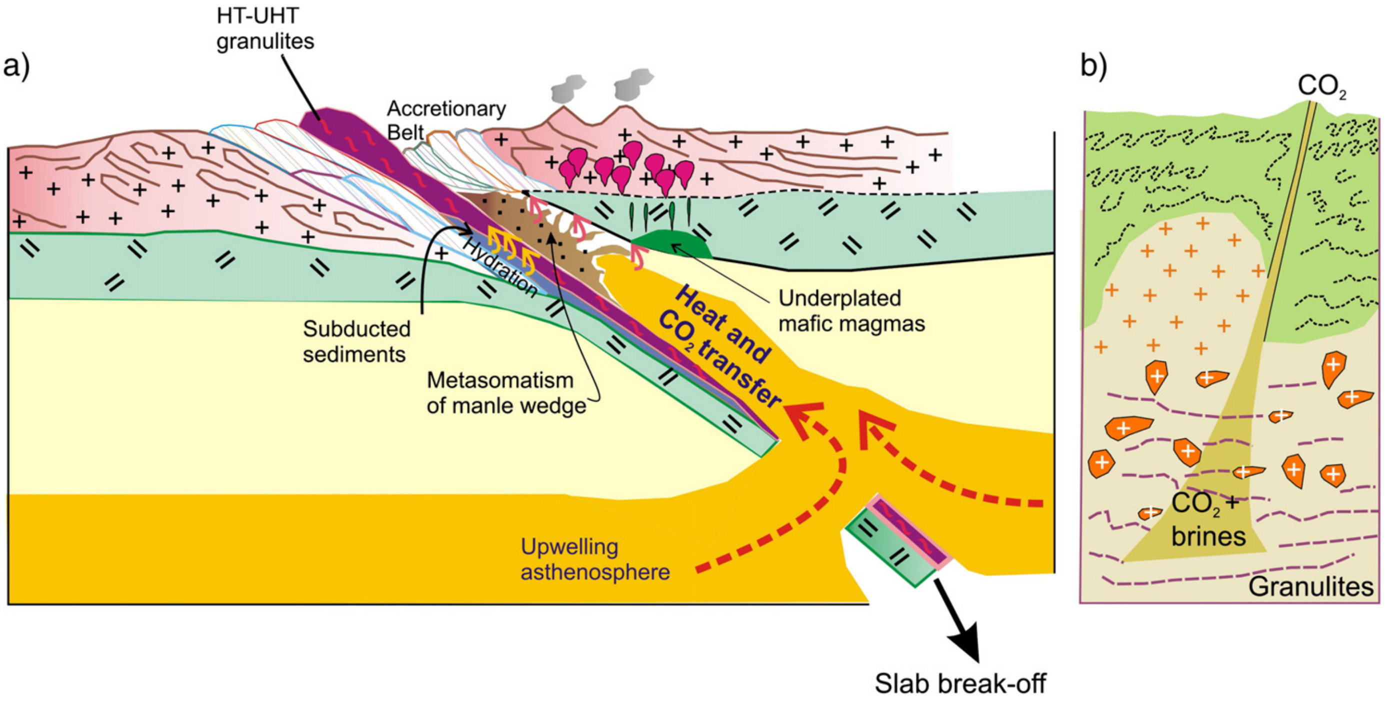


Fig. 19. Formation of HP and (U)HT granulites in a subduction–accretion–collision setting with ensuing release of CO_2. (a) Post-collisional slab break-off and asthenospheric upwelling. (b) Release of CO_2 from the lower crust to higher crustal levels and atmosphere through megashear zones. Panel a is from Santosh et al. (2012). Panel b is redrawn from Touret and Huizenga (2012).

(WPTZ), which is characterized by double-sided subduction zones and resultant mantle refrigeration between the Pacific and Indo-Australian plates, is consequently considered to be the frontier of a future supercontinent that is predicted to form in 250 million years.

Conversely, Phillips and Bunge (2007) provided evidence that suggests that periodic supercontinent cycles are unlikely if thermal instabilities originating at the core–mantle boundary are of sufficient strength. Modeling based on multiple mobile continents with vigorous mantle convection in a spherical geometry suggests that periodic supercontinent cycles are unlikely to occur in realistic Earth models. Zhong et al. (2007) and Li and Zhong (2009) modeled mobile-lid mantle convection in a three-dimensional spherical shell and their results suggest that the structure of the present-day mantle, with antipodal Africa and Pacific superplumes, is a natural consequence of very long-wavelength mantle convection interacting with the supercontinent Pangea. Their model explains the basic features of true polar wander (TPW) events for Rodinia and Pangea, including their equatorial locations and large variability of TPW inferred from paleomagnetic studies. O'Neill et al. (2009) modeled the thermal and dynamic impact of supercontinents on Earth-like mobile-lid convecting systems. Their study confirms that insulating supercontinents (over 3000 km across) can impact mantle temperatures, and that there is a robust association between rising plumes and supercontinent interiors.

On the other hand, Coltice et al. (2009) argued for mantle warming beneath supercontinents in the absence of hot plumes, and performed numerical simulations that showed that their mantle global warming model could account for the widespread magmatism that accompanied the formation of most supercontinents. However, an investigation into the effect of continental insulation in 2D and 3D mantle convection models indicates that subduction patterns determined by continental width play the dominant role in enabling the formation of subcontinental mantle upwellings (Heron and Lowman, 2011). Subcontinental plumes develop as a consequence of subduction patterns rather than continental thermal insulation properties.

The role of mantle plumes in the breakup of supercontinents has also been investigated in recent studies (see Zheng-Xiang and Zhong, 2009; Santosh, 2010c for reviews). Vaughan and Storey (2007) presented a conceptual model in which supercontinents, by focusing subduction on narrow areas of the 660 km mantle discontinuity, trigger superplume events that initiate their own fragmentation. Based on evidence that includes flood magmatism, kimberlite emplacement, plate reorganization, geomagnetic reversals, marine anoxia, deposition of carbon-rich sediments, the carbon isotope record, major mass extinctions, and global sea levels, they report a superplume between 227 and 183 Ma, coincident with the breakup of Pangea. Based on the evidence from ongoing subduction of sediments and juvenile arcs in the western Pacific, Senshu et al. (2009) emphasized the role of subducted tonalite–trondhjemite–granite (TTG) crust, enriched in K, U and Th, in the deep mantle as a potential driver in the initiation of plumes or superplumes. They propose that this mechanism of generating superplumes may have played a dominant role in supercontinent breakup.

Advancements in numerical modeling have led to many recent studies attempting to simulate the formation and breakup of supercontinents. Zhang et al. (2009) investigated the stochastic models of randomly moving continental blocks and 3-D spherical models of mantle convection with continental blocks. While the time required for all the blocks to assemble into a supercontinent was significantly longer than that inferred for Rodinia and Pangea in their stochastic models, in dynamic models with moderately strong lithosphere and lower mantle (relative to the upper mantle), continental blocks assembled into supercontinents in about 250 million years. However, in this study, as in most numerical models, the continental blocks are assumed to be rigid. But a more recent numerical study by Yoshida (2010) allows the modeling of mobile, deformable continents, including oceanic plates, and successfully reproduces continental drift similar to the processes and timescales envisaged in the Wilson Cycle. The process of supercontinent assembly induces a temperature increase beneath the supercontinent due to thermal insulation. This, in turn, leads to a planetary-scale reorganization of mantle

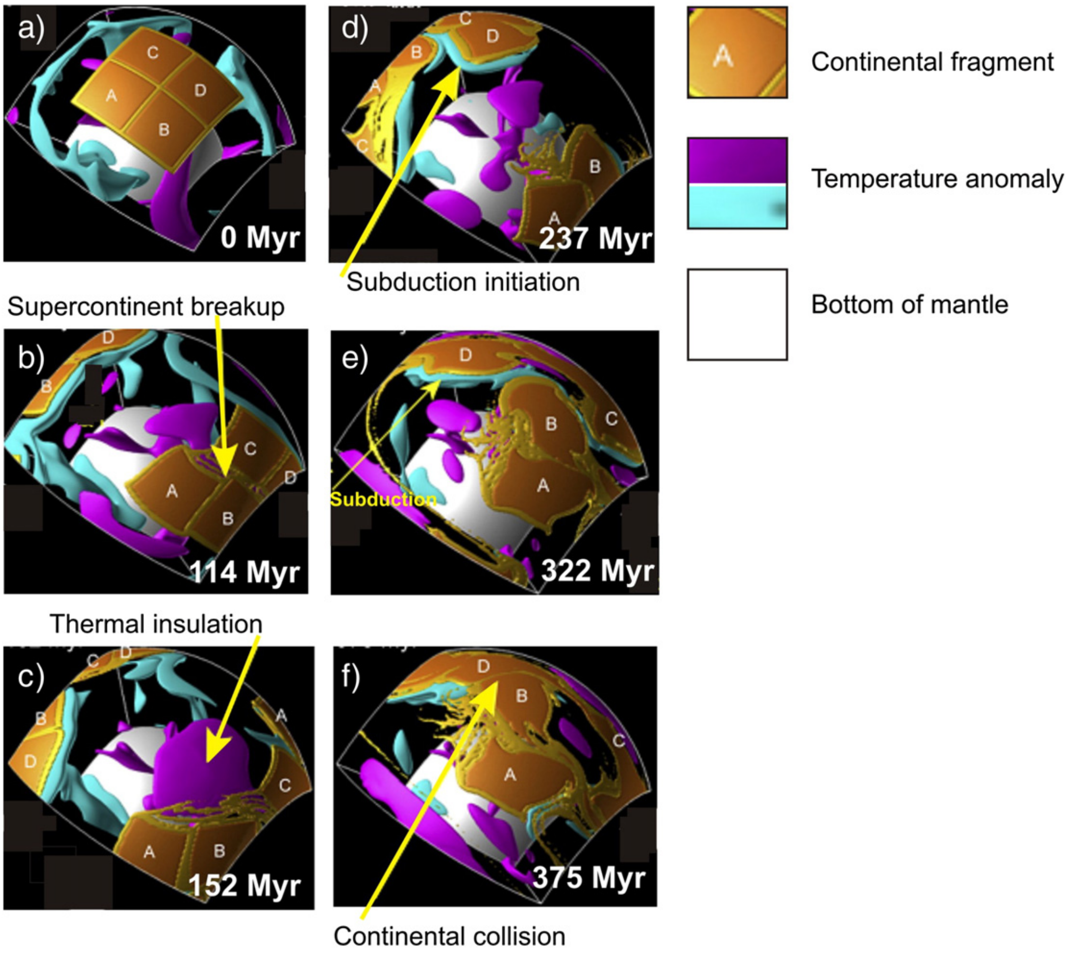


Fig. 20. Time sequence of mantle convection with deformable, mobile continents. Purple and blue regions show areas of warm and cool mantle (250°C above and below the horizontally averaged temperature at each depth), respectively, and orange areas indicate the position of continents. White spherical surface indicates core–mantle boundary. Supercontinent is composed of the four continental fragments (A–D) surrounded by weak continental margins (light orange), and is instantaneously imposed on well-developed mantle convection with temperature-dependent rheology. The elapsed times are scaled by an Earth-like timescale. From Yoshida and Santosh (2011a). Details of the numerical methodology and model parameters can be found in Yoshida (2010) and further explanation of the model in Yoshida and Santosh (2011a).

flow that results in degree-one convection, in which upwelling in one hemisphere is balanced by downwelling in the other. The formation of degree-one convection seems to be integral to the emergence of periodic supercontinent cycles (Yoshida and Santosh, 2011a). The rifting and breakup of supercontinental assemblies may be caused by either tensional stress due to the thermal insulating effect, or large-scale partial melting resulting from the flow reorganization and consequent temperature increase beneath the supercontinent (Fig. 20).

Numerical simulations of mantle convection have also been used in some recent studies to predict the configuration of the future supercontinent Amasia speculated from geological correlations. Mantle convention in the model of Yoshida and Santosh (2011b) is driven by a density anomaly compiled from global seismic tomography. The model simulates the temporal evolution of a highly viscous continent with an initial present-day configuration for the next 250 million years. The result suggests that Australia, Eurasia, North America and Africa will gather in the northern hemisphere to form the next supercontinent. However, Antarctica and South America remain in their present-day positions and do not form part of the future supercontinent configuration.

Rolf et al. (2012) investigated the feedbacks between continental drift, oceanic plate tectonics and the thermal state of the Earth's mantle using 3D spherical numerical simulations with self-consistently generated plates and mobile continents in configurations ranging from a single supercontinent to six small continents. Their findings suggest that, whereas subcontinental mantle temperatures beneath dispersed continents can be lower than those of the suboceanic mantle, supercontinents significantly increase oceanic heat flow (and, hence, decrease suboceanic mantle temperatures), and raise subcontinental mantle temperatures sufficiently to promote partial melting and possible supercontinent breakup. Hence, they argue that melting and magmatic activity below continents are episodic processes, which could account for the episodicity in the growth of continental crust. Numerical modeling by Glišović et al. (2012), while not directed at supercontinents, suggests that deeply rooted mantle plumes may be maintained over very long geological time spans.

4.9. Secular trends

Several recent studies have examined the influence of the supercontinent cycle on the Earth's long-term secular trends. According to Eriksson et al. (2005, 2012), for example, global sedimentation patterns in the Precambrian reflect three “superevents” at ca. 2.7, 2.2–1.8 and 0.8–0.6 Ga, each encompassing major changes in the Earth's evolution related to the supercontinent cycle, mantle superplumes, peaks in crustal growth rates, and significant biochemical changes within the atmosphere–hydrosphere system. Sea level associated with the first of these “superevents” led to the formation of epeiric seas within which the first giant carbonate platforms developed, while deposition of banded iron formations peaked at ca. 2.5 Ga. Alternate episodes of intraglacial CO_2-related warming and synglacial decreases in weathering can be traced to the first global glaciation at ca. 2.4–2.2 Ga. By ca.1.8 Ga, the existence of large landmasses and free oxygen in Earth's atmosphere allowed for global red bed sedimentation and the full spectrum of Phanerozoic sedimentary environments. The third "superevent" essentially recreated conditions of the second with accompanying global glaciation. Eriksson et al. (2013) go on to identify major turning points in the secular evolution of sedimentary systems at ca. 2.7 Ga, concomitant with the possible onset of the supercontinent cycle, and at ca. 2.4–2.3 Ga and ca. 580 Ma, associated with major oxidation events (see also Eriksson and Condie, 2013).

The development of passive margins through Earth history (Bradley, 2008) has also been shown to provide useful information on the breakup timetable of supercontinents and the related history of seawater $^{87}Sr/^{86}Sr$. Precambrian passive margins had longer lifespans than those of the Phanerozoic, consistent with the notion that plate tectonics was slower (Korenaga, 2004), rather than faster, in the Precambrian. Phanerozoic passive margins track the assembly, tenure, and breakup of Pangea, but the passive-margin record is not as obviously consistent with the breakup of Nuna (Columbia), the assembly of Rodinia, or the breakup and assembly of Pannotia. However, in a more recent extension of his attempt to refine the timetable of supercontinent assembly, tenure and breakup using a broader variety of secular trends, Bradley (2011) showed that many, in particular the abundances of detrital zircon ages, granulites, eclogites, carbonatites, volcanic massive sulfides and greenstone belt deformational events, bear the imprint of supercontinent cyclicity.

5. Concluding remarks

The concept of the supercontinent cycle has evolved significantly from the initial and inevitably simplistic ideas of the 1980s to the more sophisticated analyses of the past decade. As a result of improvements in zircon geochronology and isotope geochemistry, the advent of mantle tomography, and ever-more sophisticated numerical and dynamic modeling, significant advances have been achieved in our understanding of mantle dynamics, the interaction of the supercontinent cycle, and the history of the Earth's geosphere, atmosphere, hydrosphere and biosphere. Although the cycle appears to be less periodic than originally envisioned by Worsley et al. (1982, 1984) on the basis of early radiometric age compilations (see Fig. 4), it is becoming increasingly clear that Earth history has indeed been punctuated by the episodic assembly and breakup of supercontinents, at least from the Paleoproterozoic, just as they advocated. Furthermore, while the configuration of these supercontinents is, in many cases, poorly constrained, it is clear that their amalgamation and dispersal have profoundly influenced solid earth processes, surface environments and biogeochemical cycles. The assembly of supercontinents, promoted by double-sided subduction, may involve introversion (closure of interior oceans formed by supercontinent breakup), extroversion (closure of the exterior ocean), or some combination of these processes, and produces widespread collisional orogens and a high-standing landmass, the rapid erosion of which can draw down atmospheric CO_2, leading to global cooling and possible "Snowball Earth" conditions while releasing increased nutrients into the oceans and raising O_2 production through enhanced photosynthesis. This close coupling between climate, nutrient surplus and oxidation is likely to have had a profound effect on the evolution of life and, at the end of the Neoproterozoic, may have paved the way for the rise of the metazoa.

There is also growing evidence for a strong coupling between the supercontinent cycle and mantle dynamics. Dynamic models with moderately strong lithosphere and lower mantle predict relatively rapid assembly of continental blocks with consequent temperature increases in the underlying mantle as a result of thermal insulation, leading to degree-one mantle convection and supercontinent breakup. In addition, supercontinent amalgamation may be indirectly responsible for the formation of superplumes. The assembly of supercontinents involves the peripheral subduction of large volumes of oceanic lithosphere and it is speculated that these may pond at the 660 km mantle discontinuity before avalanching to the core–mantle boundary to form slab graveyards centered beneath the supercontinent. Collected in this fashion, the recycled oceanic lithosphere is thought to provide fuel for generating superplumes, which rise beneath the supercontinent and contribute to its breakup. The associated development of large igneous provinces and the climatic effects of their volcanic emissions may, in turn, lead to catastrophic changes in the surface environment that could trigger mass extinction and oceanic anoxia. A link between supercontinent assembly and mantle dynamics would, in turn, suggest that the onset of the supercontinent cycle was inevitable once continental blocks had collected in sufficient numbers to raise the temperature of the underlying mantle to a sufficient degree and/or create a superplume of sufficient size to enable the assembled continental blocks to be broken up. The rapidly unfolding relationship between the supercontinent cycle and mantle dynamics may therefore provide the key to our understanding of the evolution of the continental crust, the history of major environmental changes on the Earth's surface, and the evolution of life. With mantle tomography producing images of increasing resolution (e.g., D. Zhao et al., 2013) and quantitative methods yielding increasingly realistic geophysical models, the nature of this relationship may soon be realized.

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