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GR Focus Review

The Cambrian Explosion: Plume-driven birth of the second ecosystem on Earth

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ABSTRACT

The birth of modern life on Earth can be linked to the adequate supply of nutrients into the oceans. In this paper, we evaluate the relative supply of nutrients into the ocean. These nutrients entered the ocean through myriad passageways, but primarily through accelerated erosion due to uplift. In the 'second ecosystem', uplift is associated with plume-generation during the breakup of the Rodinia supercontinent. Although the evidence is somewhat cryptic, it appears that the second ecosystem included the demospongia back into the Cryogenian (~750 Ma). During the Ediacaran–Cambrian interval, convergent margin magmatism, arc volcanism and the closure of ocean basins provided a second pulse of nutrient delivery into the marine environment. A major radiation of life forms begins around 580 Ma and is represented by the diverse and somewhat enigmatic Ediacaran fauna followed by the Cambrian Explosion of modern phyla during the 540–520 Ma interval. Tectonically, the Ediacaran–Cambrian time interval is dominated by the formation of ultra-high pressure (UHP), high pressure (HP) and ultra-high temperature (UHT) orogenic belts during Gondwana orogenesis. Erosion of this extensive mountainous region delivered vast nutrients into the ocean and enhanced the explosiveness of the Cambrian radiation. The timing of final collisional orogeny and construction of the mountain belts in many of the Gondwana-forming orogens, particularly some of those in the central and eastern belts, post-date the first appearance of modern life forms. We therefore postulate that a more effective nutrient supply for the Cambrian radiation was facilitated by plume-driven uplift of TTG crust, subsequent rifting, and subduction-related nutrient systems prior to the assembly of Gondwana. In the outlined scenario, we propose that the birth of the 'second ecosystem' on our planet is plume-driven.

Contents

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1. Introduction

1.1. The Cambrian Explosion: nutrients as the most essential factor

One of the most spectacular events in Earth history, termed the 'Cambrian Explosion' (CE), witnessed the origin of metazoans from unicellular organisms and their subsequent evolution into large multi-cellular animals at the dawn of the Phanerozoic (Gould, 1989, 1995, 1998; Maruyama and Santosh, 2008; Meert and Lieberman, 2008). There are multiple hypotheses and proposed triggers for the CE, but many consider that the most important change that took place was an increase in the oxygen content of the oceans and atmosphere (Gould, 1998; Holland, 2006; Chumakov, 2010). It is thought that oxygen levels increased up to a hundred fold from 1/100 PAL to near present-day levels of 1 PAL near the Ediacaran–Cambrian boundary.

Whereas the increase in oxygen levels is well-documented, a biological enigma remains in that high pO_2 levels alone cannot explain the rapid rise in complexity that is observed in the Cambrian. In particular, we argue that changes in oxygen levels worked in conjunction with a stable supply of essential nutrients to produce the myriad life forms that appeared in the CE. Of utmost importance are the presence of dissolved nutrients such as P, Ca, K, Fe, Mg, Fe, Ca, S, Zn, Mo and others. Nutrients such as Ca, P and Fe are critically important to build the 'hard parts' (bones, shells, teeth) whereas some of the other nutrients are essential for cell metabolism. A continuous supply of these nutrients over time is required to sustain complex life forms.

The abiogenetic origin of primitive life on the early Earth remains a mystery. One of the myriad models for the origin of life considers the interaction of the nascent hydrosphere with mantle rocks to form serpentinites and the subsequent reaction of the vent fluids with CO_2-bearing sea water as part of the 'nutrient' equation (Sleep et al., 2011). The diverse assemblages of microbial fossils found in the 3465 Ma Apex Chert (NW Australia) are thought to represent of the earliest forms of primitive life on the early Earth (Schopf and Kudryavtsev, 2012). Brasier et al. (2013), in a recent study on the Apex basalts, reported the occurrence of pumice clasts with potential biominerals including sulfides and phosphates, together with intimate associations of C, N, P and S. They proposed that these clasts, that also contain catalytic minerals such as titanium oxide, altered clays and zeolites represent an optimum environment for the development of early life.

In addition to proper nutrients, substrates and protective cellular membranes, energy is fundamental to the formation and survival of life. Therefore, consideration of the source and mechanism of various energy yielding pathways is paramount when evaluating the origin and evolution of life. In simplistic terms, solar energy is the dominant external 'power cell' for the planet. Life on Earth took full advantage of this energy source early on with the development of cyanobacterial stromatolites in the Archean. Since the development of the first photosynthetic organisms, a large diversity of primary producers evolved strategies to capture and store solar energy as chemical fuels that are used by other life forms without photosynthetic systems (Ehleringer and Monson, 1993). Lu et al (2012) in a recent study demonstrated that semiconducting mineral photocatalysis, acting as an energy source, promoted microbial growth.

An early study of Brasier et al. (1978) recognized that nutrient supply was one of the most essential triggers for the Cambrian Explosion, although the relationship to elevated pO_2 remained uncertain. Maruyama and Liou (2005) correlated the increase in pO_2 with the deposition of large volumes of sedimentary rocks that prevented the reverse reaction of organic material burial, thereby preserving free oxygen in the atmosphere and maintaining a dynamic equilibria.

Squire et al. (2006) speculated that the abundant nutrient supply leading to the Cambrian Explosion was related to the formation of large collisional mountain belts during the amalgamation of Gondwana at ca. 540 Ma. Based on a compilation of $^{87}Sr/^{86}Sr$ isotopic ratios through time (e.g., Shields and Veizer, 2002), a sharp increase in the rapid and abundant nutrient supply was identified at the onset of the Cambrian (Maruyama and Liou, 2005; Maruyama et al., 2013). The rapid erosion of mountain belts built through continent–continent collisions associated with the formation of supercontinents releases large amounts of nutrients such as iron and phosphorus into the oceans, leading to an explosion of algae and cyanobacteria and enhanced production of O_2 through photosynthesis (Campbell and Allen, 2008). The increased sedimentation also promotes the burial of organic carbon and pyrite, inhibiting the back-reaction with free oxygen and maintaining a sustained increase in atmospheric oxygen as envisaged by Maruyama and Liou (2005).

In a recent work, Peters and Gaines (2012) reached a similar conclusion on the role of nutrients as a trigger for the Cambrian Explosion. Their work suggested that the 'Great Unconformity' resulted from a sudden denudation of a large landmass resulting in a large nutrient supply into the global oceans. The unique appearance of a huge landmass on the Earth during the Neoproterozoic was earlier addressed by Maruyama (1997a) and Maruyama and Liou (2005), who concluded that it was a consequence of the cooling Earth that triggered the initiation of return-flow of seawater into mantle, thereby lowering the sea level and exposing the landmass to enable weathering and transport of nutrient elements into the ocean. The appearance of blueschist facies rocks and low-T eclogites in subduction zones over the last 750 Ma, the extensive hydration of the hanging walls of the mantle wedge, and the hydration of the mantle transition zone were considered as the key evidence for the decreasing volume of ocean water on the Earth's surface since the Neoproterozoic. These aspects are discussed in more detail in a companion paper (Maruyama et al., 2014).

In this work, we address the following major aspects. (1) The location of mountain belts during the formation of Gondwana based on the space–time distribution of collision-type orogenic belts and their P–T estimates. (2) Continental rifts, initially elevated by rising plumes, as the most effective source of nutrient supply. (3) The role of post-collisional up-doming caused by the heated and metasomatized mantle through the effect of the 'second continents' in the mantle transition zone at 410–660 km depth, generated through subduction of TTG components.

1.2. Mechanism of nutrient supply from continents

The system of nutrient supply on Earth is generally two-fold. One is at the mid-oceanic ridge where circulating seawater transports nutrients from MORB (mid oceanic ridge basalt) crust and the steady-state supply of MORB magma plays a critical role for the heat budget. This system has been active ever since the birth of plate tectonics in the early Earth. However, this mechanism makes only a limited contribution because the volume of several key elements, such as P and K is extremely poor as compared to those on the surface of the Earth. We tentatively name this system as the first nutrient supply system (first ecosystem). Compared to this relatively minor contributor, the nutrient supply system on the Earth's surface is extremely powerful, probably 10^{12} times more than the first nutrient supply system (Maruyama et al., 2013). We refer to this as the second nutrient supply system (second ecosystem), and discuss its characteristics below.

The equatorial region of the water-covered planet Earth is heated by incoming solar radiation. This process transfers water vapor into the atmosphere, drives oceanic and atmospheric circulation and is the primary control on the Earth's climate. Weathered and eroded mountain debris is transported into the oceans via aeolian, glacial and fluvial systems. The processes of denudation and transportation progressively reduce the grain-size of particles and leads to an increase in particulate surface area available for reaction with seawater. Depending on other factors such as *p*H and pO_2 in the ocean, ions such as PO_4^{2-}, SO_4^{2-} and K^{2+} are extracted from the minerals, and become bioavailable.

The volume of continental landmass also plays a critical role in nutrient supply via erosion. For example, if the amount of continental landmass is small (high sea level), then erosional processes may proceed more slowly irrespective of the total volume of continental crust. In the case of higher sea levels, the secondary nutrient supply is diminished. The Archean Earth might have faced this situation, despite the presence of granitic crust, as evidenced by the limited record of sedimentary rocks in the Archean orogenic belts (Ronov, 1994; Maruyama and Liou, 1998, 2005; Maruyama et al., 2013). Therefore, a significant change in Phanerozoic continental landmass may also mark the transition from simple to more complex life as more erosion would result in an increased nutrient supply into the oceans (Fig. 1).

1.3. The role of Solid Earth for the Cambrian Explosion

It has long been held that the Cambrian Explosion is essentially a biological phenomenon and is unrelated to changes on the solid Earth. Life expanded from unicellular to multicellular forms with the size of the organisms increasing by more than one million times (Payne et al., 2009). Although the 'explosiveness' of the Cambrian expansion can be debated, the fossil record indicates a major pulse of evolutionary change during a relatively short 20 million year interval during the Early Cambrian (Steiner et al., 2007; Shu, 2008). This process is often nicknamed the 'Big Bang' in the history of life on our planet. Most animal phyla appeared during this short period, without any major mass extinction (Gould, 1995). However, recent studies show that at least 7–8 episodes of mass extinctions occurred within a relatively short time between 635 and 488 Ma (Zhu et al., 2007), suggesting an extensive scale of surface environmental changes during this period.

Here we propose and evaluate the role of the solid Earth in the Cambrian Explosion of life. Our model considers an abrupt and adequate supply of nutrients both from collisional orogenic belts and from the plume-related upheaval of continents. The role of mantle dynamics in the surface processes is also discussed.

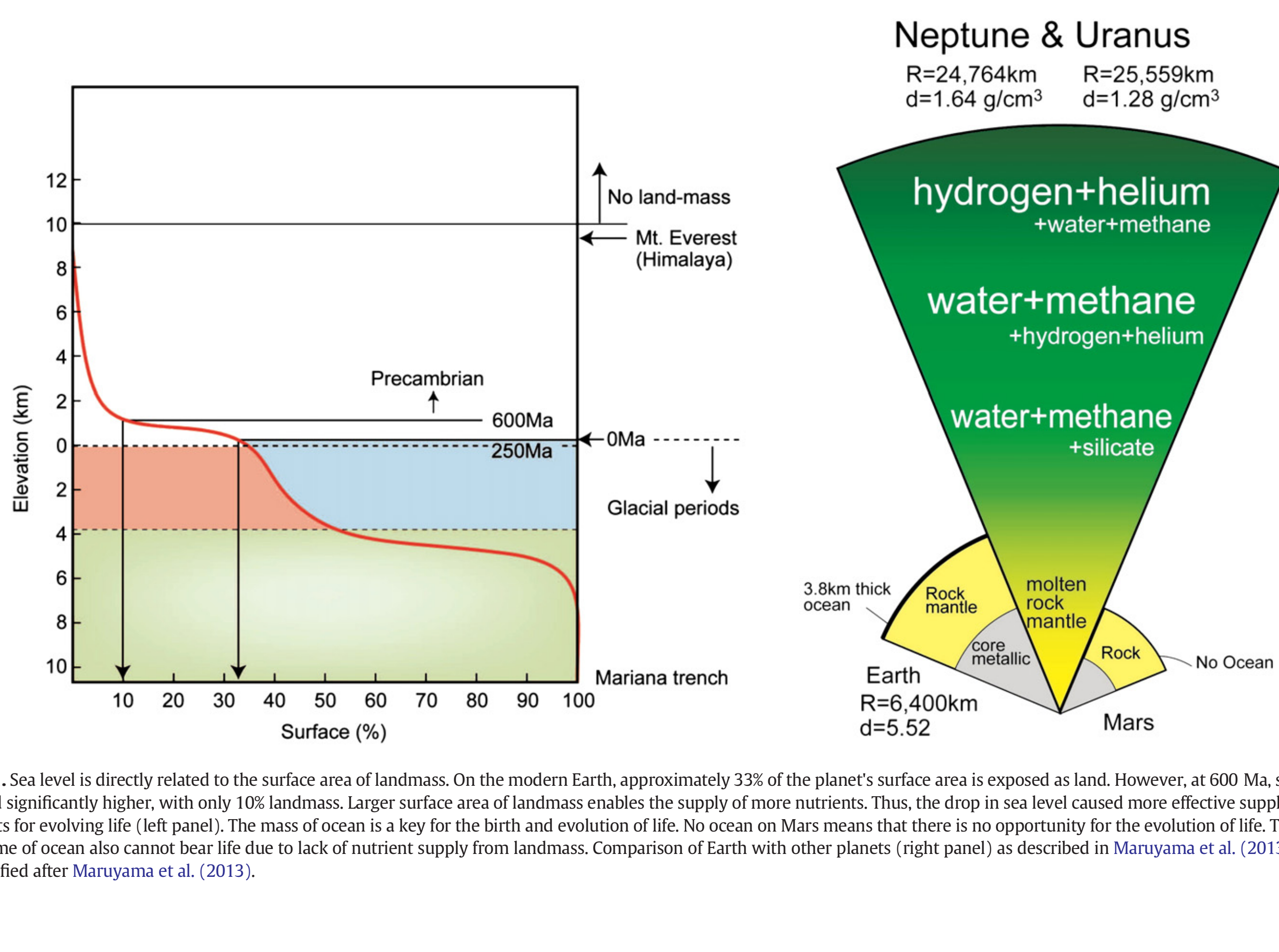


Fig. 1. Sea level is directly related to the surface area of landmass. On the modern Earth, approximately 33% of the planet's surface area is exposed as land. However, at 600 Ma, sea level stood significantly higher, with only 10% landmass. Larger surface area of landmass enables the supply of more nutrients. Thus, the drop in sea level caused more effective supply of nutrients for evolving life (left panel). The mass of ocean is a key for the birth and evolution of life. No ocean on Mars means that there is no opportunity for the evolution of life. Too large volume of ocean also cannot bear life due to lack of nutrient supply from landmass. Comparison of Earth with other planets (right panel) as described in Maruyama et al. (2013). Modified after Maruyama et al. (2013).

2. Mountain-building: potential source of nutrients

In order to supply nutrients to the oceans, a well-balanced nutrient-supply system should be present on the land, involving rocks with the relevant mineralogical constituents. The most appropriate rocks with essential components are TTG (tonalite–trondhjemite–granodiorite) or andesite, both generated largely through subduction along convergent plate margins, building the continental landmass through time. It is thought that about 1 km^3 of TTG/andesite is generated each year since the Miocene (Reymer and Schubert, 1984). While extrapolation of this rate to deep time contains many caveats, it would require about 4 billion years to generate the amount of TTG crust on the present Earth.

In contrast, rocks such as peridotite or basalt are not appropriate sources for balanced nutrients because they are extremely poor in metabolic nutrients that drive metabolism metazoans.

As mentioned in the previous section, availability of nutrients is only part of the equation. If TTG/andesitic crust is the primary source of life-giving nutrients, then there must also be an effective transport mechanism to deliver the nutrients into the oceans. Erosion on Earth's surface and transportation of nutrients to oceans is highly effective, and is 10^{12} times more efficient in terms of nutrient delivery (Maruyama et al., 2013) as compared to nutrient supply at the mid-ocean ridges.

Finally, the elevation of landmass above sea-level controls the supply of nutrients. Gravitational instability causes landslides or erosion by snowfall or rainfall, and acts more effectively in the elevated parts of landmasses. The higher the landmass, the more the materials are transported into the oceans. In the next section, we address this aspect further through evaluating the two major types of mountain-building processes.

2.1. Collision-type orogeny vs. Pacific-type orogeny

Since the pioneering work by Dewey (1969) and Dewey and Bird (1970) who classified orogeny into Cordilleran- and collision-types, our understanding of mountain-building has advanced considerably, including the contrasting styles of orogeny and the mechanisms of exhumation of the orogenic core (Santosh et al., 2010).

In terms of generating new nutrient source rock (TTG/andesite), it is important to note that collision-type orogeny does not lead to an increase in new volumes of the TTG crust. These types of orogenic belts are mostly restricted to deformation and recycling of existing TTG crust from the mountain belts into the oceans. A typical example is the Himalayan orogen. The total mass transported by the Himalayan orogeny into the Indian Ocean has generated 4–5 km thick deltaic sediments on the ocean-floor, extending over 3000 km with a width of over 1000 km. These were formed predominantly during the last 7 Myr related to the late-stage exhumation of the Himalayan orogen (Yin, 2006; Maruyama et al., 2011).

On the other hand, the Pacific-type orogeny is a productive process in terms of generating new TTG crust through magmatism in subduction zones. The steady-state formation of new TTG crust, ~1 km^3/year played a major role in expanding the volume of continental crust throughout Earth history. As first recognized by marine geophysicists, the process of tectonic erosion at the frontal margin of overriding plates in this type of orogeny has significantly contributed to the destruction of continental crust (Isozaki et al., 2010; Santosh, 2010; Maruyama et al., 2011; Stern, 2012). Furthermore, in many cases, intra-oceanic arcs are directly subducted into the deep mantle without any accretion to the hanging wall. This process is documented by the presence of at least six arcs under the active margin of SW Japan (Yamamoto et al., 2009). Terrestrial geology also strongly supports extensive tectonic erosion across the world through geologic time. Clift and Vannucchi (2004) and von Huene and Scholl (1991) show that the production of TTG crust is approximately balanced by its destruction during deep subduction into the mantle (see also Reymer and Schubert, 1984). The supply of nutrients to the ocean basins in a Pacific-type orogeny operates differently in the two largest arc systems on the present-day globe. The Western Pacific arc system consists of isolated island chains that are discontinuous along the arc. The islands of Japan, which represent the most evolved arc, contains granitic rocks dating back to the Cambrian (~500 Ma). These granites were generated during subduction along the eastern margin of Asia prior to the opening of the Japan Sea (Miocene, Isozaki et al., 2010). The 200 km wide Japan arc is cored by a central volcanic front under which a ca. 100 km wide buoyant mantle plume is currently rising, leading to a ~.1–2 km elevation difference relative to the surrounding basement rocks. Active production of felsic magma causes nutrient supply through volcanic ash, erosion and transportation to the surrounding oceans. As long as subduction continues, magmatism will supply nutrients efficiently to the surrounding regions. However, this process will not be effective if sea-level is higher than the elevation of the islands. An example is the Mariana arc, where the nutrient supply to surrounding regions is not effective.

In contrast to Himalayan-type orogenesis, Andean-type orogeny (as represented by the Cordillera Mountain belt on the eastern margin of the Pacific Ocean) is related to the subduction of oceanic lithosphere without any major collision of continental masses. The convergence of oceanic and continental crust in Andean-type orogeny, with a typical rapid motion of the overriding plate, generates continental arcs, and has produced some of the highest mountains in the world. Subduction along the Andean–Cordilleran arc system produces uplift and erosion on existing continental crust. Nutrients from this arc system are delivered to the oceanic realm via riverine and glacial systems (Fig. 2).

2.2. Continental rifts: another potential source

A rising plume beneath a supercontinent commonly splits the landmass resulting in the birth of a new ocean basin. Continental rifts will generate a small seaway similar to that of the Red Sea. If rifting continues, these small seaways will develop into major oceans similar to the present-day width of the Atlantic Ocean (~3000 km). At some point, the buoyancy of the oceanic crust in these wide oceans becomes negative and subduction can initiate along a passive margin similar to the modern Indian Ocean. Eventually, the plate tectonic system evolves into the Pacific-type characterized by active margins leading to the reduction in size of the intervening ocean in the closing phase. Finally, the ocean closes. If the oceanic plate is obducted onto the continent, a shift to the trench and final collision against the continent would occur to build large mountain belts as in the case of the Indian collision and the building of the Himalayas.

During continental rifting, landmass can be uplifted as much as ca. 2000–3000 m above the sea-level, as seen in the modern-day African Superswell (Fig. 3; Nyblade and Robinson, 1994). If we compare the elevated regions above the surrounding flat plane, such as for example, the African rifts against the Andean mountains, a strike length of over 3000 km can be noted, with a width about 3 times more in the African rifts than in the Andean belt (Fig. 3). If we compare the African rift with the Himalayan belt, a similar conclusion applies. However, if we include the Tibetan plateau and associated regions in China, the situation is different. In East Asia, an extremely broad region over 4000 km across, experienced uplift since the Miocene, presumably aided by infusion of a hydrous upper mantle. At least 40 hydrous plumes can be postulated that penetrated the continental crust to generate a number of microplates and opened a series of marginal basins in the Western Pacific and East Asia (Komiya and Maruyama, 2007).

We now attempt to evaluate sediment transport by rising plume versus collisional orogeny. There has been a longstanding notion that mountain-building by continent–continent collision was the most critical process that initiated an abundant supply of nutrients into oceans. Typically, the Himalayan Orogeny forms the *casus belli* for these arguments beginning with the India–Asia collision at 50 Ma and

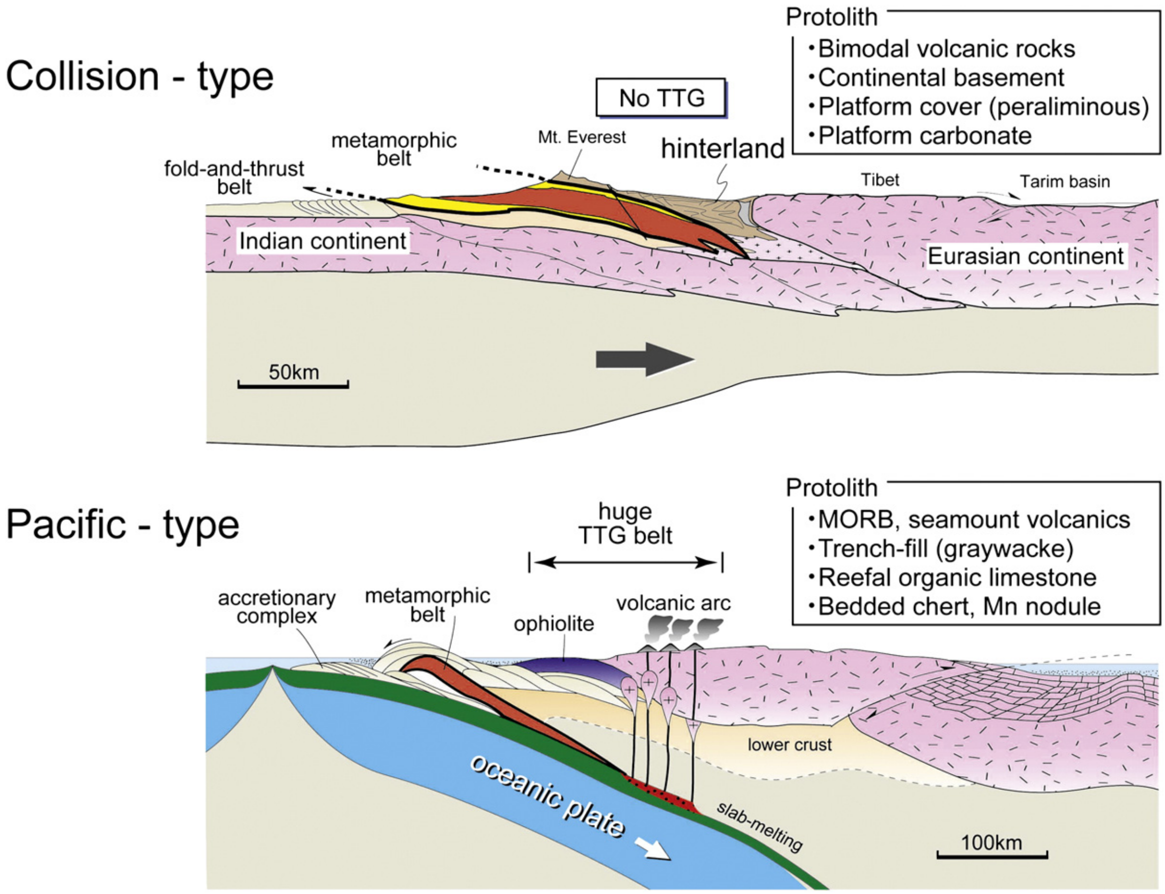


Fig. 2. Collision-type (top panel) and Pacific-type (bottom panel) as the two major types of orogenies on Earth, critical for the source of nutrients. The detailed structure of the two orogens are modified from Maruyama (1997b).

subsequent Tibetan and Himalayan uplift since ~7 Ma (Yin, 2006; Maruyama et al., 2010). $^{87}Sr/^{86}Sr$ ratios in carbonate sedimentary rocks (Shields and Veizer, 2002) support this idea because of the broad coincidence between the timing of collision and uplift with the observed Sr isotopic evolution in the ocean. Conceptually, large pulses of mafic additions to the crust associated with plume generation would act to lower the $^{87}Sr/^{86}Sr$ ratios in the sedimentary record; however, uplift associated with plume head arrival will increase continental erosion and mute this low-radiogenic signal.

Here we propose the idea that plumes elevate continental crust during continental rifting and this plume-generated uplift is responsible for delivering nutrients into the global ocean. Fig. 3 shows the distribution of the high topographic regions that rise above 500 m. The mountain-building processes in general are subdivided into: (1) those formed by Pacific-type processes such as in the Andes, Japan, Kamchatka–Aleutian region, and New Zealand; (2) those reflecting continent–continent collision such as the Himalaya, Alps (Atlas at the tip of NW Africa) and the Zagros belt; (3) continental rifts such as the East African rift and adjacent regions of the Red Sea, as well as regions on both sides of the Labrador trough between West Greenland and the NE margin of Canada, and; (4) a combination of rising plumes and Pacific-type processes observed in W. North America, or rising plumes in concert with continent collision such as in the major parts of East Asia, from Tibet through Indochina, to the Baikal rift.

With regard to the areal extent for each of the aforementioned regions, those characterized as continent-collision occupy only 10% of the present-day surface area of the globe (we ignore ancient and more eroded mountain chains such as the Appalachians and Urals). Pacific-type orogens and plume-affected regions each cover about 15% of the surface area and the remaining types dominate the globe ~60%.

Topographic highs such as in central Africa, Kolyma in Russia, Norway and along the eastern margin of North and South America are all remnant topographic highs. These regions were elevated via rising plumes beginning in the Cretaceous.

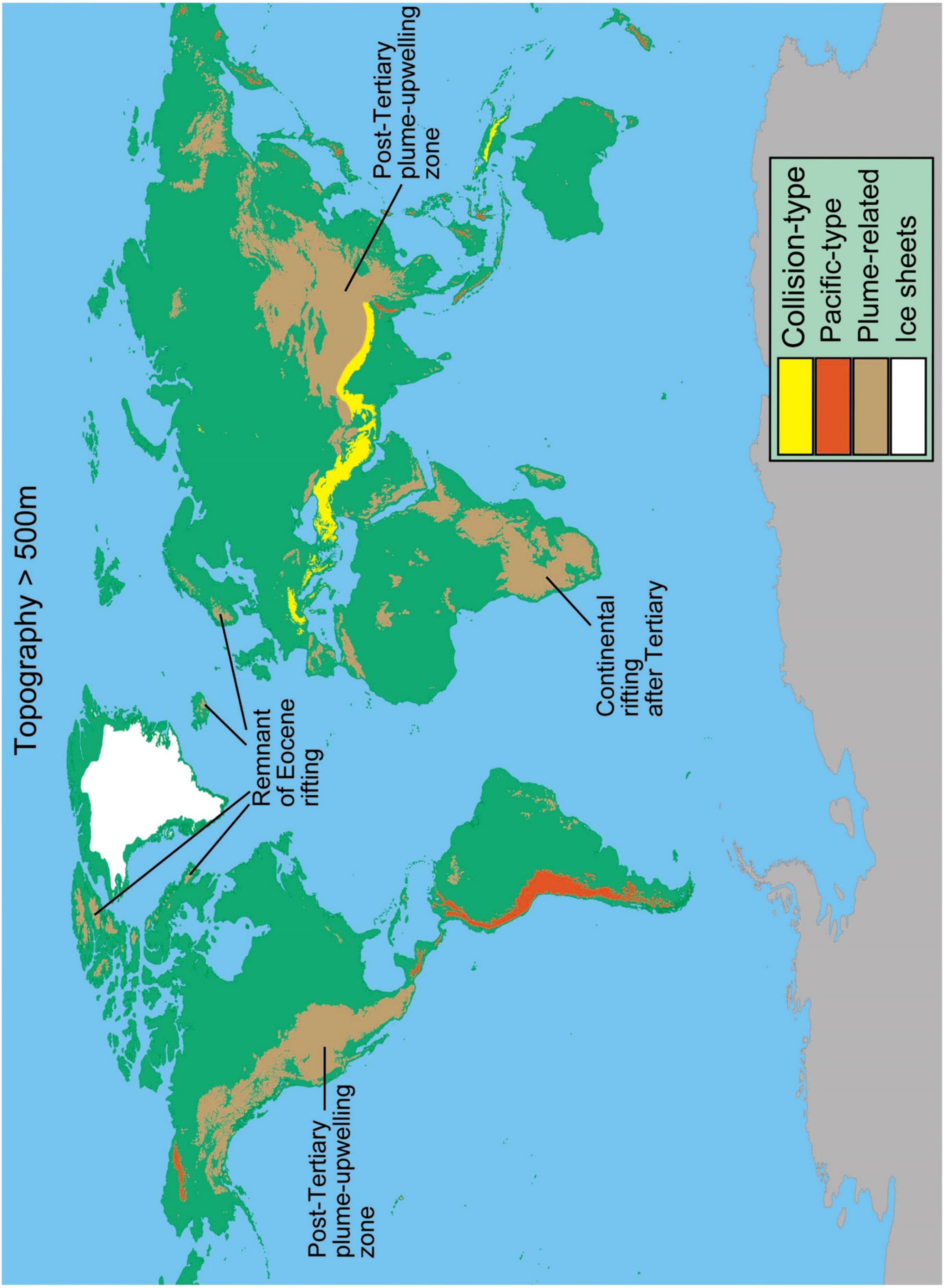
These observations indicate that a potential major source of nutrient supply may result from plume-driven topography. Total elevation changes due to plume-driven uplift may exceed 2–3 km and the resultant erosional processes may be as much as 3–4 times more effective in transporting nutrients to the ocean as compared to nutrients emanating from continent–continent collisions.

In summary, continental rifting plays a potential role for nutrient supply from continents to oceans, and can be several times more efficient than delivery from mountain belts located along collisional plate boundaries (Fig. 4).

3. From Rodinia to Gondwana

The Neoproterozoic supercontinent Rodinia was first proposed by McMenamin and McMenamin (1990). Dalziel (1991, 1992) also proposed a slightly different configuration of this supercontinent. Hoffman (1991) presented the mechanism of supercontinent cycle from Rodinia to Gondwana. In an independent study, Maruyama (1994) suggested that the birth of the Pacific Ocean is related to a 'Pacific' superplume which split the Neoproterozoic supercontinent at its center into several continental fragments including North America, Australia + Antarctica, East Asia and South America. The process initiated at ca. 600–700 Ma, and continued until 500–450 Ma, followed by the initiation of subduction zones around the Pacific rim (Fig. 5).

Between Rodinia breakup and the initiation of subduction around the Pacific rim, the globe also witnessed the formation of another very


Topography > 500m
Post-Tertiary plume-upwelling zone
Remnant of Eocene rifting
Continental rifting after Tertiary
Post-Tertiary plume-upwelling zone
Collision-type
Pacific-type
Plume-related
Ice sheets

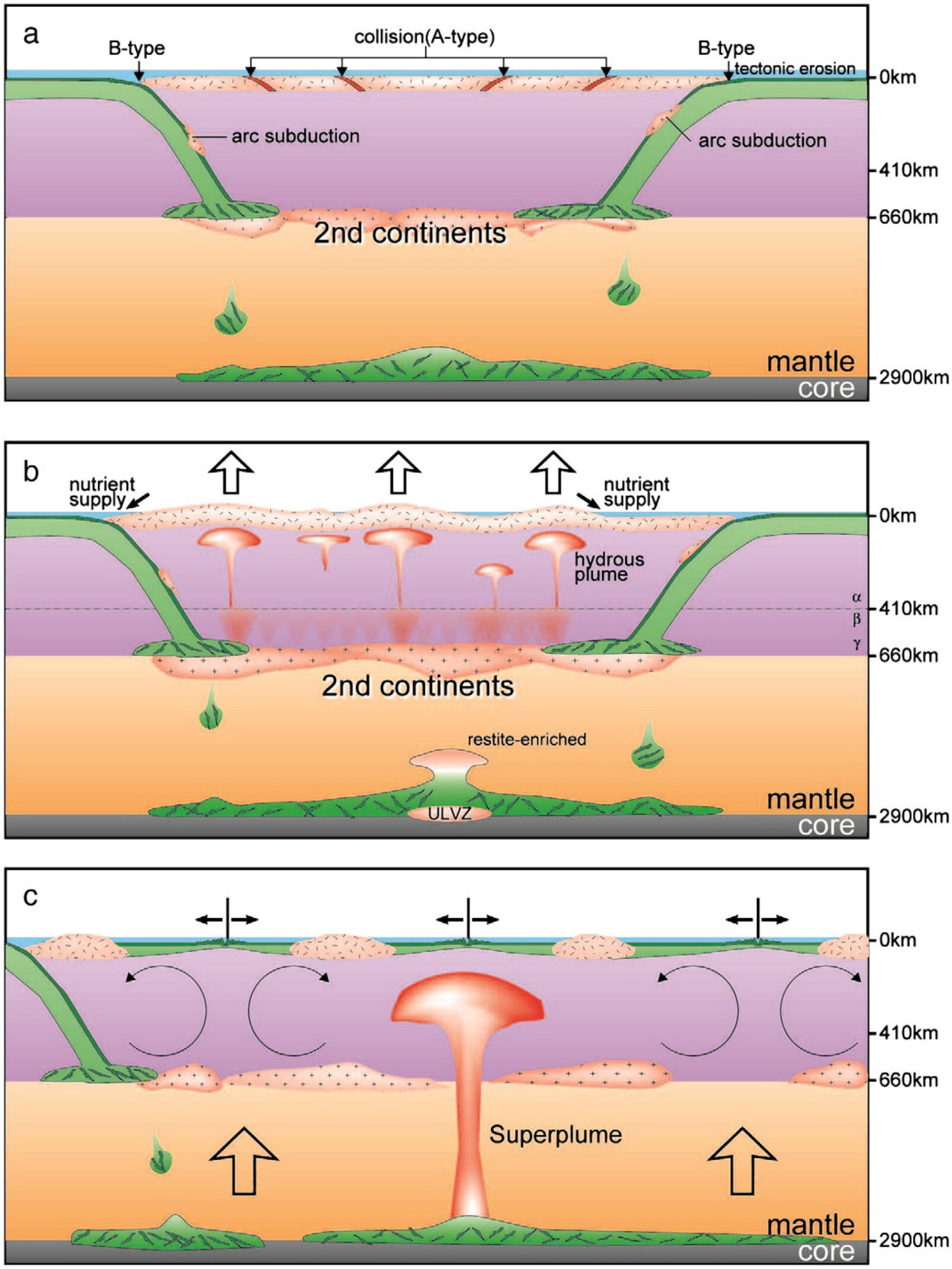


Fig. 4. Supercontinent cycle and sediment supply as a function of time. Stages 1, 2, and 3, (a, b, and c respectively) are schematically shown. Sediment supply is most efficient during the stage of plume-upwelling in both rifting of supercontinent and post-collision uplifts in amalgamated continents.
The concept of 'second continent' in the mantle transition zone that formed through the subduction of TTG materials shown in the figure is after Kawai et al. (2013).

large continent, Gondwana in the late Neoproterozoic–Cambrian, although the details of Gondwana assembly were not known in earlier days when the above proposals were made. However, the complexity of this assembly process was first noted by Meert et al. (1995). Thus, the paleogeographic transitions from Rodinia (1.0 Ga) to Gondwana (600–540 Ma), and from Gondwana to Pangea (250–200 Ma) were debated.

Fig. 3. Comparison of regions with elevation higher than 500 m between (1) continental rift, and (2) collision zone mountain belt or Andean mountain belt. Also shown is the region where Post-Tertiary plumes were active in doming up continental and oceanic lithosphere, particularly under East Asia and surrounding regions, western N. America and Africa. Note the 10 times wider regions that are 1 km above sea-level generated by plumes as compared to those in the mountain-building domains by Pacific and collision-type orogenies. A comparison is also shown among regions of sediment supply by (1) continent-collision (collision-type), (2) Pacific-type, (3) continental rifts, and (4) post-collisional uplifts (3 and 4 shown as plume related). Note the wider regions of sediment supply related to rising plumes, as compared to mountain-building by continent–continent collision. This conclusion deviates from the previous models which emphasized mountain building as the dominant source for nutrients (e.g., Squire et al., 2006).
Topographic maps after Oxford Atlas of the World (2012).

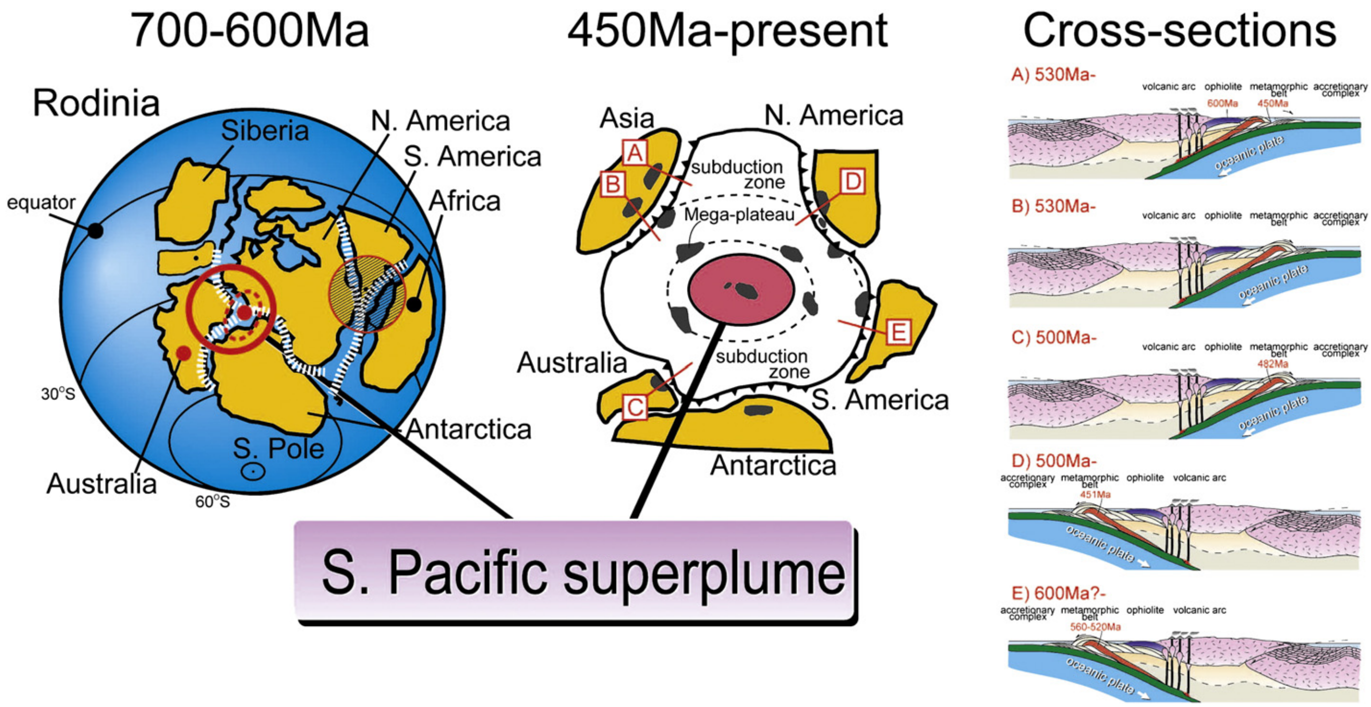


Fig. 5. From Rodinia to the present, emphasizing the role of Pacific superplume that broke up the Neoproterozoic supercontinent (after Maruyama, 1994). The recycling of a huge slab graveyard on the core–mantle boundary (CMB) under Rodinia generated by extensive subduction of oceanic lithosphere in the mid-Proterozoic gave birth to a superplume (Maruyama, 1994; Maruyama et al., 2007). North America moved NE-ward, Asia moved NW-ward, Antarctica + Australia moved southward, and S. America SE-ward, generating passive continental margins. Since the breakup of Rodinia at 700–600 Ma, the paleo-Pacific Ocean was widened until ca. 500–450 Ma when active margins appeared around the Pacific rims. Around 500–450 Ma, changes of plate margin from passive to active are recorded in orogenic belts on the Pacific rims as shown schematically on cross sections (right panels A to E) for Asia, North America, Klamath Mountains, S. America and eastern Australia. Between the two stages (left panel: 700–600 Ma and right panel 450 Ma), Gondwana was amalgamated at ca. 540 Ma or slightly afterward.

The paleogeographic reconstruction of Rodinia has also been debated among paleomagnetic specialists (e.g., Pisarevsky et al., 2000; Meert, 2001; Torsvik et al., 2001; Cordani et al., 2003; Veevers, 2004; Li et al., 2008). Despite the longstanding controversy about the relative positions of cratonic elements within Rodinia, a general consensus has emerged that a large supercontinent formed around 1.1 Ga and began to break apart during the Cryogenian. Within Rodinia, the positions of minor cratonic fragments such as Tarim, Indochina, Kazakhstan, S. China, N. China and Avalonia remain uncertain (see one example in Fig. 6).

The mode of Gondwana assembly has also been hotly debated. The ‘traditional’ views for the formation of Gondwana postulate unification of a rigid ‘West Gondwana’ (Africa and South America) with a stable ‘East Gondwana’ block (Australia, India, Sri Lanka, Madagascar, East Antarctica) during the Cambrian (e.g., summary in Yoshida, 2007; Yoshida and Upreti, 2006). This view was first challenged by Meert et al. (1995) and Meert and Van der Voo (1996) who argued that Gondwana assembly was a polyphase process and neither East nor West Gondwana existed as rigid blocks until their assembly during the Neoproterozoic–Cambrian. This more complex picture of Gondwana assembly is also supported by a number of more recent studies (Meert and Van der Voo, 1997; Meert, 2003; Collins and Pisarevsky, 2005; Meert and Lieberman, 2008; Collins et al., 2014).

The Gondwana continent can be considered as an assembly of four major continental blocks: (1) West African Craton + Amazonian Craton + Rio Plata; (2) Saudi Arabia + Sahara meta-craton + Sao Francisco–Congo Craton + Kalahari Craton, (3) Madagascar + Indian Craton(s); and (4) Australia + East Antarctica. Three of the continental collisional orogens among these were formed by the collision of (1) and (2) (termed the Brasiliano–Damara orogen; Porada, 1989), (2) + (3) (the East African Orogen or the Mozambique orogen; Collins and Pisarevsky, 2005) and (3) + (4) (the Kuunga orogen; Meert et al., 1995; Meert and Lieberman, 2008), and its western extension (Fig. 7).

3.1. The western belt

The western belt runs southward from the eastern margin of the West African Craton, through the zone between the Amazonian Craton and Sao Francisco (SF) Craton or between SF and Congo Cratons to further south between the Rio de Plata and Kalahari Cratons. Parallel to this belt, Pacific-type orogens together with collision zones (?) run along the western margin of the W. African Craton, through the eastern margin of the Amazonia Craton to the western margin of Rio de Plata facing the paleo-Pacific Ocean. Before the final collision–amalgamation of these two continents, a wide ocean was present, termed Braziliano or Adamastor Ocean (Meert, 2003; Fig. 7). A number of intra-oceanic arcs formed in this ocean during the Tonian/Cryogenian periods (Neto and Caby, 2000). Most parts of the ocean were closed by 600 Ma, preserving the collisional orogens including coesite-bearing UHP–HP (ultrahigh-pressure–high pressure) belts in between the amalgamated continents.

3.1.1. Distribution of mountain belts—western region

To estimate the nutrient supply, a reconstruction of the exhumed regional metamorphic belts is essential. Some of these were brought to the surface from deep crust or mantle depths (deeper than 100 km in the case of UHP–HP belts such as the Mali coesite-bearing UHP rocks; Caby, 1994). The space–time distribution of UHP–HP belts over the world has been compiled and reviewed in several papers since Maruyama et al. (1996) and others (Maruyama and Liou, 1998; Liou et al., 1998; Brown, 2007: Dobrzhinetskaya, 2012). These are summarized and illustrated in Fig. 6, in addition to the distribution of intermediate-type regional metamorphic belts formed mainly during the Neoproterozoic.

The major UHP–HP regional metamorphic belts in the western region are W. Hoggar, C. Hoggar, Gouma, Mali, Lato Hill, and Togo in Africa

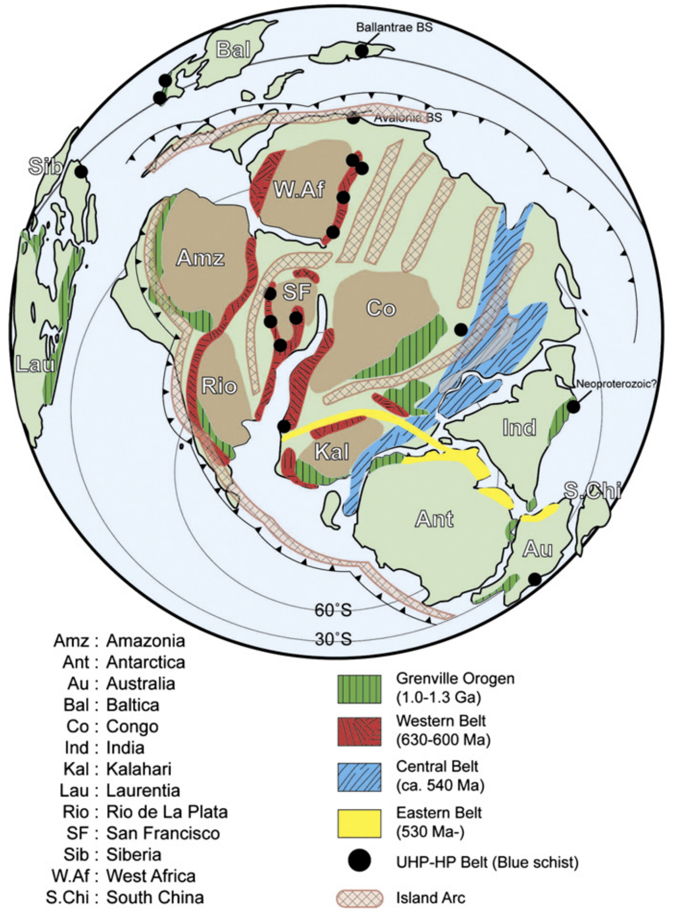


Fig. 6. Schematic tectonic map of Gondwana. Gondwana was amalgamated at ca. 540 Ma through major sutures termed here as the western, central and eastern, connecting four megacontinents. N. America was separated from Baltica. Between Gondwana and N. America and Baltica, the Iapetus Ocean was present. The major orogenic belts have slightly different metamorphic ages but show a systematic distribution with the older ones to the west, and the younger to the east, with 630–600 Ma in the west, ca. 540 Ma and younger at the center and <530 Ma in the east. The final closure of the orogen between N. America and Baltica occurred during 490–470 Ma and collision of N. America against W. Africa was at ca. 400 Ma to form the Appalachian orogenic belt.

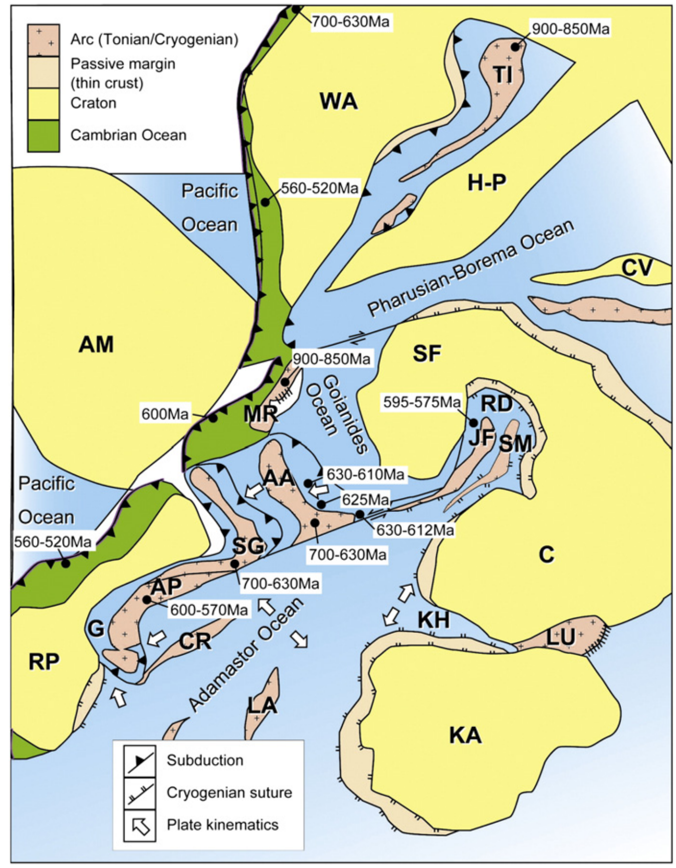


Fig. 7. Schematic paleogeographic map of Central Gondwana at ca. 750–700 Ma. Before the opening of late Jurassic Atlantic Ocean, Africa was connected with S. America. Major cratons are also shown as: S. America—RP (Rio de Plata), AM (Amazon), SF (San Francisco); and Africa—WA (West Africa), H–P (Hoggar–Potiguar), C (Congo) and KA (Kalahari). In addition to these cratonic domains, a number of intra-oceanic island arcs were present together with active continental arcs. These are TI (Tilemsi), MR (Mara Rosa), CV (Cariris Velhos), RD (Rio Doce gulf), SM (Serra do Mar), AA (Anapolis–Andrelandia), SG (Sao Gabriel), AP (Apiai), CR (Curitiba), LA (Luiz Alves), LU (Lufilian) and others (Neto and Caby, 2000). During 750–700 Ma, three important, but small oceans were present along the western major suture, and from north to south these are known as the Pharusian–Borborema Ocean, Goianides Ocean and Adamastor Ocean, respectively (Neto and Caby, 2000). These oceans were closed by ca. 600 Ma. Modified after Neto and Caby (2000).

through Mara Rosa (MR) to Anapolis–Andrelandia (AA), and Socorro–Guaxupe (SG) to Apiai (Ap) in South America (see summary by Neto and Caby, 1999). In addition, a tectonic window has been identified underneath the SF Craton, with probable UHP rocks (Maruyama et al., 1996; Maruyama and Liou, 1998). Among the various localities above, the Gouma region in Mali is the first reported locality of coesite-bearing eclogite (Caby et al., 1981; Caby, 1994), with a P–T estimate of >27 kb and 700–750 °C (Caby, 1994). Jahn et al. (2001) dated the peak metamorphic age as 623 Ma. Eclogites from W. Hoggar, C. Hoggar and Lato Hill, Togo (Affaton et al., 1980; Menot and Seddoh, 1985) were formed at >14 kb, 650–750 °C and 17 kb, 700–750 °C (Menot and Seddoh, 1985). Along the western coast of S. Africa, the Gariep mélange belt occurs (Porada, 1989) and the metabasites contain ferroglaucophane (Frimmel and Hartnady, 1992). These rocks could be of Cambrian age, although this requires further confirmation.

Prior to the formation of the western belt, a wide Brazilian Ocean was present, but it shrank into three separate oceans during 750–700 Ma, with the Pharusian–Borborema Ocean extending to the north in Africa, the Goianides Ocean at a central location and the Adamastor Ocean to the south (Neto and Caby, 2000). These isolated oceans finally closed by a series of collisional events between the West African Craton (WA), Hoggar–Potiguar (H–P), San Francisco Craton (SF), Congo Craton (C), Amazonia Craton (AM), Rio dela Plata (RP) and Kalahari Craton (KA) by 650 Ma.

In South America, ~300 km to the northwest of Rio De Janeiro, at 612 Ma (U–Pb, monazite) UHP–HP rocks with relict eclogite-facies assemblages have been reported (Neto and Caby, 1999; Parkinson et al., 2002). Further to the west in Brazil, Amaral et al. (2012) reported 613–598 Ma HP granulites from the Borborema province.

3.2. The central belt (Mozambique belt)

Africa is composed of W. African, East-Saharan, Tanzanian, Congo, Angola, Zimbabwe and Kaapvaal Cratons as the major blocks, in addition to small cratonic fragments or micro-continents and intra-oceanic arcs. Among these cratonic fragments, A-type orogens occur with or without juvenile arcs, and expose deep-crustal sections. Both Grenvillian (1.0 Ga) and 'Pan-African' orogens are distinguished, the latter better constrained by zircon U–Pb chronology. The Central belt discussed herein is shown in Fig. 10. The Pan-African orogenic belts in general, are believed to have been formed between 650–500 Ma (e.g., Kroner and Cordani, 2003). The Kaapvaal + Zimbabwe + Indian Cratons collided at 570–530 Ma against the Angola + Tanzania Cratons to form the Damara–Lufilian–Zambezi belt (de Waele et al., 2008). The N–S trending central African Mozambique belt is well-dated (e.g., Cutten et al., 2006) between 549 and 535 Ma. The Mozambique belt may be

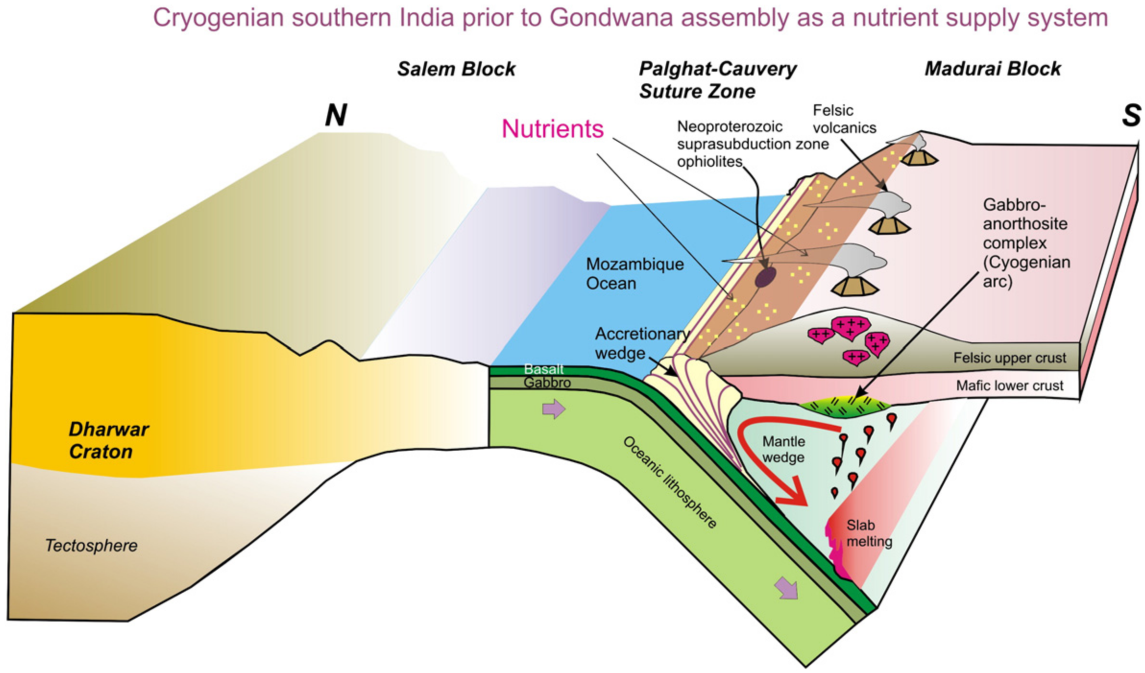


Fig. 8. A schematic plate tectonic model illustrating the Cryogenian subduction system in southern India. Southward subduction of the Mozambique Ocean lithosphere driven by a thick tectosphere-bearing Dharwar Craton is envisaged in this model. The subduction-related fore arc magmas include the suprasubduction zone ophiolites and gabbro-anorthosite and felsic volcanic suites. Other Cryogenian arc-related magmatic suites including charnockites also occur in this region. An extensive Cryogenian arc has also been traced along various domains of the East African Orogen. We propose that these would have also substantially added to the nutrient budget for setting the stage or Cambrian Explosion. After Santosh et al. (2012).

truncated by a slightly younger E–W trending Damara–Zambezi orogen in the south. Although Central Africa is marked by the single Mozambique orogenic belt, there are several sub-belts running parallel to and across the Mozambique (Fig. 9), with the amalgamated mosaic of Africa preserving several Neoproterozoic intra-oceanic arcs (e.g., Berger et al., 2011).

3.3. The eastern belt

In contrast to the earlier models (summarized in Yoshida, 2007), Squire et al. (2006) proposed that the collision–amalgamation of Australia with Gondwana was younger than that of the age of the Mozambique belt along which the two mega-continents, East and West Gondwana, fused at 540 Ma. They reported younger detrital zircons of up to 515 Ma from the Kuunga orogen, suggesting collision–amalgamation of Australia with Gondwana after 515 Ma. They interpreted that the Kuunga suture was 530–515 Ma, whereas Meert (2003) suggested an age of 570–530 Ma, coinciding with the closure of the Mozambique Ocean at 540 Ma in the central belt.

The Eastern belt runs along the western margin of Australia, and presumably continues along northern Antarctica (Shiraishi et al., 1994; Fitzsimons, 2000; Boger and Miller, 2004; Boger and Wilson, 2005). Parts of Sri Lanka and Madagascar may also belong to this Late Cambrian suture (530–515 Ma in Squire et al., 2006), that is speculated to extend through Zambezi to the Damara belts in Southern Africa, although the data are not yet conclusive. Squire et al. (2006) preferred a further southward extension along the eastern margin of South Africa. The reasons why we prefer this new model in relation to the earlier concept of the continuity of the Mozambique belt further to the southern end of Africa, are as follows. Firstly, extensive tectono-thermal overprints occur in the Mozambique belt to the north in Tanzania at 535 Ma (Cutten et al., 2006) and 520 Ma (Kroner and Cordani, 2003), rather than to the south. Although not yet conclusive, we speculate on the possibility of middle to late Cambrian sutures transecting southern Africa. However, we do not favor the more simplistic notion of East–West Gondwana collision as postulated by Squire et al. (2006).

Godard and Palmeri (2013) summarized the features of high pressure eclogite facies rocks from the Shackleton Range and Sverdrupfjella belonging to the 'Pan-African' Mozambique belt in East Antarctica and correlated these with the belt extending from Tanzania to East Antarctica. They also correlated the UHP metamorphic rocks of Northern Victoria Land to the Cambrian–Ordovician Ross orogeny with eclogites belonging to the same orogeny also identified in Tasmania and Australia.

Another key region is Peninsular India, which forms the 'heart' of Gondwana, linking the East African and Malagasy orogens with Ediacaran–Cambrian orogenic belts in Sri Lanka and the Lützow Holm Bay region of Antarctica with similar aged belts in Mozambique, Malawi and Zambia (Collins et al., 2014). The Ediacaran–Cambrian metamorphism in the Southern Granulite Terrane in Peninsular India was characterized by high-pressure (Collins et al., 2007) and ultra-high temperature (Tsunogae and Santosh, 2011) conditions. Santosh et al. (2009a) proposed a Pacific-type orogeny in the mid Neoproterozoic with evidence for suprasubduction zone ophiolites and accreted pelagic and continental sequences, followed by a Himalayan-style collision along the Palghat–Cauvery Suture Zone, the inferred trace of the Mozambique ocean suture in southern India, during which HP–UHT type orogens developed.

4. Gondwana margins

On a paleogeographic map of Gondwana, we show the locations of Neoproterozoic to Cambrian blueschist and UHP–HP belts, indicating consumptive plate boundaries. Type A refers to the location of continent collision, implying strong evidence for the collision–amalgamation of two continents, whereas type B represents the location of ridge subduction indicating annihilation of oceanic lithosphere and the presence of a subduction zone. Fig. 10 (540 Ma to 500 Ma), Fig. 11 (480–400 Ma), and Fig. 12 (300 Ma) illustrate the stages of final completion of Gondwana

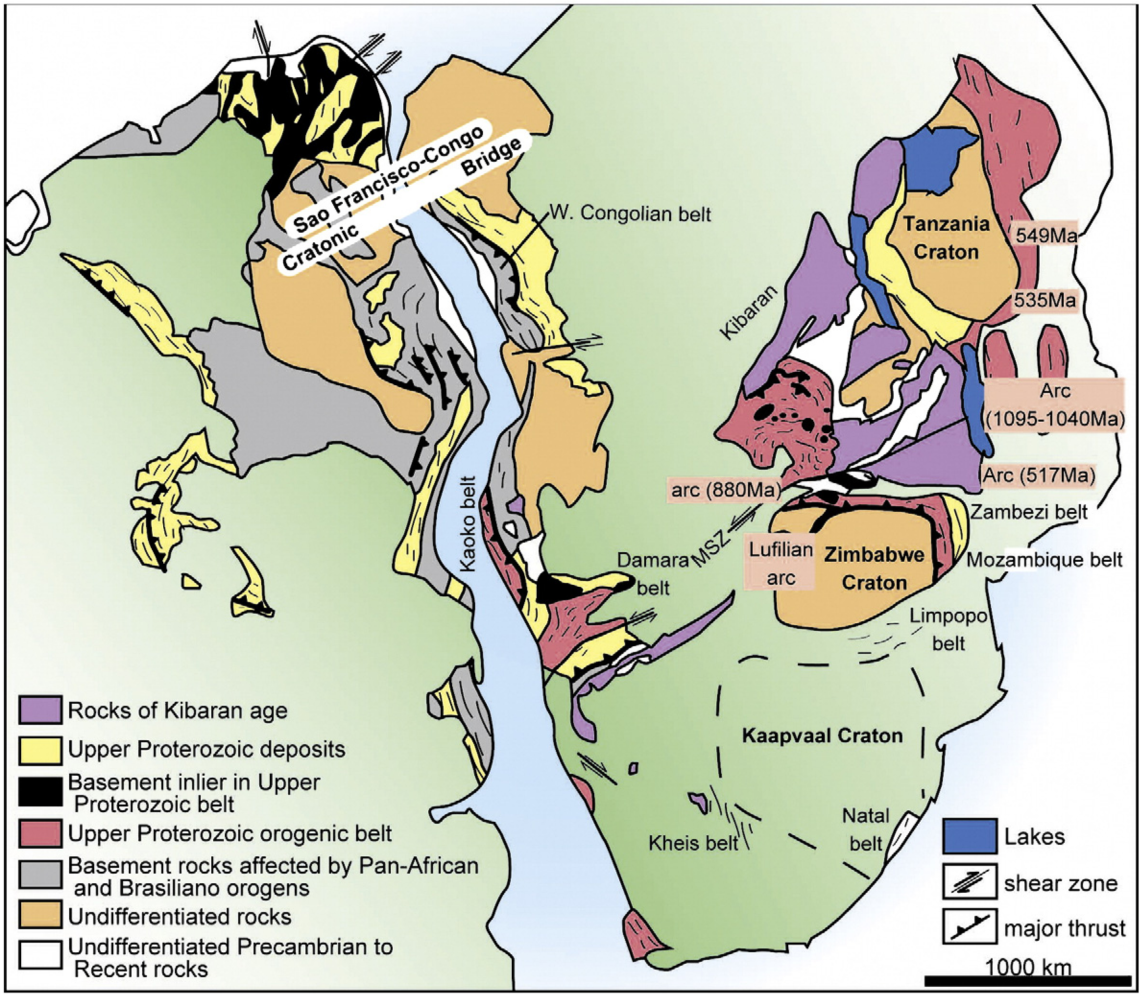


Fig. 9. Orogenic belts in Gondwana. (For details see Porada, 1989; Squire et al., 2006; Kroner and Cordani, 2003; de Waele et al., 2008; Meert and Lieberman, 2008, among others.) See text for discussion.

and subsequent rifting and dispersal to amalgamate Paleo-Asia which is a part (?) of the supercontinent Pangea by 200 Ma.

All along the Gondwana-forming sutures, UHP–HP–UHT belts were developed marking ancient mountain belts, and in the perspective of the Cambrian Explosion, these could have served as effective sources for nutrient delivery (Squire et al., 2006). However, timing of the final collisional orogeny and construction of the mountain belts in many of the Gondwana fragments, particularly some of those in the central belt, and all in the eastern belt post-date the timing of 'setting the cradle' for the birth of the second ecosystem on Earth. We therefore consider that more effective nutrient supply for the birth of modern life might have been achieved by post-orogenic uplift of the TTG crust by rising plumes underneath, and subsequent rifting of the earlier supercontinent, prior to the final assembly of Gondwana. There is also increasing evidence for abundant arc magmatism and felsic volcanism during the Cryogenian along the convergent margins of the various Gondwana fragments (Fig. 8; Santosh et al., 2012), adding to the pre-Ediacaran nutrient budget. Active production of magma supplies nutrients through volcanic ash, erosion and transportation to the oceans, as the sea level had already started lowering by this time through the initiation of water 'leaking' into the deep mantle (Maruyama et al., 2014).

4.1. Early to Middle Cambrian paleogeography

During the Early to Middle Cambrian, Gondwana was not fully formed into a closest-packed configuration. Small ocean basins persisted (particularly in the Damara region) and perhaps between the Mawson Block (East Antarctica) + Australia and the Kalahari–Dronning Maud region. Laurentia and Baltica were separated by a widening Iapetus Ocean and further separated from Siberia by the Ægir Sea (Fig. 10).

During the Cambrian–Early Ordovician, Pacific-type subduction zones developed along the present-day eastern margin of Laurentia (Newfoundland Cambrian blueschist; New Brunswick blueschist; Vermont blueschist) and western margin of Laurentia (Klamath blueschist at Skookum Gulch).

Along the southern margin of the South China Craton, NE Japan and SW Japan, 530 Ma metasomatic jadeitite (Kunugiza and Maruyama, 2011) and 450 Ma blueschist and eclogite were formed (Maruyama et al., 1996). Avalonia was present as an elongated terrain off the West Africa Craton at 560–550 Ma (Fig. 10), and rifted away from Gondwana by 500 Ma opening the Rheic Ocean between Avalonia and Gondwana (Fig. 11). The 560–550 Ma Anglesey blueschist belt (Kawai et al., 2009) of Pacific-type developed along the western margin of the West African Craton (Fig. 10).

The small oceans remaining in Gondwana were closed by 515 Ma (Gray et al., 2008; Fig. 10) with three major mountain ranges: the western belt (comprising 3–4 sub-belts), the central (Mozambique belt), and the eastern Kuunga zone lying along the western margin of Australia through the Antarctica/India boundary to the southern part of Africa (Fig. 10 bottom panel).

Large sedimentary basins were developed along the eastern margin of the Gondwana from northern Africa, through Saudi Arabia, Middle

East, India to Australia (Burke and Kraus, 2000; McKenzie et al., 2011). The hinterland of these anomalously large basins was speculated to have been a single, 8000 km long and 1000 km wide collision belt called the Trans-Gondwana super-mountain (Squire et al., 2006). The origin of this anomalously huge basin set could have been due to the subsidence of a number of intra-oceanic arcs dating back to 1.0 Ga along with the accumulation of TTG materials. This would lead to the heating of the wet mantle transition zone, the birth of a number of hydrous plumes that would proceed to disaggregate any large continental landmasses. This process is hypothesized for the generation of the rift basins along the northern margin of Gondwana during the Ediacaran–Cambrian.

Neoproterozoic–Cambrian arcs and trenches were widespread in Gondwana particularly in northern Africa, Saudi Arabia, the Middle East to northern India (marked by Neoproterozoic ophiolite, arc and blueschist; Maruyama et al., 1996; Santosh et al., 2009a, 2012). In addition, arcs and trenches were characteristic of the zone along the western belt, the central Mozambique belt, as well as the eastern belts. These modes of occurrence of abundant intra-oceanic arcs suggest a tectonic setting similar to that of the modern Western Pacific

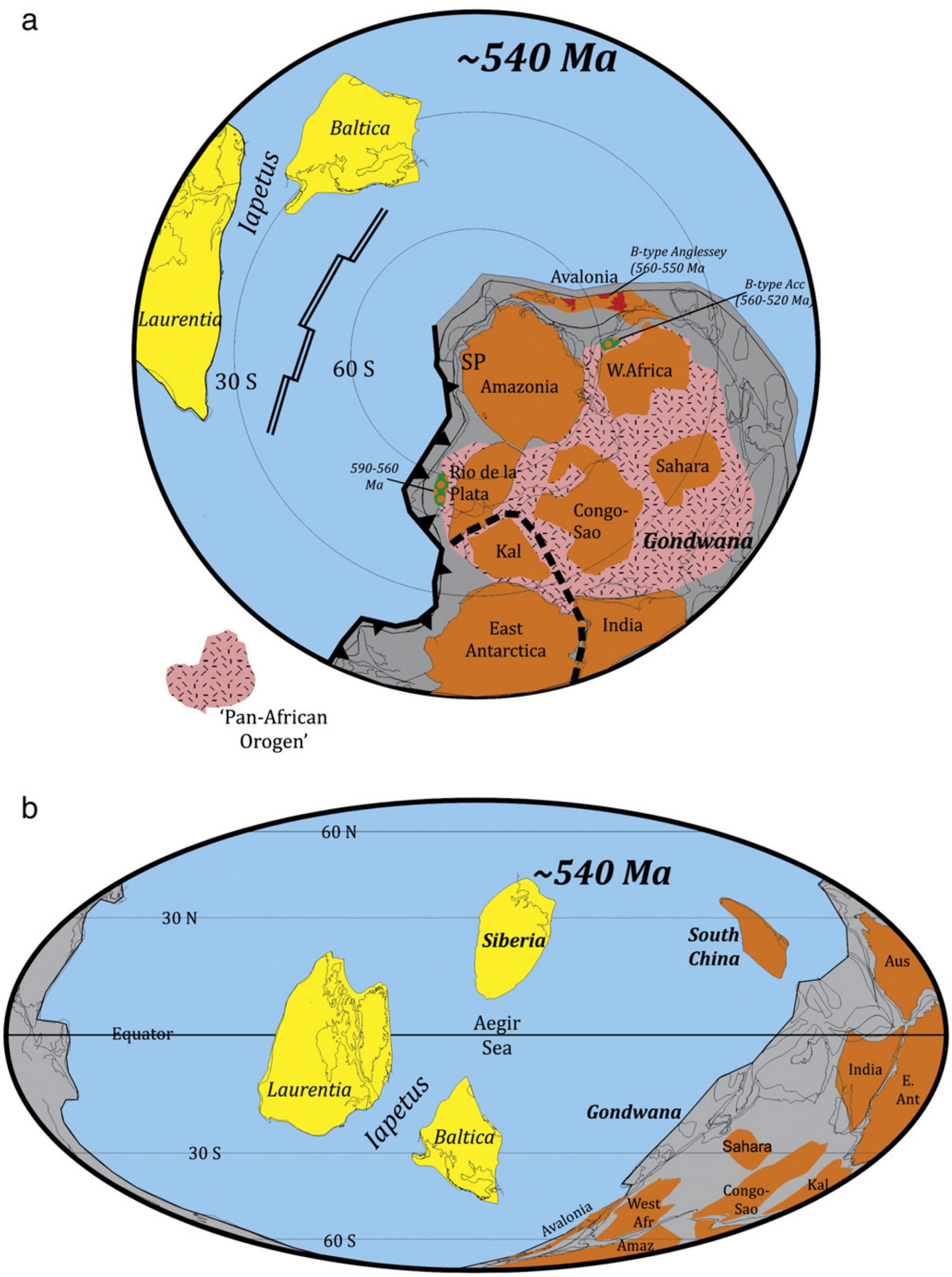


Fig. 10. (a) Paleogeographic reconstruction of the globe (Molleweide Projection) at ~540 Ma. (b) South polar projection of Gondwana at 540 Ma showing the distribution of 'Pan-African' orogenic belts. Note that Baltica had not yet collided with North America at 540 Ma. (c) Formation of a number of collisional orogens and active Pacific-type orogeny along the circum-Pacific rim at ca. 500 Ma delivered huge amounts of nutrients to the neighboring continental shelf. Note the areal distribution of blueschist and eclogite belts (marked as A-type and B-type with ages) indicating the location of subduction zones. Rifting along the northern margin of Gondwana might account for the formation of huge sedimentary basins. See more details in the text.

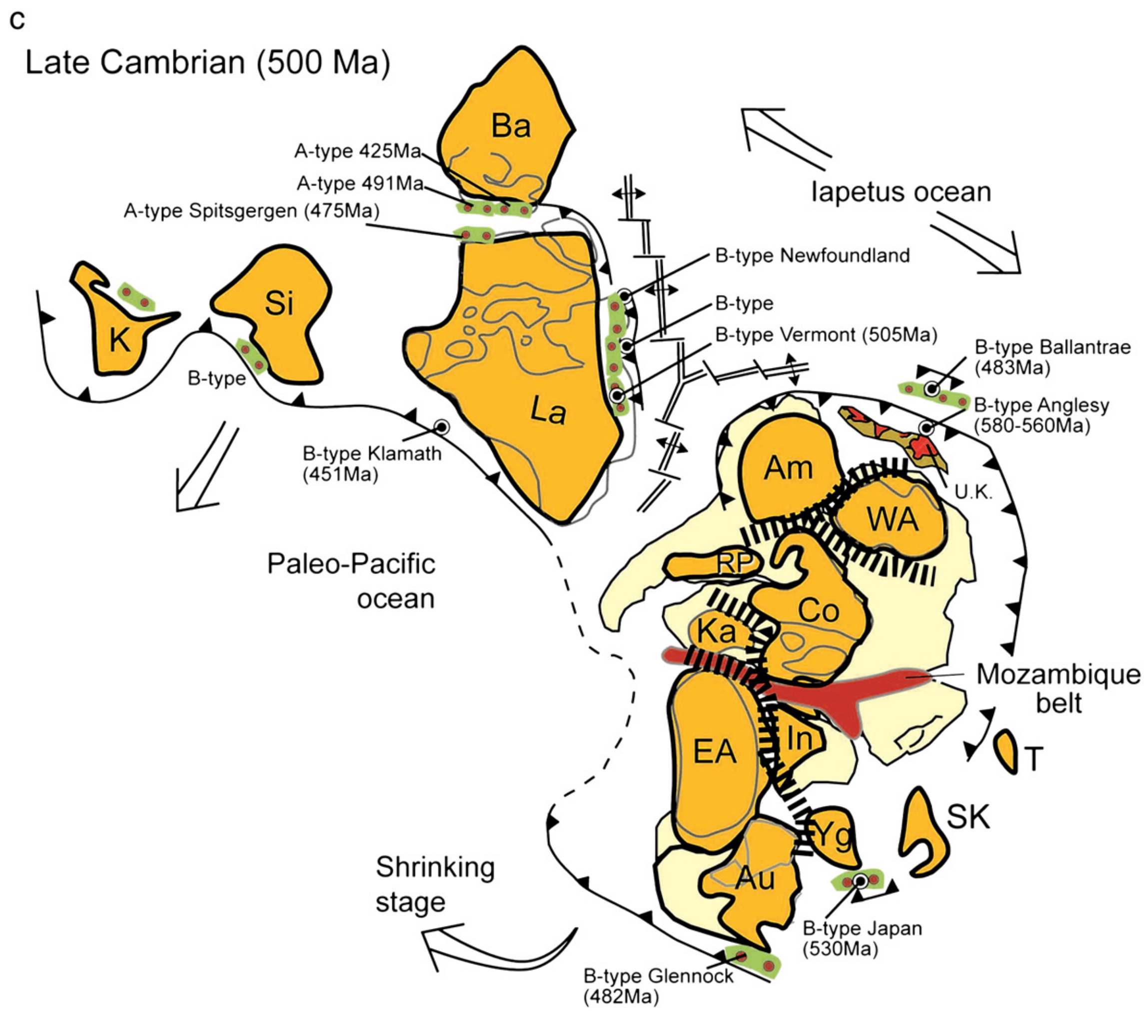


Fig. 10 (*continued*).

where a number of micro-plates and small ocean basins and island arcs are present (Komiya and Maruyama, 2007).

4.2. Ordovician to Early Devonian tectonism: the Gondwana to Pangea transition

During the Ordovician to Early Devonian interval, the Iapetus Ocean became progressively smaller and the final closure between Baltica–Avalonia and Laurentia occurred during the Siluro-Devonian Acadian Orogeny. Smaller microcontinental blocks may have been accreted to both including the formation of coesite- and diamond-bearing A-type UHP belt along the collision zones (see a summary by Maruyama et al., 1996; Liou et al., 1998). Spitsbergen exemplifies the islands formed during this time, and isolated in the Atlantic Ocean now since the Tertiary opening in the northern Atlantic. Following the Acadian Orogeny and the formation of Euramerica, it took an additional 80 Ma for the amalgamation of Pangaea. The A-type Appalachian belt was formed by this process. Before the final closure of the Iapetus Ocean, a series of intra-oceanic island arcs and micro-continents including Avalonia were accreted to the margin of Laurentia (Murphy et al., 2010, 2011), although major parts (>than 90%) were subducted into the deep mantle. The remnant arcs are preserved as the Highland border ophiolite, the topmost arc peridotite in the Buchan zone, the Newfoundland ophiolite (Malpas et al., 1973), and its western extension in the Appalachian belt, in addition to the 485 Ma Ballantrae ophiolites (Kawai et al., 2007).

On the other hand, the Gondwana continent began to rift along its northern margin because of the underlying TTG-dominated mantle transition zone that generated plumes. Models of continental rifting generally posit that the major source of heat and uplift will occur near the center of a supercontinent because of the thermal blanketing effect (e.g., Senshu et al., 2009). If we apply the concept of a three-layered continent (Kawai et al., 2009), the heat source for rifting and generation of plumes originates in the 'second continents' at the bottom of the mantle transition zone. Continental crust generated at subduction zones through arc magmatism is returned to the mantle through sediment subduction, subduction erosion, and continental subduction. Granitic rocks have negative buoyancy compared to the surrounding material in the upper mantle and transition zone (Kawai et al., 2013), and can be subducted in the depth range of 270–660 km. Thus, two reservoirs of granitic material exist, one on the surface of the Earth, and the other at the base of the mantle transition zone (Kawai et al., 2013). The radiogenic heat generation from the second layer at depth would lead to the formation of mantle plumes which eventually rise up and break the overlying continental landmass. The site of breakup depends on loci of the 'second continent' in the mantle transition zone.

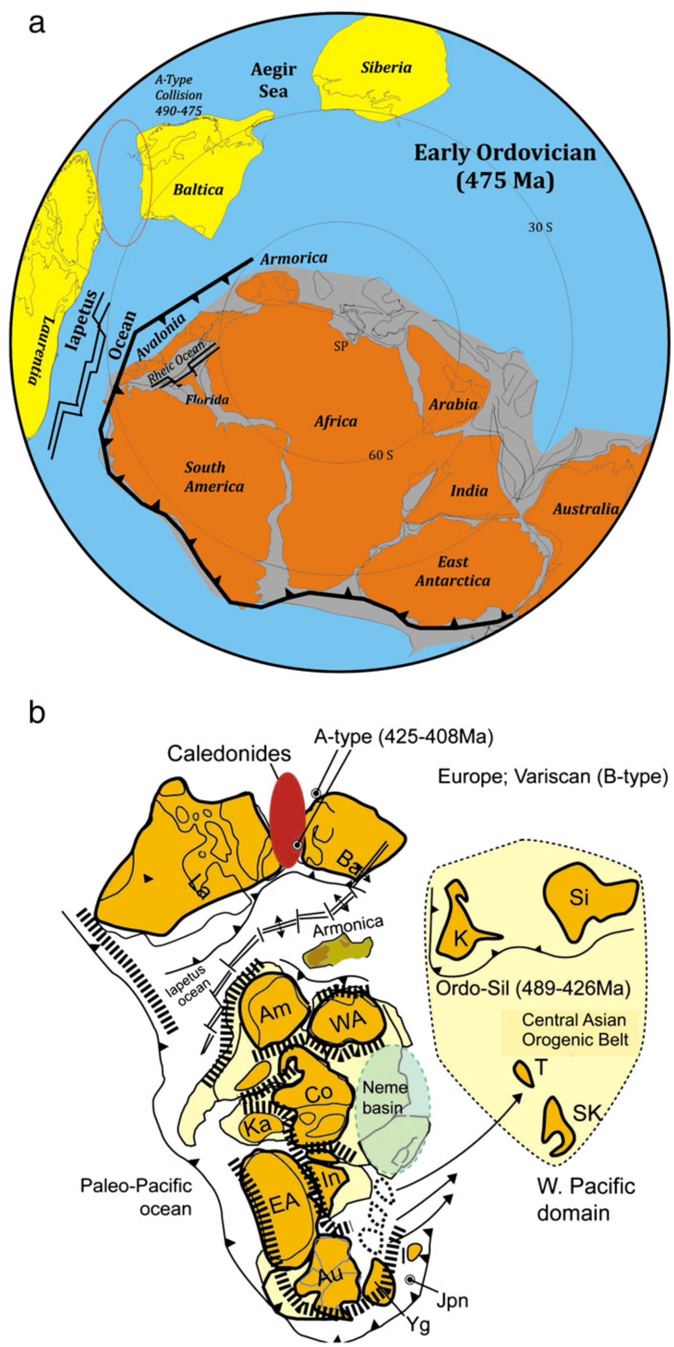


Fig. 11. Top panel: Paleogeographic reconstruction of Gondwana at 475 Ma. Bottom panel: Schematic paleogeography at 400 Ma showing the distribution of major collisional A-type belts. Baltica collided against North America to give birth to Laurentia by 480 Ma as demonstrated by the formation of A-type blueschist–eclogite belt in the Norwegian Caledonides. The Paleo-Pacific Ocean was connected to Iapetus Ocean at 480 Ma but closed by the collision of Laurentia against Gondwana at 400 Ma as demonstrated by the formation of Appalachian A-type belt. Note the development of Pacific-type active continental margin, and the formation of a huge sedimentary basin by the rifting of the northern Gondwana margin. Also note the presence of collisional A-type mountain chains within Gondwana which are geographically different from the circum-Pacific Cordilleran mountain chains including the Trans-Antarctic to eastern Australian.

A huge sedimentary basin (Burke and Kraus, 2000) with a large volume of Cambro-Ordovician sandstones was formed by rifting along the northern margin of Gondwana. The northern periphery of the Gondwana continent including Avalonia, Armorica, Tarim, Indochina and Yangtze were separated from Gondwana, and migrated northward to join the Central Altaids oceanic domain where Siberia, the Kazakhstan block and the Sino-Korean Craton eventually amalgamated leading to the formation of Eurasia.

Along the paleo-Pacific Ocean, long-lived Pacific-type subduction began at ~530 Ma (Isozaki et al., 2010; Kunugiza and Maruyama, 2011), with episodic exhumation of blueschist and eclogite, and active margin calc-alkaline volcano-plutonism (Maruyama et al., 1989; Isozaki et al., 2010) that provide important clues to reconstruct the distribution of the paleo-subduction zones.

4.3. Paleogeographic reconstruction at 300 Ma

The supercontinent Gondwana began to rift ~400 Ma along its northern periphery, promoted by the birth of the super-downwelling (Maruyama et al., 2007; cold superplume as originally proposed by Maruyama, 1994) under the Altaids (Fig. 12). A number of oceanic micro-plates with juvenile arcs and micro-continents amalgamated during the period 300–200 Ma, marking the formation of Laurasia and also the birth of Pangea.

5. Updomed regions formed by plumes during post-collision period, and rifting

Fig. 13 shows a map of Gondwana with major sutures, zones of post-collisional uplift and regions of rifting and breakup, together with the potential sites for nutrient supply.

The regions of domal crustal uplift related to the birth of plumes contributed to rifting and more effective nutrient input than the narrow mountain ranges formed by continent–continent collision. The vast sedimentary basins along the northern part of Gondwana, stretching from Northern Africa to India, might be rift-related as evidenced by the Cambrian bimodal magmatic activity in all these regions preserved beneath the basin-fill sediments (see a summary of stratigraphy and the size different continents by Squire et al., 2006).

6. Neoproterozoic and Cambrian: the most active period of Solid Earth through time

The Cryogenian 'Snowball Earth' episodes occurred during the interval from ~800 to 635 Ma and represent the most severe climatic swings on the planet (Hoffman et al., 1998). The initiation of the Snowball Earth was thought to be due to enhanced silicate weathering (and concomitant CO_2 drawdown in the atmosphere) during the breakup of Rodinia (Donnadiue et al., 2004). Escape from the snowball episodes resulted from volcanogenic CO_2 buildup due to sub-ice volcanic activity and subsequent release into the atmosphere (Hoffman et al., 1998; Maruyama and Liou, 2005). Alternatively, the Snowball Earth episodes have also been correlated to a combination of starburst activity and weakened geomagnetism (Maruyama and Santosh;, 2008; Maruyama et al., 2013).

Although previous studies considered that the Grenvillian interval was not an active period of mantle dynamics, and that the Earth was organically inactive at that time in order to explain the onset of Snowball Earth (Maruyama and Liou, 2005), recent investigations by Rino et al. (2008) showed that the Neoproterozoic was one of the most active and dynamic periods in Earth history. This observation poses a major challenge on the actual trigger for the origin of Snowball Earth, questioning the general concept of depletion of the greenhouse gas CO_2 as the major cause.

The last of the Snowball Earth episodes ended around 635 Ma and was followed by the Ediacaran radiation at ca. 580–570 Ma. We argue that this radiation resulted from the abundant and continuous supply of nutrients to the oceanic realm as a critical factor. If so, the nutrient supply chain may have been generated by the rifting of Rodinia (and associated uplift) during the mid-Neoproterozoic (Fig. 14). Rifts associated with the breakup of Rodinia encircle Laurentia and include its conjugate margin pairs including South China (Yangtze Craton), Australia,

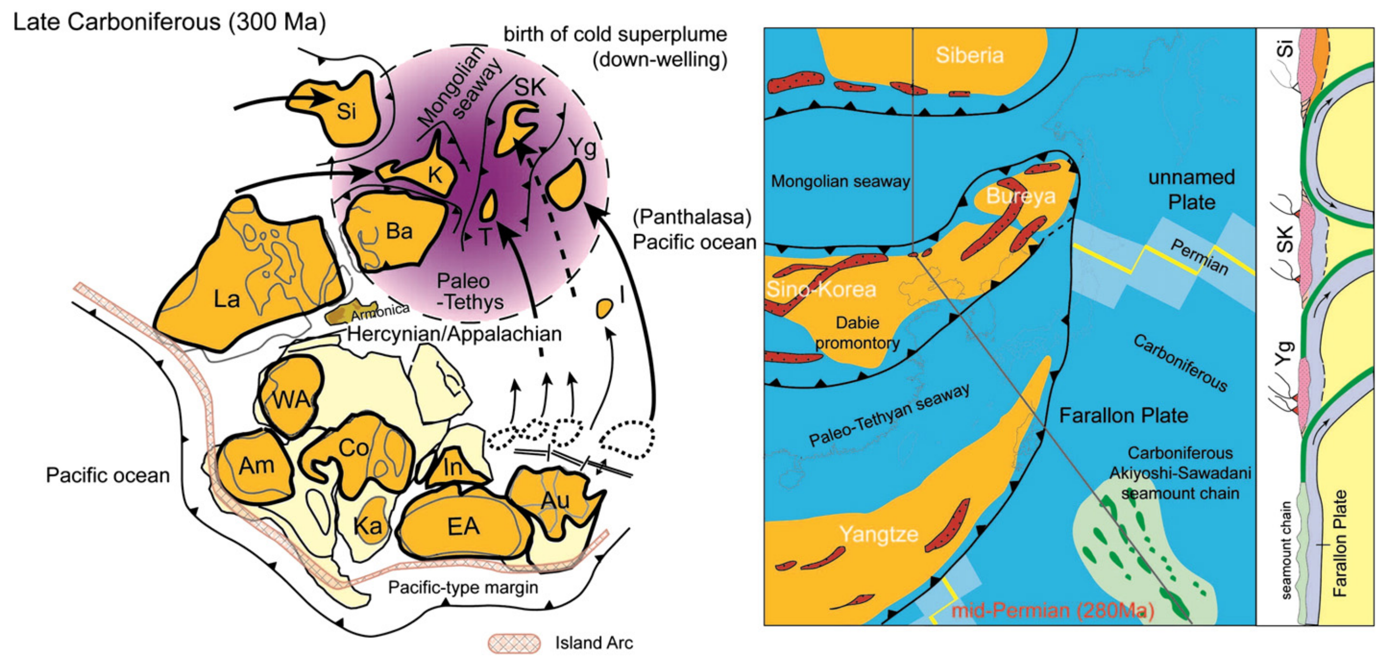


Fig. 12. Paleogeographic reconstruction of Gondwana and formation of Laurasia at 300 Ma (left panel). Note the active Pacific-type margins along the southern margin of Gondwana, successive rifting on the northern margin of Gondwana, and final amalgamation of continents and island arcs in the Paleo-Asian ocean (Altaids) by the birth of super-downwelling. Formation of Laurasia and the birth of Pangea followed. Modified after Maruyama (1997a, 1997b). Right panel figure shows an enlargement of the paleogeography for the paleo-Asian oceans separating Siberia, Sino-Korean (North China) and Yangtze Cratons (South China) facing the paleo-Pacific Ocean at 280 Ma (modified after Maruyama, 1997a, 1997b). A schematic plate tectonic setting is also shown at the right end of the right panel.

India, Siberia, Baltica (White Sea), Tarim, and Avalonia as the regions close to these rifted margins. Rifting was accompanied by >about 2–3 km of uplift of the continents, so that landmasses were brought above sea-level to enable the supply of nutrients over wide (at least ca. 1000 km) regions.

The next major event in the Neoproterozoic world was the Cambrian Explosion. Any number of extrinsic (non-biological) and intrinsic (biological) factors were considered as potential ‘fuses’ for this explosive radiation with some arguing that an increase in pO_2 into the atmosphere and oceans was the most important development for transitioning to multicellular life. Although higher levels of oxygen help facilitate size increases (through increased metabolic efficiency), pO_2 alone appears insufficient to account for the radiation of diverse species of animals. We feel that a rich and continuous supply of nutrients worked in conjunction with the rise in oxygen to provide the necessary one–two punch for the massive Cambrian radiation.

For the efficient and adequate supply of nutrients on a global scale, we need an analogue of the modern Earth system with large continents covering one third of the Earth's surface. The Sun drives the Earth system through climatic control to feed life by the continuous supply of nutrients on land and into the oceans, transported through river sediments and aeolian dust (Maruyama et al., 2013).

Fig. 15 shows a revised version of the growth of continental crust (TTG), based on the zircon age frequency distribution in major river mouth sediments, specifically around the circum-Pacific domains as reported in Rino et al. (2008). The data show that the Neoproterozoic was the period of most active magmatism through time and overlaps with the Cryogenian (0.8–0.635 Ga). During the Cryogenian phase of active magmatism along with the Paleoproterozoic Snowball Earth interval, the Earth experienced widespread (and active) magmatism and calc-alkaline volcano-plutonism adjacent to subduction zones, suggesting a most vigorous regime of plate tectonics in the Earth history. This in turn reflects active mantle convection, and hence the presence of abundant mantle plumes that must have pushed up the continental crust resulting in an increased supply of nutrients into oceans.

7. Change of Earth system and global nutrient supply

The Earth system has only two major sites of life-sustaining nutrients and energy supply: one is at the mid-oceanic ridge and the other is the Sun-driven surface system on the continents (Maruyama et al., 2013). The surface system is composed of a climate system and nutrient circulation from the TTG crust in landmass through river, glacial and aeolian transport into oceans.

7.1. Drop of sea-level by the initiation of return-flow of seawater into mantle

When the sea level was ca. 600 m higher than that of the present day, exposed continental land was restricted to only 10% of the global surface area, compared with 31% on the modern Earth (e.g., Maruyama and Liou, 2005). The ratio of exposed landmass to ocean underwent a rapid change after 750 Ma due to the changing geothermal gradient along the Benioff plane on subducting oceanic slabs. This change was recorded from the secular changes in the P–T conditions observed in regional metamorphic belts around the globe (Maruyama et al., 1996). Furthermore, the hydrated mantle wedge has a wide stability region of antigorite serpentinite, with 6.5 times more water storage capability than that of amphibole peridotite that was stable before 750 Ma. Therefore, when the subduction zone geothermal gradient hit the critical value of 600 °C at the depth of the Moho, a rapid change in water circulation began, resulting in the removal of surface water into the deep mantle and finally into the mantle transition zone where it is estimated that 5 times the volume of surface ocean water is currently stored (Maruyama and Liou, 2005; Maruyama et al., 2014).

7.2. Emergence of continental crust and enlargement of nutrient delivery system

The return flow of water into the deep mantle and consequent decrease in mean sea level led to an increase in the volume of land surface

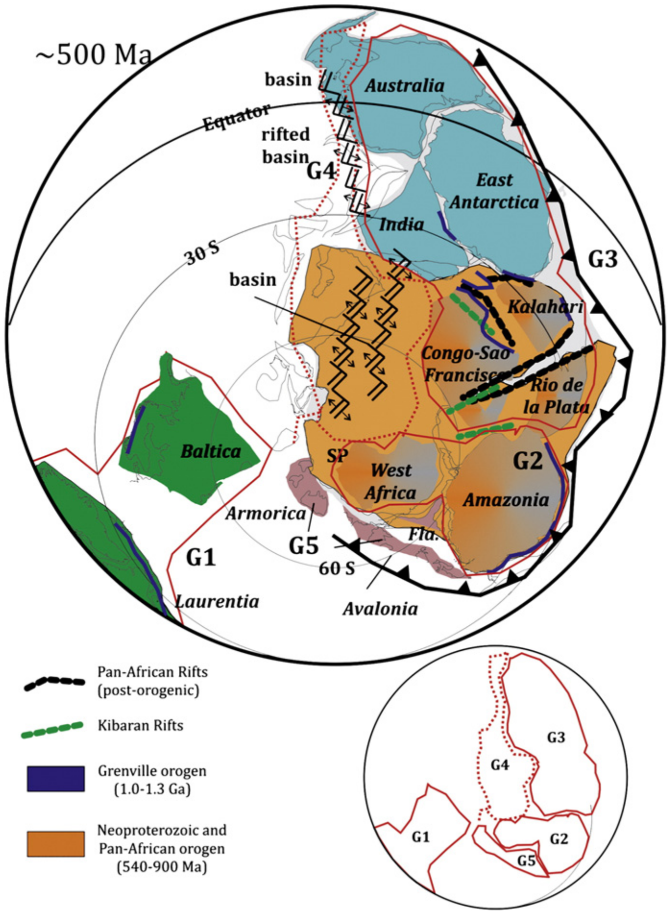


Fig. 13. Post-orogenic domal uplift regions in the 500 Ma Gondwana assembly. Note the distribution pattern of Pan-African rifts, failed rifts (aulacogen), Kibaran post-orogenic rifts, and presumably rift-related formation of Cambrian huge sedimentary basins along the northern margin of Gondwana. Domal uplifts related to the birth of hydrous plumes underneath could have contributed to the nutrient budget more effectively than the narrow mountain ranges formed by continent–continent collisions (compare with Figs. 10, 11). For the northern part of Gondwana, from Northern Africa to Saudi Arabia, the formation of huge sedimentary basins must have been rift-related because the Cambrian bimodal magmatic activity is remarkably preserved in all the regions underneath the basin-fill sediments (see a summary of stratigraphy on different continents by Squire et al., 2006). The lower panel labeled G1 to G5 shows the five groups of cratonic assemblies as described in Santosh et al. (2009b).

above sea level. This is reflected in the development of the 'Great Unconformity' beneath most Cambrian sedimentary sections. Increased exposure of continental crust to weathering processes resulted in increased erosion and development of a widespread nutrient supply across the globe. Sunlight penetrated to the bottom of the continental shelf converting the continental shelf into a paradise for the evolution of metazoans (Fig. 16; Maruyama et al., 2013). An argument against this hypothesis could be that a relative steep drop in sea level means much narrower shelves and reduced surface area thereof. However, we envisage a gradual drop in sea level through the subduction of sea water with a progressive emergence of landmass.

A second piece of evidence supporting a global decrease in sea-level is possibly reflected in a large negative $\delta^{13}C$ isotopic excursion known as the Shuram–Wonoka anomaly (Cozzi and Al-Siyabi, 2004; Le Guerroué et al., 2006; Le Guerroué and Cozzi, 2010; Meert et al., 2011). This $\delta^{13}C$ isotopic excursion is quite large (up to −10‰) and is observed in many Ediacaran sections across the globe. The explanation for this large swing (over a 20–40 Ma interval) is contentious (Le Guerroué and Cozzi, 2010); however one possibility is that it reflects a global diagenetic signal associated with an overall drop in sea level (see Kauffman, 1988).

In summary, the birth of the second ecosystem on the Earth was facilitated by the 'leaking' of seawater into the mantle at the onset of the Phanerozoic.

7.3. Role of collision-type orogeny and plume-driven regional uplifts of continents

The 'Pan-African' orogenic belts formed by continent–continent collisions during the amalgamation of Gondwana at ca. 600–540 Ma, and were considered to have facilitated nutrient supply on a global scale (Squire et al., 2006). Paleogeographic reconstructions and time–space relations of the birth of modern life in the oceans suggest that a more effective mechanism could have been post-orogenic regional uplifts and continental rifting that broke apart supercontinents, providing abundant nutrients into shallow ocean basins, thus generating a concentrated 'soup' for the birth of metazoans and setting the stage for an explosive radiation. The rifting was driven by plumes, and the uplifted regions were extremely wide, ca. 10 times more than the Andean- and Himalayan-types of collisional orogeny. Moreover, the formation of evaporites such as rock salts occurred extensively at this time on the globe which drastically reduced the salinity of the ocean. The emergence of a huge landmass enabled salinity drop in the oceans, and contributed to the rapid evolution of metazoans and plants during a golden time in the evolution of life on Earth. Thus, plume-driven uplift and rifting contributed to three major factors: (1) generation of potential sources of nutrient delivery; (2) salinity decrease in seawater; and (3) the birth of the blue ocean.

8. Discussion and conclusions

8.1. Plume-driven birth of the second ecosystem for the Cambrian Explosion

The origin and evolution of metazoans has been a major puzzle in natural science, with most models emphasizing the role of increased oxygen. Subsequent studies identified nutrients as an essential prerequisite (Brasier, 1990), with P and Ca as important elements in addition to the oxygen-enriched atmosphere. The search for nutrient supply led Squire et al. (2006) to propose the role of Pan-African mountain building associated with the assembly of Gondwana, as the major source for these nutrients.

In this paper, we propose that the nutrient supply was due to an increase in the elevation of land above mean sea level as the result of plume activity during the post-collision stage and/or initial continental rifting stage, prior to the collisional assembly of Gondwana in the latest Neoproterozoic. This conclusion is drawn from a comparison of the mountain-building stage (represented by UHP–HP–UHT regional metamorphic belts generated by continent collision) with the earlier post-collisional updoming and rifting stage marking the breakup of the Neoproterozoic supercontinent. We show that the plume-driven nutrient supply is much more effective than that associated with mountain building. The nutrient supply is reflected in a sudden increase in the volume of sedimentary rocks on the Earth, as documented by $^{87}Sr/^{86}Sr$ data on carbonate rocks through time (Shields and Veizer, 2002). Therefore, we propose that the birth of the proposed 'second ecosystem' on our planet was plume-driven.

There is a close relationship between pO_2 increase and the birth of metazoans. A continuous supply of nutrients from the increased huge landmass must have buried organic materials into the sedimentary piles on the continental shelf thereby preventing the back-reaction and oxidation which would consume free oxygen in the atmosphere (Maruyama et al., 2013). Therefore the increase of atmospheric free oxygen and its maintenance at a high level was also related to the emergence of a huge landmass. From latest Neoproterozoic to Cambrian, the emergent landmass might have been a barren desert, because of the absence of plants on land until the end of the Ordovician with the exception of microbial mat structures and biological soil crusts. The

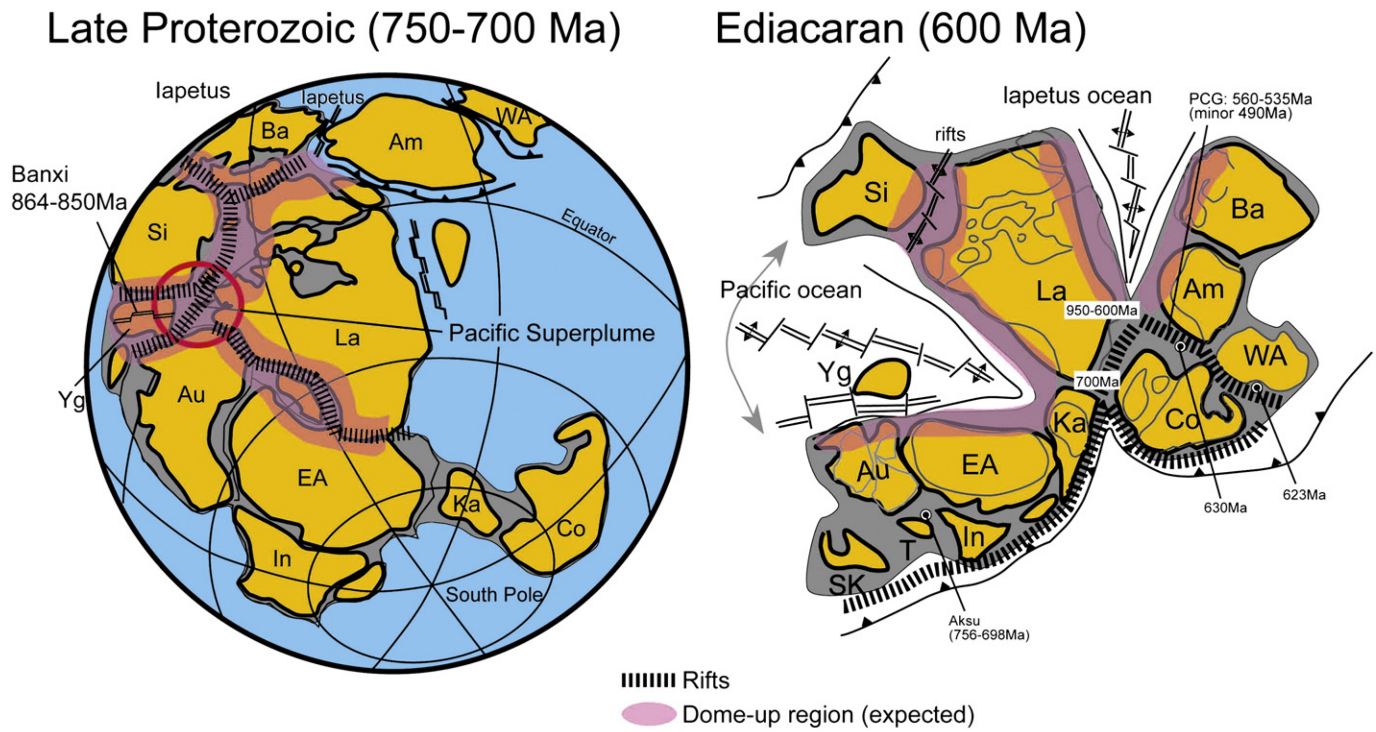


Fig. 14. Distribution of Late Proterozoic continents and rifts on Rodinia (left panel). Note the possible location of rifting upheaval of landmass along the rifts. Right panel: Birth of paleo-Pacific Ocean at ca. 600 Ma through inside-out process as proposed by Hoffman (1991) and the inevitable closure of Mozambique and other oceans on the opposite side of Pacific Ocean. Also plotted are the sites of Neoproterozoic eclogite and blueschist showing ages in Ma.

Neoproterozoic sandstones in Pan-African orogens are characterized by well-developed mature textures and compositions and reflect the surface environment at the initial stage of the metazoan world (Avigad et al., 2005). The strontium isotopic composition of the oceans changed markedly at the Cambrian–Ordovician transition, and this shift greatly affected the first bio-invasion of the land and the ensuing terrestrial-surface environments (Masuda and Ezaki, 2009). A series of environmental changes culminated in the bio-invasion onto land during the end-Ordovician.

8.2. Four-step completion of the supercontinent Gondwana

The timing of the Gondwana assembly has been a focal theme of investigation in studies related to the origin and evolution of supercontinents, as well as on the dawn of modern life on Earth (e.g., Meert, 2003; Gray et al., 2008; Meert and Lieberman, 2008; Santosh et al., 2009b; Collins et al., 2014). A major consensus is that Gondwana assembly was completed by ~540 Ma through the closure of a series of ocean basins and the assembly of a number of continental fragments. The Mozambique

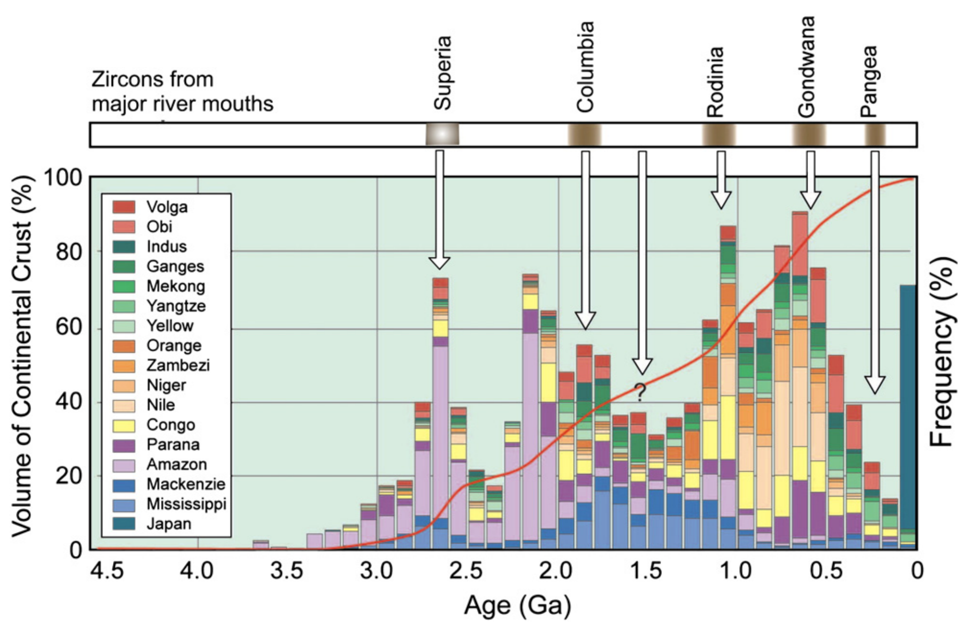


Fig. 15. Zircon age-population diagrams of river-mouth sands over the world. Data source of rivers are shown on the left column. See text for discussion. Modified after Rino et al. (2008).

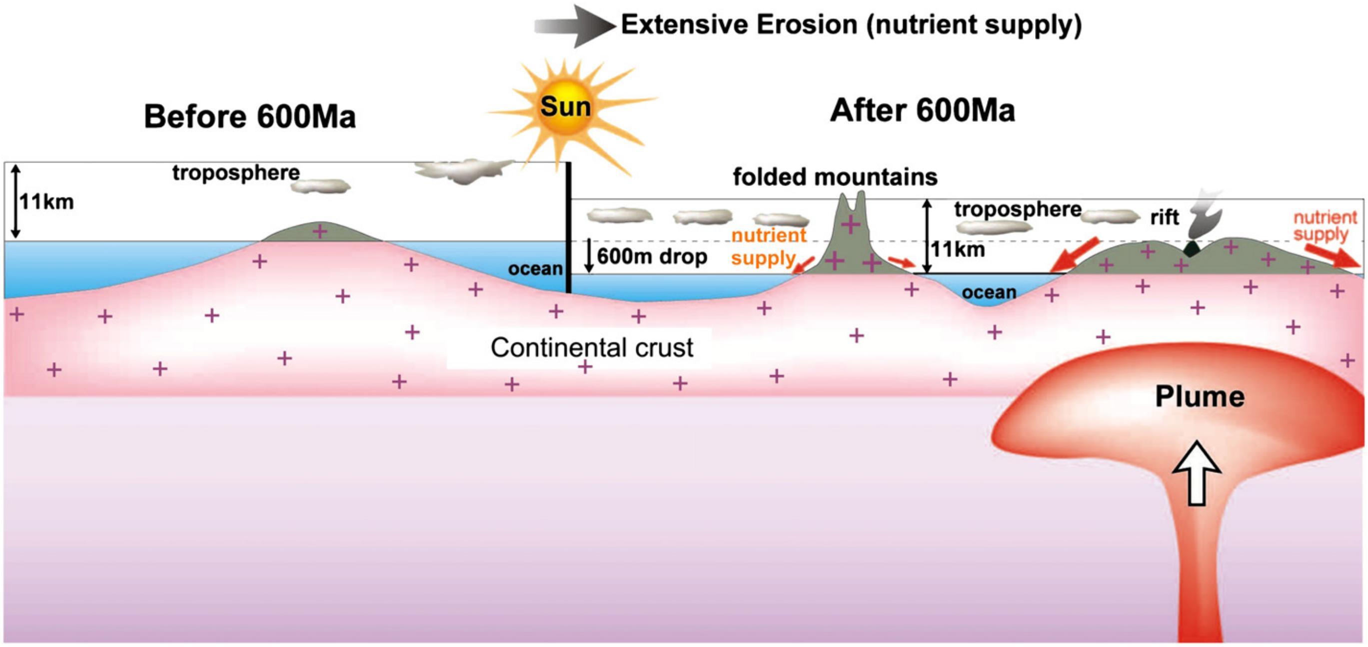


Fig. 16. Birth of the Second Ecosystem on the Earth. A combination of lowered sea-levels by initiation of return-flow of seawater into mantle with plume-driven uplift of continents is proposed as the reason in this study for the abundant nutrient supply into continental shelf, setting the stage for the beginning of modern life through Cambrian Explosion.

belt in the central part of Gondwana defines a major suture of Gondwana assembly, the trace of which runs through a number of constituent continental fragments, such as the Palghat–Cauvery Suture Zone in southern India (Collins et al., 2007; Santosh et al., 2009a). Meert (2003) proposed a polyphase model of amalgamation of Gondwana. Meert and Lieberman (2008) classified the Gondwana sutures into three: the Braziliano–Damara orogen (western), East African orogen (central) and Kuunga orogen (eastern). Squire et al. (2006) studied detrital zircons from the Kuunga orogen, and concluded that the Kuunga suture is 530–515 Ma, notably younger than the previously suggested age of 570–530 Ma (e.g., Meert, 2003). If this is correct, Gondwana must have been amalgamated through several major steps, successively

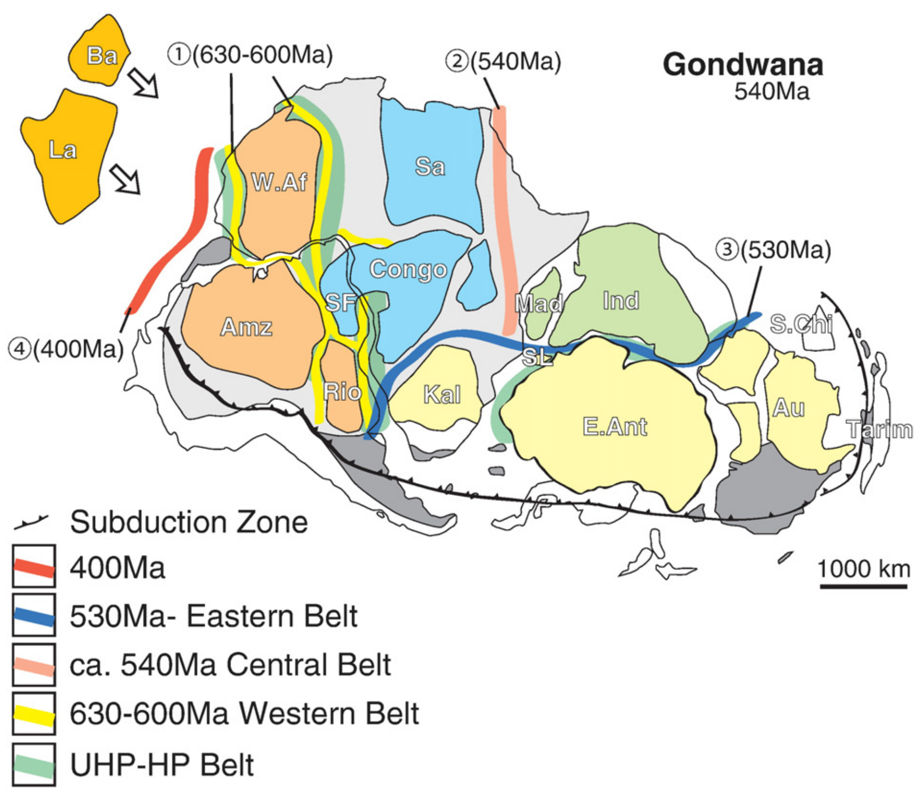


Fig. 17. Four-step model of Gondwana amalgamation in comparison to one-step, three-step and multiple steps (Meert, 2003). Note the three major collisional orogens, termed Western, Central and Eastern belts. The Western belt was mostly consolidated at 630–600 Ma, with the remaining minor orogens of 560–520 Ma in a triangular region between W. Africa, Amazonian and SF-Congo Cratons.
Gondwana reconstruction after Gray et al. (2008).

from the west (ca. 630–600 Ma), through central (540 Ma) and finally to the east (530–515 Ma). Recent studies show increasing evidence for the late Cambrian assembly of Gondwana in the eastern domain, particularly from precise U–Pb ages of metamorphic zircons in high grade orogens such as those along the trace of the Gondwana sutures in southern India (e.g., Santosh et al., 2009a, and unpublished data, Collins et al., 2014). The uncertainties surrounding the time span of orogeny, number of thermal pulses, and associated plume events in relation to supercontinent cycles remain equivocal (e.g., Meert and Lieberman, 2008; Nance et al., 2014). However, in this study we have attempted to evaluate the signature of arc-collisions from major Pan-African orogenic belts, providing critical clues on ocean closure and formation of the sutures. We proposed a four-step amalgamation model for Gondwana with three sub-assemblies: the western (South America + Sahara + Congo), the central-north (Arabian–Nubian Shield + Madagascar + India) and eastern (Australia + East Antarctica + Kalahari) assemblies. Our model depends on the southern extension of the Mozambique belt and the western extension of the Kuunga suture, particularly their continuity into the suture between the Congo Craton and the Kalahari Craton (Fig. 17). To solve this debate, the cross-points of orogenic belts provide key regions for further investigations.

It is also important to mention the presence of a number of intra-oceanic arcs in all the major sutures within Gondwana, and even in those associated with the zone of final closure between North America + Baltica during the Acadian Orogeny during the Siluro-Devonian. Presently, only a few traces of these arcs remain as minor fragments in between the sandwiched continents. Even in the present day Western Pacific region of active convergence, the thickness of intra-oceanic arcs is only 20–30 km, and many of these are being dragged down and subducted into the deep mantle. Therefore, we infer that several hundred arcs might have been subducted into the deep mantle during the 'Pan-African' orogeny in the Neoproterozoic, particularly along the northern margin of Gondwana, including the region from Northern Africa to Saudi Arabia (Gass, 1981; Burke et al., 1984). These dominantly TTG rocks would have accumulated on the bottom of the upper mantle (Kawai et al., 2009, 2013) and since these rocks are enriched in U, K, and Th, the radioactive self heating would have resulted in the generation of plumes which ultimately caused the breakup of Gondwana.

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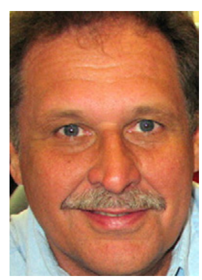

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