



UNRAVELING THE FORMATION OF CONTINENTAL CRUST : A REVIEW AND OUTLOOK

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UNRAVELING THE FORMATION OF CONTINENTAL CRUST : A REVIEW AND OUTLOOK

Eason Hong and Wei-Ting Kao

Key words: continental crust, hadean ocean, anatexis process, plutonic granitoids, craton.

ABSTRACT

The early Earth is generally believed to be a hot planet with a primitive basaltic oceanic crust. However, the question of how a batholiths-bearing continent was formed is still unresolved. Although many hypothetical interpretations seem appealing, the origin and volume dilemma of the batholiths is still under debate. According to recent literature, the Hadean Ocean is characterized by heat, acidity and reduction, significantly unlike its counterparts in Earth's history. We have found that this crucial marine setting, favoring the chemical weathering of basaltic rocks, is the key element for forming and stabilizing the primitive continents through convergent tectonics and the anatexis of voluminous weathering-induced amorphous quartz and clay minerals.

I. INTRODUCTION

It is generally believed that the earth was initially a hot melt (Sleep and Windley, 1982; Hamilton, 1998). Through cooling, an unstable thin-layered crust was repeatedly formed and torn apart to be recycled back into the earth's mantle. This pre-plate-tectonic setting is most probably predominated by vertical mantle upwellings and/or plume diapirism along with delamination or sagduction rather than lateral movement of plates (Sharma and Pandit, 2003; Bedard, 2006; Sankaran, 2006; Rollinson, 2007; van Hunen et al., 2008).

As the hot dry recycling process continued, the out-gassing processes resulted in a water-layered primitive ocean (de Wit, 1998; Morse and Mackenzie, 1998; Watson and Harrison, 2005; Cawood et al., 2006; Papineau, 2010). This allowed plate tectonics to proceed below sea level, signifying the onset

of modern-style plate tectonics. A common viewpoint holds that the process started earlier in the Archaean (Kusky and Polat, 1999; Cawood et al., 2006; 2009; Witze, 2006; Rollinson, 2007; Condie and Kröner, 2008; Windley and Garde, 2009) or even Hadean time (de Wit, 1998; Harrison et al., 2005).

Only a few intra-plate basaltic plateaus and seamounts or volcanic islands developed under the plume dominated pre-plate-tectonic setting in the primitive ocean. As modern plate tectonics succeeded, primitive basaltic island arcs began to develop alongside trench systems. These amalgamations of arcs and plateaus resulted in micro-continents (Kusky and Kidd, 1992), continents, and eventually even super-continents as a result of secular collision, folding, and granitization (Kisters et al., 2010; Tani et al., 2010; Griffin et al., 2011). Evidence of such growth at accretionary convergent margins throughout geological time are well documented (Ben-Avraham et al., 1981; Card, 1990; de Wit, 1998; Komiya et al., 1999; Kusky and Polat, 1999; Sharma and Pandit, 2003; Cawood et al., 2009; Xiong et al., 2011).

As a result of the high temperatures (Witze, 2006; Brown, 2008), the newly formed primitive crust is widely accepted to have been basaltic crust (de Wit, 1998; Sharma and Pandit, 2003; Furnes et al., 2007). Similarly, the magma generated and involved in processes operating at any intra- and inter-plate regions must also have been basaltic. The greatest dilemma currently facing us is the issue of how the continents gained their average andesitic composition as well as significant granitic batholiths from their original basaltic setting.

Various hypothetical models have been proposed (Table 1). In general, most of the models suggest that the partial melting of wet subducting slabs or the remelting and fractional crystallization of the lower intra-crust are required to induce intermediate to silicic melts and leave the eclogitic residue sinking back into mantle (delamination). These explanations seem appealing. However, there are problems which remain unsolved: the mass balance problem, where the formation of huge batholiths appears to require far greater volumes of basaltic magma than were actually present; the issue of granitic rocks in regionally metamorphosed areas seem to be of metamorphic origin; the lack of differentiation in oceanic basalts (Sharma and Pandit, 2003; Bedard, 2006; Foley, 2008; Shen et al., 2009), etc.

Table 1. Various hypothetical models.

Hypothetical models	References
Partial melting of subducted plates	Foley et al., 2003; Lopez et al., 2006; Smithies et al., 2003.
Intracrustal melting	Bowring and Housh, 1995.
Arc magmatism and/or rising plumes	Bedard, 2006; Campbell, 2003; Draut et al., 2009; Kroner and Layer, 1992; Sharma and Pandit, 2003.
A few others	

Based on laboratory experiments, there are three ways to induce intermediate to acidic melts: differentiation of basaltic magma through fractional crystallization, chemical differentiation by wet partial melting, and the anatexis of sediments. Among these, the first two processes lead to the mass balance problem mentioned previously. Therefore, the anatexis process must be the most probable solution. Even so, accepting this hypothesis raises further questions: is there any evidence supporting the anatectic origin of plutonic granitoids which are present in plate-convergence zones? When and how were the water-bearing quartzose sediments or sedimentary rocks generated? Where and how did these sediments and rocks accumulate in quantity? What is the course of continent formation within the scope of the anatexis process? In solving these questions, this study integrates the results of interdisciplinary geoscience studies in order to explore the critical role which the anatexis process plays in Earth's early history.

II. DISCUSSION

There is increased geochemical evidence, trace elements ratio (Ce/Pb, Th/La, Th/Nb), REE, Sr-Nd and Sr isotopic data, indicating that continental sediment was involved in the formation of many of the granitic plutons (Kusky and Polat, 1999; Plank, 2005; Windley and Garde, 2009; Tani et al., 2010; Bento dos Santos et al., 2011). Meanwhile, the melting of formerly near-surface hydrothermally altered basalts, along with the melting of some combination of sediments, igneous rocks, and metamorphic rocks has also been found to give a melt of granitic composition, thus demonstrating the unequivocal and indispensable role of chemical weathering in crust formation (Foley, 2008; Shen et al., 2009). Additionally, large granitic bodies found within plate-convergence zones worldwide have been interpreted as a result of anatexis (Hutton and Reavy, 1992; Plank, 2005; Tani et al., 2010; King et al., 2011; Macera et al., 2011; Wang et al., 2011; Zheng et al., 2011; Adam et al., 2012). In other words, there is sufficient evidence to support the anatexis origin of plutonic granitoids in plate-convergence zones.

The hot, acidic and reducing primitive Hadean Ocean is unique in geologic history. Under such conditions, cation depletion was much greater, a condition which favored the chemical weathering of basaltic rocks (Morse and Mackenzie,

1998). Through the decomposition of basaltic crust, soluble ions (Fe⁺², Mg⁺², Na⁺¹, Ca⁺²) and amorphous quartz were continuously released in the primitive ocean. This increased ion and amorphous quartz content led to the deposition of quartzose and iron-rich sediments, carbonate and evaporates (McGreevy, 1982; Morse and Mackenzie, 1998; Papineau, 2010). As a result, significant generation and accumulation of higher proportions of clay minerals and quartzose sediments occurred worldwide at the expense of the basalt in Hadean and early Archean oceans. It worth noting that the increase of amorphous silica and iron ions was the crucial requirement needed in forming the unique banded iron formation at that early stage.

The formation of the juvenile basaltic island arcs and plateaus gradually increased the basalt-weathering products present. In particular, clays and quartz-enriched sediments were deposited across the seafloor, accumulating at the marginal shelves and slopes of island arcs and plateaus. Since the juvenile basaltic island arcs and plateaus were fated to collide with each other, these unique sediments were scraped off, thrust-faulted, deformed, and coalesced into a larger landmass -- what we term a juvenile continent. Along the course of collision, under strong compressional and shear stress, as well as higher temperatures within the elevated and thickened convergent zones, the clays and quartz enriched accretionary sedimentary deposits underwent complex deformation, metamorphism, and then syn- or post-tectonic intracrustal anatexis to form tonalite-trondhjemite-granodiorite plutons (Fig. 1).

Once a juvenile continent had been formed, marginal accretionary terrains proceeded to develop, creating further complex orogenic deformation, metamorphism, and magmatism responsible for the further growth of a continent. It is believed that the formation, emplacement and/or intrusion of anatectic rhyolitic melt played the role of cement, fusing the juxtaposed tectonic terrains to assemble and stabilize the continents. The convergence and amalgamation of various tectonic terrains and voluminous sedimentary deposits led to a thick, rigid cratonic lithosphere, while the anatexis-induced plutonic granitoids lightened the lithosphere and prevented it from sinking into the asthenosphere. This lighter rigid lithosphere was also classified as buoyant tectosphere or relatively high-velocity mantle root (Abbott et al., 1997; Schoene et al., 2008).

As a whole, a newly formed juvenile continent may be composed of juvenile mafic island arcs, plateaus, and obducted fragments of oceanic crust, as well as accretionary sedimentary wedges, including shallow peripheral shelf, trench and deep sea sedimentary deposits. These different tectonic terrains were thrust-faulted and coalesced through complex accretionary orogenic deformation, metamorphism and magmatism, comprising sedimentary, mafic to felsic volcanic and plutonic rocks as well as various metamorphic grade of said rocks. These unique heterogeneous rock assemblages have been shown to have close similarities to those reported at Archean granite-greenstone terranes (Kusky and Polat, 1999; Windley and Garde, 2009; Adam et al., 2012).

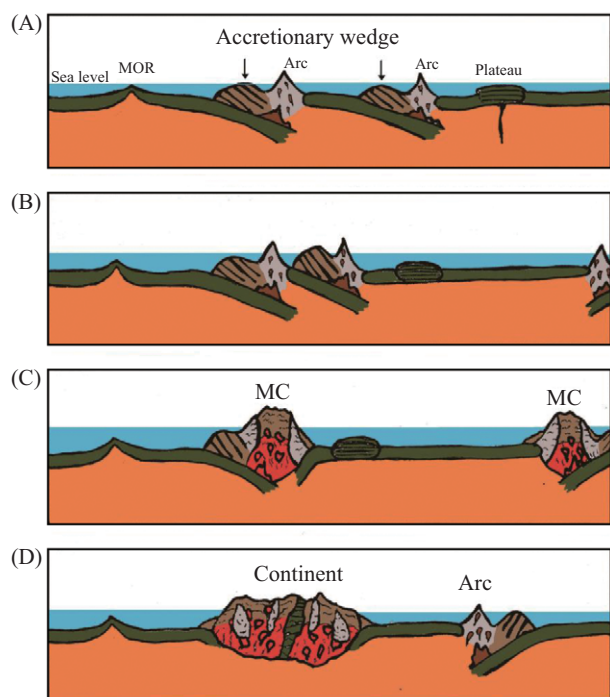


Fig. 1. The conceptual model of forming a primitive continent. (A) For the first time, plate tectonics proceeded below sea level, earlier in the Archean. Meanwhile, through subduction the juvenile basaltic arcs, plateaus were formed. Besides, clays and quartz-enriched sediments were gradually accumulated at the accretionary wedges (denoted by arrow). MOR means middle ocean ridge. (B) The juvenile basaltic island arcs and plateaus were fated to collide with each other. (C) These unique sediments were scraped off, thrust-faulted, deformed, and coalesced with arcs/plateaus into a juvenile micro-continent (MC). Tonalite-trondhjemite-granodiorite plutons were formed through syn- or post-tectonic intracrustal anatexis of the crucial sediments. (D) A primitive granitic-batholiths-bearing continent was formed through secular convergent tectonics and the anatexis of voluminous weathering-induced amorphous quartz and clay minerals.

As plate tectonics proceeded, accretionary growth continued, alongside the rifting, consumption, and reworking on Earth's continents. However, the gradual cooling of the mantle and the emergence of thriving life in the ocean -- likely commenced during Hadean or Archean time -- caused irreversible evolutionary global changes in all four inter-reaction earth systems. These changes included the vast increase of the mineral inventory (Card, 1990; Hazen and Ferry, 2010; Papineau, 2010). As a result, the compositional and kinematic complexity of the juvenile continent and other tectonic terrains within the Hadean and early Archean is significantly unlike those of their counterparts in later periods of Earth's history (Card, 1990; de Wit, 1998).

III. CONCLUSION

In summary, there is a wide consensus that secular collision under plate tectonics is the main driving force which incor-

porates different juvenile arcs and plateaus to form continents. However, the presence of the hot, acidic and reducing Hadean Ocean is critical to our theory. By chemically weathering basaltic rocks in order to produce amorphous quartz and clay minerals, the ocean directly catalyzed the anatexis of accretionary sedimentary rock wedges, creating the cement necessary to form and stabilize the cratonic core of our primitive continents.

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