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Episodic continental growth models: afterthoughts and extensions

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Abstract

Although there are still problems that need to be resolved with episodic models for continental growth, a large number of geochemical and geophysical observations can be explained with these models. The models have in common episodic collapse of subducted slabs through the 660 km seismic discontinuity, mantle convection changing from layered to whole mantle, and each collapse correlates with major episodes of crustal formation. Isotopic age distributions of juvenile continental crust suggest that crustal formation episodes at 2.7, 1.9, and 1.2 Ga may have been very short, each ≤100 My in length. The supercontinent cycle probably operates independently of slab avalanches at the 660 km seismic discontinuity, except for the first supercontinent at 2.7 Ga, which may have formed in response to the first slab avalanche. The production rate of continental crust may increase during slab avalanches in response to increased production rate of oceanic plateaus and of subduction-related crust.

Crustal recycling rate may drop significantly below crustal production rate during slab avalanches due to the formation of supercontinents, which trap juvenile crust. If supercontinents are responsible for the preservation of large amounts of juvenile continental crust, then they play an important role in the growth of continental crust with time. During each of three superevents at 2.7, 1.9, and 1.2 Ga, the mantle may have been well mixed, thus losing geochemical evidence for enriched mantle sources.

Keywords: continental growth; isotopic ages; mantle plumes; supercontinents

1. Introduction

Several models have been published in the last few years that propose a relationship between catastrophic slab avalanches in the mantle and the episodic distribution of ages in continental crust (Condie, 1998a). Most of these models have in common episodic collapse of subducted slabs that accumulate at the 660 km seismic discontinuity, changing mantle convection from layered to whole mantle, and each catastrophic collapse correlates with major episodes of crustal formation.

Several important problems have appeared for these models and it is the purpose of this short contribution to discuss these problems and to suggest some solutions. First, let us briefly review the major models that have appeared in the literature in recent years.

2. Review of models

One of the first models for episodic continental growth is that of McCulloch and Bennett (1994).

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They propose a non-recycling model involving three reservoirs: continental crust, depleted mantle, and primitive mantle. The model is based chiefly on Nd isotopic data but also accommodates Sr and Pb isotopes and incompatible element distributions in each reservoir. It assumes that the volume of depleted mantle increases with time in a stepwise manner, which is linked to major episodes of continental crust formation at 3.6, 2.7, and 1.8 Ga. The isotopic and trace element composition of the upper mantle is buffered by progressive extraction of continental crust and increasing size of the depleted mantle reservoir. The buffered composition of the upper mantle remains depleted in incompatible elements through time.

Stein and Hofmann (1994) were among the first to advocate that episodic instability at the 660 km seismic discontinuity may control the growth of continental crust. They suggested that convection patterns changed in the mantle from layered convection (the normal case), when the growth rates of continental crust were relatively low, to whole-mantle convection when the growth rates were high. Whole-mantle convection occurs in short-lived episodes during which subducted slabs that have accumulated at the 660 km discontinuity catastrophically sink into the lower mantle, in a manner similar to that proposed by Tackley (1997). Stein and Hofmann (1994) show that such a model can account for several geochemical observations, including: (1) ϵ_{Nd} values of the upper mantle are maintained between primitive and depleted mantle values; (2) trace element models for crustal extraction require that the mantle reservoir source is larger than the upper mantle (above the 660 km discontinuity), but less the entire mantle; (3) primordial ^{3}He and radiogenic ^{40}Ar must be present in both the lower and upper mantle; (4) trace element distributions and Pb isotopes require the upper mantle and continental crust to have evolved as an open system. One of the important features of the Stein and Hofmann (1994) model is that during periods of whole-mantle convection, plumes rise from the D″ layer above the core and replenish incompatible elements to the upper mantle, which has been depleted by oceanic crust and arc formation.

Based on the same theme of instability at the 660 km discontinuity and using parameterized mantle convection, Davies (1995) proposed catastrophic global magmatic and tectonic events at 1 to 2 Gy spacings. The favored models show layered convection, which becomes unstable and breaks down episodically to whole-mantle convection as in the Stein and Hofmann (1994) model. The Early Archean overturn cycles may occur on time scales of a few hundred million years. During the catastrophic mantle overturns, hot lower mantle material is transferred to the upper mantle and may be responsible for rapid episodic growth of juvenile crust, as well as replenishing the upper mantle with incompatible elements.

Peltier et al. (1997) extended thermal constraints to evaluate the catastrophic mantle models more thoroughly. These investigators quantified the physical processes that control the Rayleigh number at the 660 km discontinuity, which in turns controls the frequency of slab avalanches at this discontinuity. They also suggest a correlation between avalanche events and the supercontinent cycle. Their results imply that slab avalanches occur at a spacing of 400–600 My, and that they are brought about by the growth of an instability in the thermal boundary layer at the 660 km discontinuity. During and after slab avalanches a large mantle downwelling is produced directly above the avalanches, and this downwelling attracts fragments of continental lithosphere, thus leading to the formation of a supercontinent.

Based on the episodic age distribution of continental crust, Condie (1998a) proposed that continents grew episodically, with major periods of growth at 2.7, 1.9, and 1.2 Ga (Fig. 1). Each maximum in continental growth reflects a superevent in the mantle caused by catastrophic slab avalanching at the 660 km discontinuity, and also correlates with supercontinent formation. The total duration of each of the three major superevent cycles is about 800 My. In addition to the three major superevents in the Precambrian (Fig. 1), the superplume events in the late Paleozoic and Mid-Cretaceous (Larson, 1991) may have been caused by minor slab avalanches at the 660 km seismic discontinuity. The intensity of slab avalanches should decrease with time because the seismic discontinuity becomes increasingly permeable to

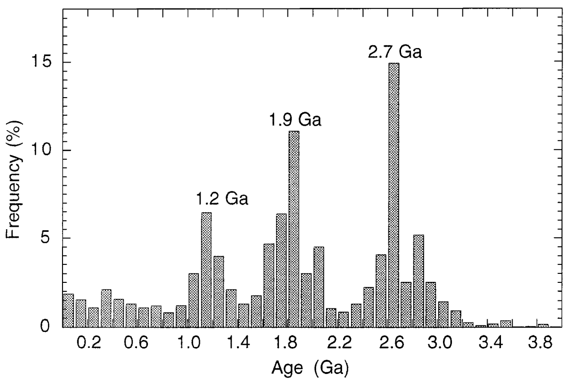

Fig. 1. Distribution of U/Pb zircon ages in juvenile continental crust. After Condie (1998a).

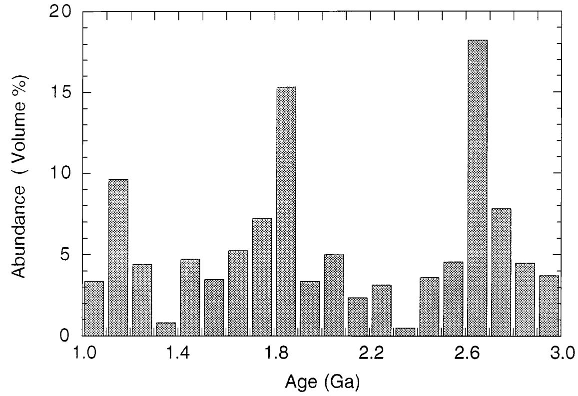

Fig. 2. Revised distribution of U/Pb zircon ages in juvenile continental crust between 3 and 1 Ga. Abundance is proportional to aerial distribution of juvenile age provinces scaled from an equal-area projection of the continents.

slab penetration as the mantle cools and the Rayleigh number decreases.

3. Discussion

3.1. Duration of superevents

Condie (1998a) suggested that each of the catastrophic superevents responsible for the three peaks in continental crust production rate may last for several hundred million years. Each superevent may comprise several subevents (Condie, 1998a, pp. 100–101), each lasting from 50 to 80 My. Since a superevent should happen rather rapidly in response to instability at the 660 km seismic discontinuity, a duration of 300–500 My seems unexplainably long, even if several 'breakthroughs' occur at the discontinuity at different locations as proposed by Condie (1998a).

Because new zircon ages have appeared since Condie (1998a), it is useful to re-examine the distribution of juvenile crustal provinces in light of these data. Zircon ages coupled with Nd isotopic data suggest that juvenile crust of 1.6–1.4 Ga may be much more widespread than suggested in Fig. 1. A potentially large belt of juvenile crust of this age has recently been recognized in western Amazonia (Condie and Melis, 1998; Geraldes et al., 1998), and several remnants of juvenile crust of this age are found in the Grenville province in Canada and in SW Scandinavia (Ahall et al., 1995; Rivers, 1997). Also, numerous zircon ages and Nd isotopic analyses suggest the existence of juvenile crustal belts of 2.3–2.1 Ga rocks in West Africa extending into the Guiana shield and in the basement of western Canada (Abouchami et al., 1990; Ross et al., 1991; Condie and Melis, 1998).

A revised histogram of the time interval from 3 to 1 Ga, based on zircon ages and Nd isotopic data and extrapolated to unexposed regions in the basement suggests that the abundance of juvenile continental crust between the three major peaks varies between about 3 and 7% for each 100 My age increment (Fig. 2). This could mean that the 'subevents' suggested by Condie (1998a) to accompany each major superevent may be part of the 'noise' in background growth rate of continental crust in the Precambrian. It is interesting that only two 100 My windows at 1.4–1.3 Ga and 2.4–2.3 Ga lack significant juvenile crust, and this could be due to inadequate sampling of rocks of these ages. The Late Archean spike straddles 2.7 Ga with ages falling between 2.75 and 2.65 Ga.

If the subevents associated with each of the three major events are not real, but part of the background crustal growth, each superevent is restricted in time to no more than about 100 My. Because rocks associated with each superevent are found on all of the continents today, the effects of superevents may have been very widespread in the mantle. Whether the superevents record slabs breaking through the 660 km discontinuity at one or at several locations at the same time is not yet clear.

3.2. Supercontinent and superevent cycles

One aspect of the catastrophic crustal growth models that has not been addressed is whether the supercontinent cycle can operate independently of the superevent (slab avalanche) cycle. Peltier et al. (1997) suggest that the supercontinent cycle is caused by slab avalanche events in the mantle. In their model, the avalanches produce mantle downwellings directly over the avalanches, which act as 'catchment basins' for an aggregating supercontinent. However, if supercontinents accumulate over geoid lows and break up over mantle upwellings (Anderson, 1982; Gurnis, 1988; Lowman and Jarvis, 1996), both of which are a consequence of the supercontinent cycle, slab avalanches in the mantle may not be a necessary part of supercontinent formation. The mantle upwellings that eventually break supercontinents result from thermal shielding of a large volume of mantle from subduction (and cooling) beneath supercontinents (Hager et al., 1985; Gurnis, 1988) (Fig. 3). If so, how is the superevent cycle (Condie, 1998a) related to the supercontinent cycle? Perhaps slab avalanches can be considered as an 'add-on' to the supercontinent cycle (Fig. 3). A slab avalanche, which initiates plume bombardment of the lithosphere and consequent production of continental crust, may occur at any time during the supercontinent cycle. In the model of Condie (1998a), supercontinent breakup involving increased rates of subduction may trigger a slab avalanche, and this may be the only common denominator to both cycles. This applies, however, only to the Mid and Early Proterozoic avalanches, since there may not have been any supercontinent to fragment for the Late Archean avalanche. In the model of Condie (1998a), the superevent cycle 'injects' juvenile crust into the supercontinent cycle, thus increasing the volume of each succeeding supercontinent.

If this model is correct, as the Earth gets older the superevent cycle will end before the supercontinent cycle because the 660 km seismic discontinuity becomes more permeable to descending slabs as the mantle cools and the Rayleigh number drops. With the exception of possible mini-events in the late Paleozoic and in the Cretaceous, superevents appear to have ended after 1.2 Ga (Fig. 1). The supercontinent cycle, however, may continue as long as convection continues in the mantle, in response to shielding of parts of the mantle by large lithospheric plates.

3.3. The first supercontinent

One of the intriguing yet puzzling questions of any of the episodic models is that of just how and why the first supercontinent formed. There are no robust data that support the existence of a supercontinent prior to the Late Archean. For a supercontinent to form requires a significant volume of continental crustal fragments that survive recycling into the mantle. Prior to the Late Archean, the high mantle temperatures and inferred large mantle convection rates in response to large Rayleigh numbers probably resulted in rapid recycling of continental crust, presumably before continental pieces had time to collide to make a supercontinent

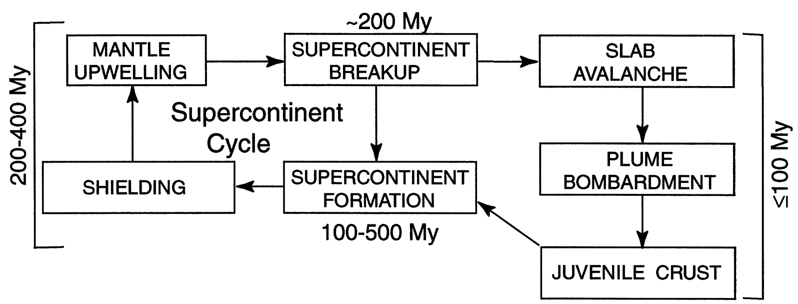

Fig. 3. The superevent cycle modified after Condie (1998a).

(Armstrong, 1991; Bowring and Housh, 1995). So what happened in the Late Archean that led to formation of the first supercontinent?

One possibility is that the first slab avalanche in the mantle at 2.7 Ga, which liberated mantle plumes from the D″ layer, led to the production of large volumes of continental crust in a relatively short period of time (≤100 My). If this is the case, unlike later supercontinents, the first supercontinent would form in response to the first slab avalanche. The mantle plumes resulting from the avalanche could produce juvenile crust in two ways: directly, by the production of oceanic plateaus, and indirectly by heating the upper mantle and increasing the production rate of ocean crust due to increased convection rates or/and increasing the total length of the ocean ridge system (Larson, 1991). The increased production rates of oceanic crust are accompanied by increased subduction rates, and hence increased rates of production of juvenile continental crust in arc systems. A supercontinent may form by collision of Archean oceanic plateaus (especially the thicker ones, which are negatively buoyant) (Cloos, 1993; Condie, 1997a), surviving fragments of continental crust older than 2.7 Ga, and oceanic arc systems. Also contributing to growth of the Late Archean supercontinent is a thick Archean subcontinental mantle lithosphere which is relatively buoyant (Griffin et al., 1998), thus resisting subduction during plate collisions.

If oceanic plateaus were a major contributor to the Late Archean supercontinent, the frequency of Late Archean greenstones with oceanic plateau geochemical affinities should be higher than their frequency in post-Archean greenstones. This seems to be the case from our limited database, using such incompatible element ratios as Th/Ta, La/Yb, and La/Nb (Rudnick, 1995; Condie, 1994, 1997a; Tomlinson and Condie, 1999). Plume-derived lavas contaminated by continental crust may acquire a pseudo-subduction zone geochemical signature (Ta–Nb depletion and Th enrichment). Hence, some Archean greenstone belts that have been described as arc-type based on geochemistry may represent crustally contaminated plume-type magmas. To distinguish these two cases, greenstone successions must be examined carefully, including lithologic assemblage, trace element distributions (including Th/Ta, La/Nb and La/Yb relationships), and Nd isotopic studies to evaluate crustal contamination (Tomlinson and Condie, 1999). Because crustal contamination increases Th/Ta, La/Nb, and La/Yb ratios, the abundance of Archean greenstones with plume geochemical signatures represents a minimum.

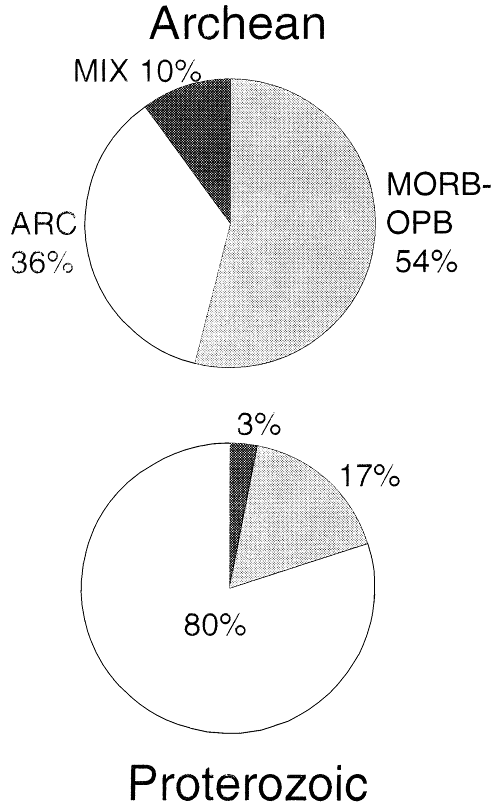

Fig. 4. Relative abundances of greenstones with arc and MORB-OPB affinities based on incompatible trace element distributions. Data sources given in Condie (1994). MORB, ocean ridge basalt; OPB, oceanic plateau basalt; MIX, greenstones with mixed tectonic affinities.

Greenstones with MORB-OPB (oceanic plateau) affinities comprise about 50% of all Archean greenstones, whereas in the Proterozoic, only 17% have MORB-OPB affinities (Fig. 4). If a significant volume of Archean oceanic plateaus became incorporated in the lower crust (Condie, 1997a), we should see evidence for this in the trace element distributions of lower crustal and upper mantle

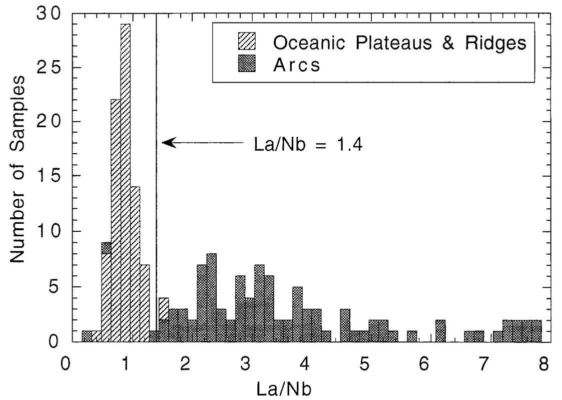

Fig. 5. La/Nb ratio in basalts from young oceanic plateaus and oceanic ridges compared with basalts from arcs. After Condie (1999).

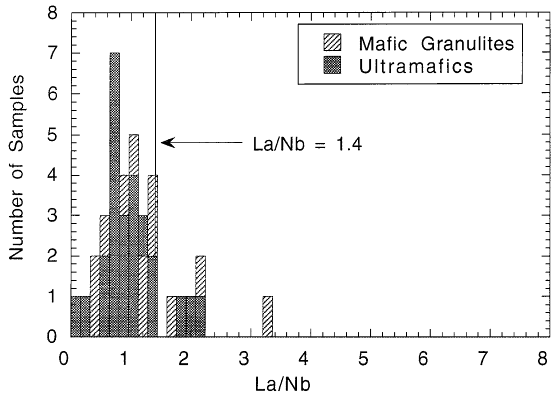

Fig. 6. La/Nb ratio in lower crustal and subcontinental lithospheric xenoliths (and exposed mantle fragments) of Archean age. References: Rogers (1977), Collerson et al. (1991), Huang et al. (1995) and Boyd et al. (1997).

xenoliths. The La/Nb ratio is a sensitive indicator of crust (and associated mantle lithosphere) with oceanic plateau and MORB affinities compared with crust with subduction affinities (Rudnick, 1995; Condie, 1999). Based on data from young basalts, Condie (1997a) suggested that OPB and MORB have La/Nb ratios <1.4, whereas arc-related basalts have ratios >1.4 (Fig. 5). One problem with using xenoliths to monitor Archean lower crust and mantle lithosphere composition is that these xenoliths (especially the mantle xenoliths) are often metasomatized, showing enrichment in LIL elements. Since LREE can be enriched during mantle metasomatism (Bodinier et al., 1990), only the lowest values of La/Nb may be useful in characterizing the original rocks. Although the database is small, most of the published La/Nb ratios for Archean lower crustal and mantle lithosphere xenoliths are low, consistent with dominantly mantle plume or MORB sources (Fig. 6). The Th/Ta ratio is an important index to distinguish between mantle plume and MORB sources, with oceanic plateau basalts derived from plumes typically having Th/Ta ratios >1, whereas MORB sources have ratios generally <1 (Tomlinson and Condie, 1999). An increasing database of Th and Ta data, especially from the Archean Superior Province in Canada, indicates that a significant proportion of Archean greenstones may have had mantle plume sources (Tomlinson and Condie, 1999). Although trace element distributions in greenstones and xenoliths seem to support a period of enhanced mantle plume activity in the Late Archean, which in turn could give rise to the first supercontinent, we need more geochemical data from greenstones and xenoliths of both pre- and post-2.7 Ga age to test this possibility further.

3.4. How do we make continental crust from mantle plumes?

In the model of Condie (1998a), mantle plumes produced by slab avalanches are responsible for producing juvenile continental crust during three superevents. Since mantle plumes give rise to basaltic magmas, which occur as oceanic plateaus, flood basalts, or mafic underplate of continental crust, how do plume-derived mafic rocks change into felsic continental crust? There are at least two ways of doing this (Condie and Chomiak, 1996; Condie, 1997a): (1) oceanic plateaus, being thick and buoyant, collide with and become part of the continental crust, and (2) mantle plumes heat up the upper mantle, increasing the production rate of both oceanic crust and arc-related crust, the latter of which becomes, at least in part, continental crust.

From a comparison of Th/Ta, La/Nb and Ni distributions in greenstones, Condie (1994, 1997a, 1999) suggested that oceanic plateaus may be

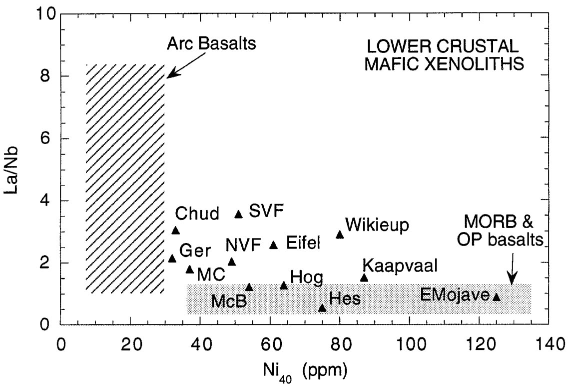

Fig. 7. La/Nb versus Ni_{40} diagram showing the distribution of lower crustal mafic xenoliths. References given in Condie (1999). Chud, Chudleigh, Australia; McB, McBride, Australia; Ger, Geronimo, Arizona; MC, Massif Central, France; SVF, San Francisco volcanic field, Arizona; NVF, Navajo volcanic field, Arizona/New Mexico; Hog, Hoggar, Algeria; Hes, Hessian, Germany; Eifel, Germany; Kaapvaal, South Africa; E Mojave, California. (For Eifel, Ni estimated from Ni/Co = 3; Nb from Nb/Ta = 17). Ni_{40} = Ni content in parts per million at Mg# of 40.

important in at least parts of the lower continental crust. For instance, Wrangellia in NW Laurentia may be an example of a relatively young oceanic plateau accreted to a continent (Condie, 1997a). The average composition of many mafic lower crustal xenoliths plot in or near the field of MORB-OPB compositions on a La/Nb versus Ni_{40} plot (Fig. 7). Because both crustal and host magma contamination should raise the La/Nb ratio in mafic xenoliths, the proportion of plume component in the lower crust deduced from xenolith compositions (approximately 30%; Condie, 1997a) should be considered a minimum value. Also supporting an important plume component in the subcontinental lithosphere are the compositions of spinel lherzolite xenoliths. These xenoliths typically have median Th/Ta (<1.0), La/Yb (2.85), and La/Nb (0.29) ratios similar to oceanic plateau basalts (McDonough, 1990), consistent with the subcontinental lithosphere containing a significant plume component, either as accreted oceanic plateaus or as a plume-derived underplate. In both cases, the spinel lherzolites represent restite remaining in the lithosphere after extraction of basaltic magma.

It has long been recognized that continental crust may also form in arcs from subduction processes (Taylor and McLennan, 1985; Pearcy et al., 1990). Arcs may become part of continents either directly as continental margin arc systems, or by terrane accretion of island arcs (Condie and Chomiak, 1996). Hence, higher rates of subduction during superevents will also enhance the rate of formation of continental crust.

Whether plume or subduction components are most important in the formation of continental crust is not yet clear. From our current geochemical database for greenstones and lower crustal xenoliths, however, it would appear that arc components exceed plume components in most post-Archean continental crust (Rudnick, 1995; Condie and Chomiak, 1996; Condie, 1999).

3.5. Recycling and episodic growth of continental crust

Higher temperatures in the Archean mantle should enhance both extraction and recycling rates of continental crust (Fig. 8). Large recycling rates in the Archean may be responsible for the very minor amount of continental crust older than 3 Ga preserved in the geologic record (Armstrong, 1991; Bowring and Housh, 1995). It would seem also

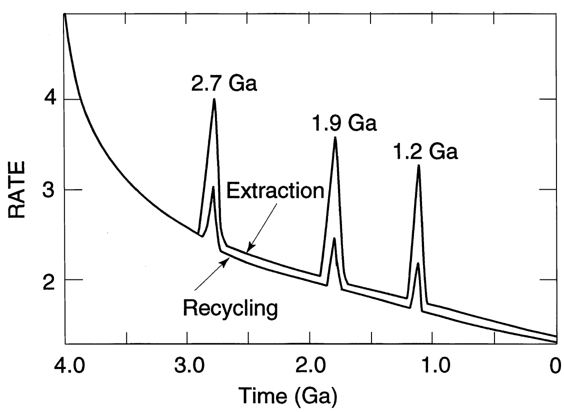

Fig. 8. Postulated rates of extraction and recycling of continental crust with time, relative to the present rates. Prior to about 3 Ga, extraction and recycling rates are assumed to be approximately equal. Background curves are assumed to follow the decrease of radiogenic heat in the mantle with time, and the relative height of peaks is arbitrary.

that during the three pulses of accelerated continental crustal growth rate at 2.7, 1.9, and 1.2 Ga, both extraction and recycling rates should increase. If this were the case, however, why do we have large volumes of continental crust of these ages that have survived?

Recycling of continental crust into the mantle can occur by at least two mechanisms, both of which appear to be potentially important (Kay and Kay, 1998; Plank and Langmuir, 1998): sediment subduction and delamination or slab break-off of lower crust during collisional events. If large amounts of continental crust are to be preserved during each of the three alleged superevents (Condie, 1998a), the extraction rate of continental crust must significantly exceed the recycling rate at these times (Fig. 8). Perhaps growth of a supercontinent during each superevent may be responsible for a *relative* decrease in mantle recycling rates. A large amount of juvenile continental lithosphere produced during each superevent may be 'trapped' and preserved in a growing supercontinent faster than it can be recycled. Because there is less perimeter per unit volume in a supercontinent than in the same volume of smaller continents, collisions should be less frequent, as should recycling by delamination and slab break-off. Also, internal river drainages should be more common in supercontinents and the total number of rivers entering the ocean per unit length of continent perimeter should be smaller in supercontinents than in small continents. Both of these features may lead to less sediment delivered to subduction zones for recycling and to less dissolved material from the continents being recycled into the mantle as altered oceanic crust.

If supercontinents are responsible for the preservation of large quantities of juvenile continental crust accompanying each superevent, then clearly they play a very important role in the growth of continental crust with time. If there were no supercontinents during episodes of enhanced juvenile crust formation, perhaps the total volume of continental crust today would be considerably less.

3.6. The appearance of enriched mantle

At least four, and perhaps as many as six compositional end members have been recognized in the mantle from radiogenic isotope and incompatible trace element distributions in basalts (Hart et al., 1992). The origin and location of these end members in the mantle is still a subject of controversy, although the depleted mantle component (DM) appears to comprise most or all of the mantle above the 660 km seismic discontinuity, and enriched mantle components (EM1, EM2, HIMU, FOZO) appear to reside in the lower mantle (Hart et al., 1992; Hofmann, 1997). The enriched components probably represent continental crust and lithosphere (EM) and oceanic crust (HIMU) that have been recycled into the mantle during subduction or during delamination or slab break-off. The enriched components are recognized chiefly in the Southern Hemisphere today, and are best represented in oceanic island basalts.

Only a few examples of Archean basalts with geochemical evidence for enriched mantle sources have been recognized (Xie et al., 1993; Francis et al., 1999; Tomlinson and Condie, 1999; Tomlinson et al., 1999), with the first major record for these sources appearing in basalts at about 1 Ga (Condie, 1994, 1997b). Why are these mantle components uncommon in most pre-1 Ga greenstone basalts that were erupted in oceanic tectonic settings? In particular, the HIMU component should be widespread in Archean greenstones, since the dominant crust in the Archean was probably oceanic crust and it was probably recycled rapidly into the mantle. Two reasons deserve consideration for the apparent absence of HIMU and EM components in Precambrian basalts. First, since these components are best developed in oceanic island basalts, and such basalts are rare in Precambrian greenstones, basalts with enriched mantle sources may have been overlooked. Equally plausible is the possibility that these components did not survive in the Precambrian mantle and especially in the Archean mantle due to more rigorous mixing in the mantle as suggested by Blichert-Toft and Albarede (1994) for the Archean. Also, during each of the three possible superevents the mantle may have been well mixed, thus losing much of the geochemical evidence for enriched and HIMU mantle domains. Mantle isochrons (Nd, Pb, Sr), however, suggest that geochemical domains began to be preserved in the mantle by about 2 Ga (Carlson, 1994; Hofmann, 1997), yet they are not recorded in mafic magmas until after this time. Why this is the case remains problematic, although it may be related to inadequate sampling of minor components in Proterozoic greenstones.

4. Conclusions

Consideration of the episodic distribution of ages of juvenile continental crust suggests that neither the ‘big bang’ nor the ‘steady state’ models of continental growth are acceptable. Instead, it would appear that there were three moderate ‘bangs’ in crustal growth at 2.7, 1.9, and 1.2 Ga. Although there are still problems that need to be resolved with episodic models for continental growth, a large number of seemingly unrelated geochemical and geophysical observations can be explained with such models. To evaluate the models more quantitatively we need more greenstone isotopic ages and incompatible element data, especially from greenstones that fall in the time windows between the three major age peaks at 2.7, 1.9, and 1.2 Ga (Figs. 1 and 2). Lower crustal and mantle xenolith ages and geochemical data are also needed to test the importance of plume components in the lower continental crust and subcontinental lithosphere. And finally, we need more Nd isotopic data, which together with zircon ages can better constrain the amount of juvenile continental crust formed during each of the three crustal growth episodes.

Geophysical data are needed to better constrain the slope to the 660 km seismic discontinuity reaction and more precisely relate stability of this discontinuity to increasing Rayleigh number with increasing mantle temperature in the Precambrian. Also, experimental data are needed to evaluate more precisely the role of change in composition at the 660 km seismic discontinuity. Increasingly sophisticated geophysical models, including three-dimensional models, will also help constrain the timing of slab avalanches and their relation to plume generation in the D″ layer.

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