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EPISODIC GROWTH OF JUVENILE CRUST AND CATASTROPHIC EVENTS IN THE MANTLE

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Abstract: Episodic growth of continental crust and supercontinents at 2.7, 1.9, and 1.2 Ga may be caused by superevents in the mantle as descending slabs pile up at the 660-km seismic discontinuity and then catastrophically sink into the lower mantle. A superevent cycle involves supercontinent breakup that initiates both slab avalanches and the onset of formation of a new supercontinent; arrival of slabs at the D″ layer triggers mantle plumes that rise and bombard the base of lithosphere producing juvenile crust trapped in the growing supercontinent; and shielding of the mantle beneath the new supercontinent results in a mantle upwelling that eventually breaks the supercontinent as the cycle starts over. Superevents comprise three or four events each of 50-80 My duration, each of which may reflect slab avalanches at different locations and times at the 660-km discontinuity. Superplume events in the late Paleozoic and Mid-Cretaceous may have been caused by minor slab avalanches as the 660-km discontinuity became more permeable to the passage of slabs. The total duration of a superevent cycle decreases with time probably reflecting the cooling of the mantle.

key words: crustal growth, supercontinents, mantle plumes, episodic ages

1. Introduction

It is now well established that the production of juvenile crust has been episodic (GASTIL, 1960; STEIN and HOFMANN, 1994; CONDIE, 1994, 1995). Although not as well documented, it appears that episodic crustal growth is also related to the supercontinent cycle (HOFFMAN, 1989; CONDIE, 1995). BREUER and SPOHN (1995) and STEIN and HOFMANN (1994) propose models by which layered convection in the earth catastrophically changes to whole-mantle convection during short-lived episodes as descending plates accumulate at the 660-km seismic discontinuity and then suddenly sink into the lower mantle. When the slabs arrive at the D″ layer, they trigger plume production, and the plumes rapidly rise to the base of the lithosphere, where they are either directly or indirectly responsible for crustal growth. CONDIE (1995) and PELTIER *et al.* (1997) propose similar models, although limiting the catastrophic episodes to three: at about 2.7, 1.9, and 1.2 Ga.

2. Supercontinents in Space and Time

In the last 1 Gy, the formation and breakup of three major supercontinents has been documented (Rodinia, Gondwana, and Pangea), with a possible short-lived supercontinent, Pannotia, in the latest Proterozoic (SCOTESE and MCKERROW, 1990; TORSVIK *et al.*, 1996; UNRUG, 1997). Geologic data support the existence of at least two earlier supercontinents, one at the end of the Archean and one in the Early Proterozoic (HOFFMAN, 1989; ROGERS, 1996). As more precise ages for the breakup and aggregation of supercontinents have become available, it seems clear that in the supercontinent cycle, one supercontinent is accompanied in part or entirely by the formation of another supercontinent. For instance, Gondwana was forming at about the same time (650 and 550 Ma) as Rodinia broke up (700–530 Ma) (TORSVIK *et al.*, 1996; VEEVERS *et al.*, 1997; UNRUG, 1997). Also, the breakup of Pangea in the last 160 My is accompanied by several major terrane and microcontinent collisions (India, North American Cordillera, SE Asia), which may represent the beginnings of a new supercontinent. Perhaps this is not surprizing or unexpected, if we consider that supercontinents fragment over large mantle upwellings (geoid highs) and the fragmented blocks travel to mantle downwellings (geoid lows), where they collide with other blocks to form a new supercontinent (ANDERSON, 1982; PELTIER *et al.*, 1997). Thus, collisions are occurring over the geoid lows while the supercontinent is still fragmenting over a geoid high.

Another aspect of the supercontinent cycle, which is not well understood, is the question of just which forces are most important in fragmenting supercontinents. Most modelling of mantle plumes has concluded either that they cannot fragment large supercontinents, or they can fragment them only when the lithosphere is already under stress (HILL, 1991; COFFIN and ELDHOLM, 1992; STOREY, 1995). Perhaps the most convincing energy source for the breakup of supercontinents is large mantle upwellings (HAGER *et al.*, 1985; PELTIER *et al.*, 1997). It is known, for instance, that Pangea was centered over such an upwelling when it began to fragment 160 Ma (ANDERSON, 1982), and this upwelling, perhaps reduced in size, is still present beneath Africa (HAGER *et al.*, 1985). If indeed, mantle upwellings are a necessity for the breakup of supercontinents, how are they produced ? Some models (GURNIS, 1988) have suggested that the continental lithosphere acts a thermal blanket, and the mantle beneath such lithosphere heats up, eventually producing a mantle upwelling that breaks the supercontinent (GURNIS, 1988). However, it is now known that the thermal insulation effect of lithosphere is quite small, and probably lags behind a plate "shielding" effect, which can result in heating the mantle beneath both continental and oceanic plates if they are large (LOWMAN and JARVIS, 1996). Shielding by large plates can result in the production of a large mantle upwelling beneath the plates, simply because the plates shield the underlying mantle from the cooling effects of subduction (HAGER *et al.*, 1985). The shielding mechanism is also appealing in that today large mantle upwellings are recognized beneath both the African and Pacific plates, the first dominated by continental lithosphere and the latter by oceanic lithosphere.

3. Production of Juvenile Continental Crust

Juvenile continental crust is produced at two tectonic settings: subduction zones and mantle plumes. The former is most important for the upper continental crust and the latter perhaps, for the lower continental crust (CONDIE, 1997a). The energy for crust production in both tectonic settings is tied to the earth's thermal budget at any given time. In slab avalanching models, the increased production rate of juvenile crust associated with each avalanche is generally related to mantle plumes triggered when the sinking slabs arrive at the D″ layer above the core. The plumes give rise to juvenile crust either directly, by partial melting as they arrive at the base of the lithosphere, or indirectly, by heating the upper mantle. Heating of the upper mantle increases the rate of production ocean-ridge lithosphere, and hence also the rate of subduction of oceanic lithosphere, which in turn, increases the rate of production of subduction-related magmas.

The importance of large mantle upwellings in producing juvenile crust is not well understood. Clearly, if the upwellings penetrate the mantle solidus melting will begin, and the widespread magmatism in Africa in the last 135 My (BAILEY, 1992) may, in part, reflect melting of the large mantle upwelling beneath Africa. It is more likely, however, that mantle plumes, which are concentrated within the African upwelling (CROUGH, 1983), are responsible for most of the African magmatism during this time interval. Although the volume of juvenile magmas added to the African crust during this time is unknown, the fact that most of western and southern Africa is underlain by thick Archean lithosphere (ZHANG and TANIMOTO, 1993; PEARSON *et al*., 1995) suggests it may be rather minor.

4. The 660-km Seismic Discontinuity

Most models for the episodic growth of continents involve catastrophic sinking of slabs through the 660-km seismic discontinuity in the upper mantle (STEIN and HOFMANN, 1994; PELTIER *et al*., 1997). Although seismic tomographic results clearly suggest that descending slabs sink into the lower mantle today (VAN DER HILST *et al*., 1997; GRAND *et al*., 1997), this may not have been the case in geologic past when the earth was hotter. CHRISTENSEN and YUEN (1985) have shown that in a hotter mantle with a larger Rayleigh number, such as probably existed in the Archean (SOLHEIM and PELTIER, 1994; TACKLEY, 1997), the amount of leakage across the 660-km discontinuity is considerably reduced, resulting in layered convection. Computer models of mantle evolution also suggest that increased internal heating of the mantle strongly favors layering in the mantle (ZHAO *et al*., 1992), and this would be the case during the Archean when heat-production by radiogenic isotopes was more pronounced than it is today. Layered convection in the Archean is important in that slab avalanches would not occur. It would not have been until the Late Archean when the 660 became less "robust" that slabs occasionally fell through to the lower mantle (STEIN and HOFMANN, 1994; CONDIE, 1995; PELTIER *et al*., 1997). Cooling of the earth may also have been responsible for the shut-down or decrease in intensity of slab avalanches after 1.2 Ga. As the mantle temperature and Rayleigh number dropped, slabs would more easily penetrate the 660-km discontinuity, leading eventually to whole-mantle convection.

5. Discussion

As shown by CONDIE (1995), earth history can be broadly divided into three stages: Stage I ($>$3.0 Ga), characterized by the absence of superevents and rapid recycling of juvenile crust into the upper mantle; Stage II (3.0–1.0 Ga), during which three major superevents occurred in the mantle and led to enhanced production of juvenile continental crust; and Stage III ($<$1.0 Ga), during which two rather minor superevents occurred in the mantle.

Stage I. The probable occurrence of coexisting depleted and enriched upper-mantle reservoirs in the same geographic area prior to 3.0 Ga as shown by Nd isotopic studies suggests rapid recycling of continental crust into the mantle (BOWRING and HOUSH, 1995). The changes in the Nd isotopic composition of clastic sediments with time is also consistent with such recycling (ARMSTRONG, 1991). Before 3 Ga, continental crust survived only as small microcontinents, some (or all) of which are "captured" in Late Archean orogens, and there is no evidence to support the existence of supercontinents before 3 Ga. As the mantle cooled and continental crust became less easy to subduct, collisions between continental blocks led to the formation of the first supercontinent beginning about 3 Ga and culminating with major collisions at 2.7 Ga. Minor growth of the supercontinent occurred in what is now North China and India at 2.5–2.6 Ga.

Just what caused the three Late Archean events at 3.0, 2.7, and 2.6 Ga is not clear. However, because it is likely that the upper mantle convected separately from the lower mantle, perhaps subducted slabs were not entirely recycled into the upper mantle, but some collected at the 660-km discontinuity. If so, by 3 Ga this discontinuity may have destablized because of the slab load and cooling of the mantle, and perhaps it failed at different places and at three different times (3.0, 2.7, and 2.6 Ga), leading to three slab avalanches. The first two avalanches may have occurred over a wide distribution on the surface the 660, whereas the last one at 2.6 Ga, may have been more localized, since it is represented only in China and India today. It would appear that the avalanche at 2.7 Ga was most intense. Each slab avalanche produced mantle plumes in the D″ layer, and these rapidly bombarded the base of the lithosphere (<10 My; LARSEN and YUEN, 1997), where they underwent decompression melting and produced juvenile crust. Plumes may have been temporarily stalled at the 660 due to the displaced phase boundary within the plumes (CHRISTENSEN, 1995). The plumes also heated the upper mantle resulting in enhanced rates of juvenile crust at ocean ridges and arcs. Multiple slab avalanching is supported by three-dimensional computer simulations in which unsynchronized and spatially localized flushing is observed to occur at different locations on the 660 surface (TACKLEY *et al*., 1994). After the Late Archean slab avalanche, a return to layered convection occurred as the Rayleigh number of the boundary layer at 660 returned to its previous, subcritical value, as the flux of plates crossing the boundary eliminated the temperature gradient across the boundary (PELTIER *et al*., 1997). When avalanches occur, they cause "super" subduction zones above them, which attract plates from great distances (PELTIER *et al*., 1997), thus aiding in the growth of a new supercontinent over the avalanche sites. Also contributing to the growth of the supercontinent is juvenile crust produced directly or indirectly by mantle plumes generated in D″ as the avalanches reached the base of the mantle.

Stage II. During Stage II of earth history, the superevent cycle occurs two more times at 1.9 and 1.2 Ga. After formation of the Late Archean supercontinent, the mantle returns to layered convection, and some fragments of descending slabs again begin to accumulate at the 660. Due to shielding by the large Late Archean supercontinental plate, a mantle upwelling develops beneath the supercontinent leading to breakup between 2.2 and 2.0 Ga. As the supercontinent breaks up, fragments move towards geoid lows, where they collide initiating the growth of a new supercontinent. With the supercontinent breakup, subduction rates begin to increase and perhaps the increase in slabs arriving at the 660 causes another slab avalanche, which in turn initiates mantle plumes, many of which rise within the mantle upwelling(s). Again, the slab avalanches are indirectly responsible for an increase in the production rate of juvenile crust as well as contributing to the formation of another supercontinent. The width of the 1.9 age peak reflects four slab avalanches at approximately 2.1, 1.9, 1.8, and 1.7 Ga, of which only the 1.9-Ga avalanche appears to have had worldwide effects. As the Late Archean supercontinent breaks up over a prolonged period of about 200 My, fragments travel to geoid lows and a new supercontinent begins to form, the oldest portion of which is the Birimian-Guiana craton, which formed at about 2.15 Ga. This is followed by the 1.9, 1.8, and 1.7 Ga collisions, which trap juvenile crust in orogens between colliding blocks. The superevent cycle occurs once more in the Mid-Proterozoic as shielding beneath the Early Proterozoic supercontinent results in a mantle upwelling that eventually breaks the supercontinent between 1.5 and 1.3 Ga. This initiates another slab avalanche resulting in a new episode of juvenile crust production and formation of a new supercontinent, Rodinia, at 1.32 to 1.0 Ga. Juvenile crust ages record at least three slab avalanches at approximately 1.3, 1.2, and 1.1 Ga.

Stage III. Rodinia survives for about 600 My, when a new mantle upwelling fragments it between about 700 and 530 Ma. The formation of Gondwana (650–550 Ma) overlaps the breakup of Rodinia, and this is followed by the formation of Pangea between 450 and 250 Ma. Pangea began to fragment about 160 Ma, and as previously mentioned, a new supercontinent may have begun to form in the last 100 My. Perhaps each of these events was initiated by a "small" avalanche of slabs at the 660. The events were small because the relatively cool mantle with a low Rayleigh number made it easier for slabs to penetrate the 660, and only small amounts of slab material collected at this boundary before collapse occurred. The last event, the Mid-Cretaceous superplume event, may have resulted from the last slab avalanche in earth history. The mantle upwelling beneath the Pacific plate may have developed in the last 100 My because the large Pacific plate shielded the underlying mantle from subduction. The fact the Pacific plate has not moved appreciably between 130 and 95 Ma supports a shielding origin for the upwelling (TARDUNO and SAGER, 1995).

6. Conclusions

1) Maxima in the production of juvenile continental crust at 2.7, 1.9, and 1.2 Ga correspond to formation times of supercontinents.

2) Each of these maxima reflects a superevent in the mantle as descending slabs catastrophically sink through the 660-km seismic discontinuity.

3) Evidence supports a correlation of slab avalanches with supercontinent (and juvenile crust) formation rather than with supercontinent breakup.

4) A typical superevent cycle is as follows (duration in parenthesis): supercontinent breakup (200 My) initiating slab avalanches ($\approx$ 100 My) and the beginning of formation of a new supercontinent; arrival of slabs at the D″ layer at the base of mantle triggers mantle plumes that rise and bombard the lithosphere producing juvenile crust trapped in the growing supercontinent (100–500 My); and shielding of the mantle beneath the new supercontinent results in a mantle upwelling (200–400 My) that eventually breaks the supercontinent and the cycle starts over.

5) Each of the 2.7, 1.9, and 1.2 Ga superevents comprise three or four events each of 50–80 My duration. Each event may reflect slab avalanches at different locations and times along the 660-km discontinuity.

6) Superplume events in the late Paleozoic and Mid-Cretaceous may have been caused by minor slab avalanches as the 660-km discontinuity became more permeable to the passage of slabs.

7) The total duration of a superevent cycle is 700–800 My for Precambrian cycles and 300–600 My for Phanerozoic cycles. This decrease in duration probably reflects cooling of the mantle.

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