Evolution of continents, cratons and supercontinents: building the habitable Earth

M. Santosh*
School of Earth Science and Resources, China University of Geosciences, 29 Xueyuan Road, Beijing 100083, China

Modern concepts of plate tectonics provide new insights into the processes of construction and destruction of continents, cratons and supercontinents. Starting from the magma ocean stage at around 4.6 Ga, and evolving through a water-covered oceanic realm in the early Archean with island arcs floating on a double-layered convecting mantle, the dynamic planet Earth commenced the building of continents and cratons. These were then episodically assembled into large supercontinents and broken apart. Plate tectonics cleaned up the early toxic oceans, built mountain chains and exposed these through sea-level drop in the Neoproterozoic, enabling weathering and transport of nutrients for evolving life. Drastic environmental changes influenced by both galactic and terrestrial processes in the late Neoproterozoic finally set the stage of making the Earth a habitable planet for modern life.

Keywords: Continents, cratons, plate tectonics, supercontinents.

Introduction

The formation of continents, cratons and supercontinents constitutes a focal theme of wide interest for not only evaluating the geological and tectonic history of the Earth, but also in understanding how our planet became habitable through drastic changes in the surface environment. The early history of the Earth during Hadean is shrouded in mystery with only traces of evidence preserved relating to the oldest continental crust. Granitic crust is the main source of nutrient supply to evolve and sustain life, and therefore the timings and relationships between crustal evolution and life evolution are emerging as an important theme in understanding the history of the Earth. The formation of cratons through building cold, rigid and thick rafts beneath ancient continents, and their subsequent erosion are also topics of wide interest. The episodic amalgamation of continents into large land masses and their disruption, termed as supercontinent cycle, have significantly influenced the biogeochemical cycle and surface environmental changes. Above all, the impact of all these processes in evolving modern life on our planet and its implications on the search for life on other planets are attracting considerable attention on a broad and multidisciplinary scale.

In this brief overview, I present a synopsis of some of the recent concepts on the mechanism of evolution of continents, cratons and supercontinents and its implications on the surface environmental changes and the dawn of modern life.

Building continents

The Earth was born dry at around 4.6 Ga, and before this ‘naked’ planet was covered by the thin veneer of ocean water, a hot magma ocean is considered to have prevailed in the Hadean. One of the speculative models proposed that all the Hadean anorthositic crust was deep subducted and lost, dragged down to the bottom of the mantle where it formed a major component in the D″ layer above the core–mantle boundary.

The birth of ocean might have marked the onset of primitive plate tectonics, with water acting as the lubricant to drive the plates, as well as to promote melting and magma generation. Among the two principal magma factories associated with plate tectonics, one is located at the spreading centers where basaltic oceanic crust is generated in mid-oceanic ridge, and the other at subduction zones in convergent margins where slab melting produces a variety of magmas. Although the question of when plate tectonics began on Earth is still being debated, the discovery of detrital zircons from the metasedimentary belt in Jack Hills, Yilgarn Craton, Western Australia has revealed the oldest preserved fragments of the Earth’s crust. The Jack Hills zircons prove the existence of granitic continental crust and oceans on our planet from almost 4.4 Ga onwards. Although the production of granitic crust signals the onset of the primitive plate tectonics, the question whether abundant granitic crust was present in the early Earth remains unanswered.

The history of continental growth through time is a much debated topic, with end-member models presenting diverse views, including bulk production of continental crust in the early history of the Earth, gradual or episodic growth through time, and dominant growth in the Phanerozoic (see Rino et al. for a discussion). The advent of modern analytical tools, particularly zircon U–Pb...
Figure 1.  
a. Schematic illustration of the mechanism of building primitive continents through the parallel collision of arcs and formation of composite arcs. The composite arcs then amalgamate to form embryonic continents (modified from Santosh et al.8).  
b. Tectonic framework of the North China Craton showing ancient continental blocks welded by Meso-Neoarchean greenstone belts (after Zhai and Santosh12).  
c. Cartoon illustrating the growth of continents through the collision of intra-oceanic arcs with continental arcs.

chrono-logy and Hf isotopes, has fuelled this debate in the recent years5–7. On one side, the presence of voluminous granitic crust in the early Earth has been negated based on the history of supercontinents which suggests that the first coherent supercontinent was built only in the Paleoproterozoic, after continental fragments grew into adequate size to be assembled into large land masses8. The history of evolution of life on Earth identifies that nutrient supply to give birth to modern life requires granitic sources and that such sources were not dominant in the early Earth1. On the other hand, the wide occurrence of granitic crust in Archean greenstone terranes and the preservation of undisturbed and near-horizontal Archean sedimentary sequences laid over buoyant granitic basement in some of the ancient continents do not support the notion that granitic continental crust was dominantly absent in the early Earth1. There are also contrasting views on the process of construction of continental crust, with some models proposing that juvenile magma production in convergent margins associated with supercontinent building generates new continental crust, and others arguing that convergent tectonics largely destroys the continental crust through subduction erosion, and that juvenile crust production is dominantly associated with supercontinent break-up5,9. Recent estimates on the volume of global crust generation and destruction along modern subduction zones show that the rate of destruction equals or exceeds the rate of production10. If this is true, the present volume of continental crust on the globe should have been established 2–3 Ga ago7. Clearly, more studies are required to understand the growth (and recycling) of continental crust through time.

If the early Earth was analogous to the present-day Western Pacific as suggested in some studies5, then the surface of the globe should have been dominated by island arcs in an oceanic realm. The collision of intra-oceanic arcs led to the formation of embryonic continents. Among the three modes of arc–arc collision such as vertical, orthogonal and parallel, the parallel collision of arcs is considered to be the most effective mechanism to build composite arcs (Figure 1), since the other two processes will partly or entirely destroy the arc through
Examples of composite arc bundles amalgamated to create micro-continents with evidence for island arc to continental arc magmatism implying continental collision is present in many Archean cratons such as in the North Atlantic Craton of West Greenland, and in the North China Craton (NCC) that forms one of the important ancient nuclei in Asia.

The growth of continents is promoted through vertical and lateral accretion (Figure 2). Melting of the downgoing oceanic slabs in convergent margins generates juvenile magmas which result in the vertical growth. The accretion of oceanic and trench material, sometimes together with other exotic blocks, onto the continental margin results in lateral growth. With continued arc–arc and arc-continental collision, continents grow through time. One of the best examples for continental growth is illustrated by the Central Asian Orogenic Belt (CAOB), representing the largest Phanerozoic accretionary belt on the globe. Lateral accretion of young arc complexes and old micro-continents together with vertical growth through underplating of mantle-derived magmas has been clearly documented from the CAOB. Post-orogenic mantle-derived magmatic intrusions also contributed to the growth of the CAOB.

Building cratons

Cratons are ancient continental nuclei and many of the ancient cratons on the Earth, particularly those which are older than 2.0 Ga, are underlain by thick subcontinental lithospheric mantle (SCLM). The thickness of the lithospheric mantle varies from a few tens of kilometres beneath rift zones to more than 250 km beneath some of the ancient continents. The relationship between the lithospheric mantle and the denser asthenosphere beneath is considered to be like that of an iceberg, buoyant but partly submerged. Most of the Archean cratons on the globe are characterized by ancient, cool and thick lithospheric mantle, mainly composed of high-refractory harzburgites and lherzolites. In the absence of active magmatism they remain dormant, except for sporadic eruptions of kimberlites due to the thick lithosphere and low geotherms. A well-known exception is NCC which has lost most of its original cratonic character through widespread magmatism, deformation and associated metallogeny in the Mesozoic, providing a classic example for cratonic destruction.

Jordan proposed the term ‘tectosphere’ for the highly depleted and relatively low-density upper mantle layer, and tomographic images beneath old cratons clearly show high-velocity roots extending to at least 200 km depth, and in some cases even up to 300 km (ref. 24). Tectosphere, also known as continental keel, is thus a rigid, cold and chemically distinct raft that supports the continental crust. The marked difference in the thickness of the tectosphere beneath continents of different ages can be demonstrated from the significant variation in depth to the lithosphere–asthenosphere boundary (LAB) among Archean, Proterozoic and Phanerozoic continents as documented through seismic investigations and petrological studies on mantle xenoliths (Figure 3).

The formation of tectosphere is a complex process and diverse models have been proposed to explain the building of the cratonic root (Figure 4). The tectosphere is considered in some models as a restite of mantle magmas, predominantly komatiites. Extensive slab melting in the Archean and extraction of felsic magmas which reacted with olivine in the hanging wall are considered to have generated the orthopyroxene-enriched mantle peridotites which characterize the cratonic keel. Because of the high degree of magma extraction from the primitive mantle to build the early continental crust, the lithospheric mantle beneath ancient cratons became highly depleted in basaltic components, resulting in lower density and higher viscosity than that of the asthenosphere beneath. The contrast in density and viscosity probably explains why most cratons have remained chronically stable over time.

Lithosphere formation, plume subcretion and lithosphere accretion?

Wyman et al., based on the co-existence of plume-related and arc-related volcanic sequences in Neoarchean greenstone terranes, proposed that migrating arcs capture thick plume crust, which then becomes imbricated with arc crust. According to this model, the low-density and refractory buoyant residue from plume melting is coupled to the crust generating the continental lithospheric mantle. In a recent study, Manikyamba and Kerrich applied this model to explain the building of the Archean Dharwar Craton in India. In another recent study, Aulbach evaluated three major modes of craton building. (1) Depending on the depth of initiation of partial melting, the upwelling of plumes to shallow levels would leave...
behind a thick and highly depleted residue. (2) Subcretion of plumes beneath a pre-existing lithospheric lid produces less depleted residues owing to narrower melting intervals. (3) Subduction-accretion of oceanic or continental lithosphere leads to lithospheric stacking. The crustal nuclei comprising tonalite–trondhjemite–granodiorite (TTG) and greenstone sequences formed from shallow plate interactions are subsequently penetrated and subcreted by plume-derived melts, and following the delamination of dense eclogite and komatites, TTG would be trapped by buoyant plume residues to build the cratonic mantle.

In recent years, seismic tomography has been used as a tool to image the structure of the Earth’s crust and underlying mantle. One of the best regions to evaluate the structure of the cratonic root is the NCC, where high resolution and comprehensive geophysical data are available from recent studies. Chen et al.29 employed S-receiver function (S-RF) technique and applied a wave equation-based migration method on a combined S-RF dataset collected from more than 200 broadband seismic stations in the NCC to evaluate the subcontinental mantle architecture. Their results show a thick lithosphere (>200 km) in the western part of the NCC, whereas the lithosphere becomes considerably thin (60–100 km) towards the eastern part (Figure 5). Santosh30 reinterpreted the seismic structure of the NCC and identified a prominent layered nature and stacking of contrasting velocity domains, with the thickness (>20 km) of the individual domains correlating well with the thick oceanic crust of the Archean/Paleoproterozoic. These stacked layers would thus define the tectosphere beneath the NCC. A possible interpretation for the layered structure with clear anisotropy is that it represents repeated accretion of the mid-oceanic ridge basalt (MORB) crust and mantle peridotite. The slabs were stacked because they could not penetrate deep due to the double-layered convection prevailing in the Archean mantle31. A similar scenario of a thick continental root with seismic anisotropic layering has been observed beneath Archean cratons elsewhere on the globe, including the Dharwar Craton in India (Figure 5), which might suggest that stacking of subducted oceanic lithosphere served as an important mechanism to build the lithospheric keel beneath ancient continents.

The continental crust has low rigidity and an average thickness of only 35 km. The tectosphere acts as a rigid raft on top of which the thin granitic continental crust is mounted. Therefore, Santosh et al.8 proposed that the tectosphere plays a key role in amalgamating wandering continents and assembling them into supercontinents. The extreme indentation of India during its collision with Asia, a process that is still continuing, may also reflect a thick tectospheric keel beneath the Indian subcontinent.

The volume of tectosphere beneath Archean cratons was gradually reduced through thermal and material erosion by rising plumes during the break-up of supercontinents and by the subsequent intrusion of high-temperature magmas. The NCC provides one of the classic examples for destruction of the tectosphere, with substantial erosion of the cratonic keel in its eastern part. Extensive hydration and erosion through the subducting Pacific plate from the east, coupled with thermal and material erosion by rising magmas have destroyed the constitution and architecture of the subcontinental mantle beneath this craton30.

Supercontinents

The process of assembly of continental fragments into supercontinents and their subsequent break-up is termed as supercontinent cycle, which significantly influenced the course of the Earth’s geologic, climatic and biological evolution5,32–36. In contrast to the rather simple ‘opening and closing’ mechanism envisaged in the Wilson cycle involving the production and destruction of the ocean
Figure 4. Schematic illustration depicting the formation of subcontinental mantle lithospheric root beneath cratons. a and b, The model of Wymann et al.26 (modified from Manikyamba and Kerrich27) proposing the capture of plume crust by migrating arcs. c and d, Aulbach’s28 model of plume subcretion. e, Subduction-accretion model generating stacked oceanic lithosphere. See text for discussion.

floor, supercontinent cycles involve more complex processes to assemble multiple continental fragments of various ages in different ways, including the suturing of ancient cratons with accreted terranes. The Y-shaped topology of triple junctions in major supercontinental assemblies prompted Santosh et al.9 to propose two types of subduction zones on the globe: the Circum-Pacific subduction and the Tethyan. In the scenario where the subduction is double-sided, the triangular regions with Y-shaped topology would selectively reorient the underlying mantle and turn down the temperature in these domains compared to the surrounding regions. These domains also accelerate the refrigeration through larger amounts of subduction and thus promote stronger downwelling. Once this process is initiated, a runaway growth of cold downwelling will be initiated which soon develops into a large zone of super-downwelling, pulling together the continental fragments on the surface into a tight assembly. The western Pacific region illustrates an ongoing example of double-sided subduction (Figure 6), and is considered as the frontier for the future supercontinent37. Multiple subduction zones promote the rapid amalgamation of continental fragments into supercontinents and also act as major zones of material flux into the deep mantle transporting substantial volume of trench sediments and arc crust through sediment subduction and tectonic erosion33,38. Due to buoyancy, the subducted TTG material is stacked in the mid-mantle region and may not sink down to deeper levels, where they are speculated to form the ‘second continent’ in the mantle transition zone39. The high heat-producing elements in the granitic components of the subducted TTG material would account for the generation of plumes rising from the mantle transition zone. On the other hand, the deep subducted material drops down to the bottom of the mantle and forms ‘slab graveyards’ at the D″ layer near the core–mantle boundary. Coupled with heating from the core, such material (postulated to be recycled oceanic lithosphere) could be viewed as a potential trigger of, and contributor to, the superplumes rising from the
Figure 5. A part of the Ps migrated section from Ramesh et al.24 for the Dharwar Craton (a), compared with the migrated S-receiver function image for the North China Craton (b) from Chen et al.27. Note the striking similarity in the topology of the subcontinental mantle down to 250 km beneath the two cratons. A possible interpretation of this crustal structure is that it represents the frozen image of Archean subduction.

Figure 6. a, Schematic illustration depicting the process of double-sided subduction, a process that is considered to promote the rapid amalgamation of continental fragments during the assembly of supercontinents (after Santosh et al.13). b, Numerical model of multiple subduction zones using mobile, deformable continents (after Yoshida and Santosh6). c, Ongoing example of double-sided subduction in the western Pacific region, considered to represent the frontier of future supercontinent (after Maruyama et al.37).

The process of assembly of supercontinents induces a temperature increase due to the thermal insulating effect. This would lead to a planetary-scale reorganization of mantle flow and results in longest-wavelength thermal heterogeneity in the mantle, termed as degree-one con-
vection in 3D spherical geometry. The rifting and break-up of supercontinental assemblies may be caused by either tensional stress due to the thermal insulating effect, or large-scale partial melting due to the flow reorganization and the resultant temperature increase beneath the supercontinent. Recent numerical study allows the modeling of mobile, deformable continents, including oceanic plates, and successfully reproduces the processes and timescales envisaged in the supercontinent cycle, including multiple subduction zones and reorganization of mantle thermal structure during supercontinent amalgamation and disruption40 (Figures 6 and 7).

**Surface environment and life**

During the 4 billion year history of its evolution, the Earth has gone through extreme climatic perturbations, when global glaciations alternated with warm periods which were accompanied by atmospheric oxygenation (Figure 8). Enhanced weathering of huge mountain belts erected through the collisional assembly of continents and incorporated within supercontinents stripped CO₂ from the atmosphere, initiating a runaway cooling that resulted in continental glaciations35,36. The ice cover prevented weathering, subsequent build-up of CO₂ in the atmosphere, finally leading to the melting of the ice sheets. The Earth thus switched from snowball to spring ball. The intervals between the glacial cycles were dominated by the flushing of nutrients into oceans by the weathering of granitic crust, stimulating photosynthetic activity and starting the atmospheric oxygen pump.

Maruyama and Santosh41 presented a synopsis of events in the late Proterozoic during which time two ‘snowball Earth’ glaciations occurred – in the Sturtian (715–680 Ma) and Marinoan (680–635 Ma) – following which large multicellular animals of the Ediacara fauna-flourished as a prelude to the Phanerozoic world. The geochemical bridge to trigger the evolution of modern life in the Cambrian was in place when atmospheric oxygen levels were elevated and nutrient supply was enhanced into 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, modern life bloomed on the Earth. Thus, although the biological blueprint of modern life involving bilateral symmetry was established probably in the early Neoproterozoic, the drastic evolution of the biosphere had to wait until end Neoproterozoic, illustrating a galactic to genome-level link41.

The stepwise increase in the concentration of oxygen in the Earth’s atmosphere has also been linked with the processes associated with the amalgamation of Earth’s land masses into supercontinents. Campbell and Allen42 suggested that the continent–continent collisions associated with the formation of supercontinents produce vast mountain belts (Figure 9), 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 and enhanced production of O₂ through photosynthesis. Simultaneously, the increased sedimentation promotes the burial of organic carbon and pyrite, thereby preventing back-reaction with free oxygen and maintaining sustained increases in atmospheric oxygen. In a recent synthesis, Maruyama et al.1 traced the processes which might have led to the birth of early life on Earth and its aftermath, finally leading to the evolution metazoans. They identified several key factors such...
as: (1) the source of nutrients, (2) chemistry of primordial ocean, (3) initial mass of ocean, and (4) size of rocky planet. The primordial ocean was extremely acidic and toxic, inhibiting the birth of life. Plate tectonics probably acted as a cleaner to generate the blue ocean. Even if granitic continental crust was present in the early Earth, this was largely submerged, which inhibited weathering and nutrient supply. The Neoproterozoic witnessed the initiation of return-flow of sea water into mantle, leading to the emergence of a huge land mass above level, its weathering and distribution of nutrients on a global scale. The oxygen pump has also played a critical role in maintaining high oxygen levels in the atmosphere since then, leading to the emergence of the ozone layer as a roof to shield radiation, and thereby enabling animals and plants to finally invade the land.

Conclusions

Granitic crust is the fundamental source of life-building nutrients. The timescales and rates of production (and destruction) of continental crust are equivocal. Arc–arc parallel collision built primitive continents which subsequently grew through vertical and lateral accretion. Continental mass fragments were episodically assembled and reassembled into supercontinents. The formation of cratons through the construction of thick keels beneath ancient continents is principally linked to convergent margin processes involving either plumes or subducted oceanic lithosphere, or both. It took nearly 4 billion years for the Earth to build a habitable environment for life, involving cleaning up of the oceans, building granitic crust, bringing down the sea level to enable weathering and nutrient supply, and starting the oxygen pump, among other factors, finally leading to the bloom of modern life in the dawn of Phanerozoic.

36. Young, G. M., Precambrian supercontinents, glaciations, atmospheric oxygenation, metazoan evolution and an impact that may have changed the second half of Earth history. *Geosci. Front.,* 2012; http://dx.doi.org/10.1016/j.gsf.2012.07.003.

ACKNOWLEDGEMENTS. I thank Prof. P. Balaram for his kind invitation to contribute this article. Comments from Dr G. Parthasarathy and an anonymous referee helped improve the manuscript. This work is supported by the ‘1000 Talents Award’ grant to me from the Government of China. I also thank all my collaborators for their support and patronage.