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Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga)

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> *Out of theories we create a world: not the real world, but our own nets in which we try to catch the real world.* Karl Popper, *Unended Quest* (1976)

ABSTRACT

It is postulated that a mantle superswell (convective upwelling thousands of kilometres in diameter) developed beneath a stationary supercontinent aggregated in the late Early Proterozoic, giving rise to Middle Proterozoic anorogenic magmatism across Laurentia. Magmatism is attributed to invasion and ponding of mantle melts in the crust, causing uplift and anhydrous partial melting of the lower crust. Products include vast sheets of rhyolite, syenogranite, anorthosite, and gabbro, extensive mafic dike swarms, and rifts containing up to 20 km of basalt. Rifting occurred as a consequence rather than the cause of mantle upwelling. Thermal dissipation of lithospheric mantle may have provided rheological conditions favorable for whole-crustal imbrication observed in the parautochthonous Grenville orogen. The Middle Proterozoic supercontinent engendered more pronounced anorogenic magmatism than subsequent supercontinents because of secular cooling of the mantle. Before the Middle Proterozoic, crustal mass may have been insufficient to produce supercontinents large enough to effectively insulate the mantle and promote superswells. The theory of supercontinental episodicity makes testable predictions concerning paleolatitudes, relative sea levels, and globally synchronous episodes of Proterozoic orogenic and anorogenic activity.

INTRODUCTION

Early compilations of Precambrian isotopic mineral ages indicated that orogeny is globally episodic, appearing to have a period of about 400 m.y. (Gastil, 1960). Sutton (1963) proposed a "chelogenic cycle," in which such orogenic episodicity is related to the aggregation and fragmentation of antipodal supercontinents, governed by changing patterns of mantle convection. Although global orogenic episodicity had been an ideal of tectonicists for the previous century (Greene, 1982), it fell into disfavor with the acceptance of continuous sea-floor spreading and plate recycling. Many expected that the long-term episodicity displayed by mineral age frequencies would degrade as the data base expanded and its reliability improved. It did not.

Independent of Sutton's (1963) forgotten hypothesis, there has been a revival of interest in supercontinental episodicity (Sawkins, 1976; Anderson, 1982; Chase and Sprowl, 1983; Le Pichon and Huchon, 1984; Gurnis, 1988) and its implications for eustasy (Worsley et al., 1984; Heller and Angevine, 1985), seawater chemistry (Shaw and Wasserburg, 1985; Worsley et al., 1985), and biotic evolution (Fischer, 1984). The Phanerozoic record is dominated by the breakup of a Late Proterozoic supercontinent at 0.6 Ga (Sawkins, 1976; Bond et al., 1984), its reassembly as Pangea at 0.3 Ga, and subsequent breakup after 0.2 Ga. Relative sea levels, combining eustatic and geoidal effects, fell after supercontinental aggregation and rose following supercontinental breakup (Anderson, 1982; Heller and Angevine, 1985).

Supercontinents and lower mantle convection, expressed by the geoid, may be interactive (Van Bemmelen, 1964; Schuiling, 1973; Anderson, 1982; Chase and Sprowl, 1983; Davies, 1984; Le Pichon and Huchon, 1984; Gurnis, 1988). While stationary, supercontinents tend to insulate the mantle beneath their interiors because they provide a radiogenic thermal blanket and because the cooling effects of subduction and sea-floor spreading are absent. As the mantle heats up, convective upwelling ensues, causing uplift of the continental lithosphere, injection of mantle melts into the continental crust, and extensive partial crustal melting. Eventually, the weakened supercontinental lithosphere is fragmented by divergent mantle flow from the upwelling. The thermal effects on the lower mantle lag behind the motions of the continental plates. Accordingly, the present Atlantic geoid high and its associated hotspots may be a "memory" of heating beneath Pangea; circum-Pangea subduction zones may have their "memory" in the global ring of geoid lows.

Supercontinents may be a result, as well as a cause, of mantle convection. Continental fragments may be swept toward convective downwellings, where they reaggregate. Mantle flow converging on the aggregating supercontinent may initiate subduction at its periphery, resulting in accretion of island arcs, oceanic plateaus, and other forms of juvenile crust. A mantle upwelling eventually develops beneath the interior of the supercontinent to balance the downward mantle flow at its periphery (Gurnis, 1988). Alternatively, supercontinents may simply be consequences of Atlantic-type oceans, which open inexorably at the expense of other oceans because the stress required to initiate subduction at passive margins increases with the age of the margin (Cloetingh et al., 1984).

The time scale of supercontinental episodicity (only 1.5 cycles in the Phanerozoic) makes it mandatory that the Precambrian geologic record be invoked to test the validity of the concept and to provide means of evaluating various causative factors. My purpose here is to draw attention to aspects of Laurentia's first gigayear (2.0 to 1.0 Ga) which might be manifestations of the Sutton cycle.

LAURENTIA'S FIRST GIGAYEAR

Laurentia's first gigayear resembles a symphony in four movements: 2.0–1.8 Ga (allegro), 1.8–1.6 Ga (andante), 1.6–1.3 Ga (adagio), and 1.3–1.0 Ga (allegro). In the first movement, seven microcontinents were aggregated to form a north-central protocraton (see Hoffman, 1988, for references and a detailed review). The former microcontinents survive as the Superior, Wyoming, Nain, Slave, Rae, Hearne, and Burwell Archean provinces. Tracts of juvenile Proterozoic crust were accreted to the western, southern, and southeastern margins of the protocraton (in the Wopmay, Penokean, and Ketilidian orogens, respectively). The maximum size of the continent formed by 1.8 Ga is unknown, but it surely included Baltica (Gower, 1985). The importance of coeval orogenic belts in South America, Africa, Asia, and Australia invites supercontinental conjecture.

The second movement (1.8–1.6 Ga) combines the dominant themes of the movements before and after—tectonic accretion and anorogenic magmatism, respectively. Juvenile crust was accreted in a belt up to 1200 km wide extending from southern California to southern Sweden, including much of the parautochthonous part of the Middle Proterozoic Grenville orogen (Rivers et al., 1988). Concurrent anorogenic magmatism began in areas assembled prior to 1.8 Ga. Dozens of epizonal batholiths of 1.79–1.73 Ga syenogranite, locally associated with comagmatic ash-flow tuff, occur in a 350 000 km^2 area of Archean crust west of Hudson Bay, 2000 km away from the nearest known contemporaneous plate margin (Hoffman, 1988).

The third movement (1.6–1.3 Ga) was characterized by widespread anorogenic magmatism, the tectonic significance of which has long been debated (Bridgwater and Windley, 1973; Emslie, 1980; Anderson, 1983; Van Schmus et al., 1987). Plutons are typically composed of subalkalic to mildly peraluminous syenogranite, layered gabbro and anorthosite associated with mangerite, and subordinate alkalic complexes. Many of the granites and anorthosites are sheetlike bodies thousands of square kilometres in area. Extensive erosion surfaces developed on such bodies indicate that uplift, equivalent to emplacement depth (generally less than 12 km), occurred during and/or following magmatism. Twin pulses of anorthosite and granite batholiths intruded Archean crust in Labrador (1.46–1.43 and 1.39–1.27 Ga) and Early Proterozoic crust in the southern midcontinent (1.51–1.43 and 1.41–1.32 Ga) and southwestern United States (1.46–1.41 and 1.40–1.36 Ga). Their metamorphosed equivalents occur in the parautochthonous Grenville orogen. In Labrador, where they are best exposed, the batholiths were intruded in a neutral stress regime (Emslie, 1980).

Orogeny returned in the final movement (1.3–1.0 Ga). Seismic reflection profiling reveals a major east- to southeast-directed thrust belt bordering the Beaufort Sea in northwestern Laurentia, possibly equivalent to the Racklan orogeny of the northern Canadian Cordillera (Cook, 1988). The thrusting involves flood basalts believed to be coeval with the Mackenzie dike swarm (1.27 Ga; L. Heaman, 1988, personal commun.) and may have occurred about 1.1 Ga (Cook, 1988). The Grenville orogen extends for 5000 km from Mexico to Sweden and manifests the collision of Laurentia-Baltica with a large unknown continent to the southeast. Northwest-directed ductile thrusting imbricated the Archean and Early Proterozoic crust previously accreted to Laurentia in the parautochthonous Grenville between 1.16 and 1.10 Ga (Rivers et al., 1988), possibly beginning as early as 1.24 Ga at the Grenville front (Green et al., 1988). Juvenile 1.29–1.23 Ga crust of the Central Metasedimentary Belt was thrust northwestward onto the parautochthon at 1.06 Ga (Rivers et al., 1988). Flood basalt, mafic dike swarms, and alkalic ring complexes penetrated the Grenville foreland between 1.43 and 1.14 Ga (Baragar, 1977). The 1.33 Ga alkalic intrusions and the 1.32 Ga Seal Lake flood basalts in Labrador may be related to rifting at the continental margin against which the Grenvillian allochthons would later impinge, but much of the foreland magmatism was coeval with Grenvillian thrusting (e.g., the 1.15 Ga granites and rhyolites of west Texas, and the 1.11–1.10 Ga basalts and gabbros of the midcontinent rift). Farther inboard, sparse anorogenic magmatism persisted with intrusion of the San Gabriel anorthosite at 1.20 Ga and the Pikes Peak granite batholith at 1.02 Ga.

CAUSES OF ANOROGENIC MAGMATISM

Various theories have been advanced to explain the Middle Proterozoic anorogenic magmatism in Laurentia: (1) intracontinental rifting; (2) crustal thickening, melting, and gravitational collapse of an orogenic plateau; (3) low-angle subduction at an Andean-type margin; and (4) large-scale mantle upwelling. I point out some problems of the first three theories and then pursue some implications of the fourth.

1. If lithospheric stretching was the primary cause, then thick alluvial and lacustrine sediments (e.g., Basin and Range) should be widespread. Such sediments are locally present, but in Labrador and Colorado, where best exposed, epizonal plutons intrude basement rocks (Emslie, 1980; Tweto, 1987), indicating no thick contemporaneous sedimentary cover. Extensive subhorizontal seismic reflections in the upper 6 km of the midcontinent granite-rhyolite province (Nelson et al., 1988) contrast with the tilted fault blocks observed in the Basin and Range.

Stretched continental lithosphere subsides upon cooling (McKenzie, 1978), whereas evidence of uplift is observed. In Labrador, uplift of 8–12 km was required to expose the Harp Lake (1.46–1.43 Ga) and Nain (1.39–1.30 Ga) anorthosite-granite complexes before deposition of the 1.32 Ga Seal Lake (Emslie, 1980) and 1.27 Ga Flowers River (Hill, 1982) cover rocks, respectively. The extensive anorogenic granites of the midcontinent were unroofed before deposition of their Paleozoic cover.

2. Crustal melting as a consequence of tectonic thickening fails to account for the mantle-derived components (e.g., anorthosite and gabbro) of the bimodal suites and for the persistence of magmatism for 300 m.y. after orogenic shortening.

3. Low-angle subduction could conceivably account for the distribution of 1.5–1.3 Ga magmatism in southern and southeastern Laurentia if a continental margin existed there then. It could not explain the older granite-rhyolite province west of Hudson Bay, nor the younger mafic dike swarms exposed over most of the Canadian Shield. Furthermore, most of the anorogenic rocks are more potassic and silicic than the extensive dacitic ignimbrites of the Andean Altiplano-Puna region of low-angle subduction (Kay et al., 1988), and they display iron-enriched fractionation trends unlike subduction-related magmas, implying anhydrous melting conditions.

4. Bimodal intraplate magmatism and permanent uplift may result from large-scale mantle upwelling and melting and consequent underplating and melting of the continental crust (McKenzie, 1984). Rifting may be promoted by divergent mantle flow and the gravitational potential of dynamically and isostatically induced doming.

The apparent pulsatory nature of the anorogenic magmatism (1.79–1.74, 1.70–1.54, 1.50–1.42, and 1.40–1.34 Ga) is of approximately the same time scale as the postulated cycles of eustatic sea level and magnetic field reversal frequency, attributed to oscillatory modes of heat transfer across the core-mantle boundary (Sheridan, 1988, and references therein). The relative paucity of anorogenic magmatism in the Archean Superior province compared with the Early Proterozoic crust of southern Laurentia is often noted. The correlation with crustal age is not universal, however; Archean crust hosts anorogenic anorthosites and granites in Labrador and west of Hudson Bay (Ashwal et al., 1986; Hoffman, 1988). If the Superior province was insulated by a refractory Archean tectosphere (Lerner-Lam and Jordan, 1987), such a tectosphere may have been dissipated by the effects of Early Proterozoic subduction beneath the other Archean provinces.

IMPLICATIONS OF MANTLE UPWELLING

The linkage of a large-scale mantle upwelling, or superswell (McNutt and Fischer, 1987), to a Laurential supercontinent as an explanation for anorogenic magmatism, as advocated independently by Anderson (1987), has implications also for problematic aspects of the Grenville orogen, the Mackenzie dike swarm, and the Midcontinent rift. Seismic reflection profiling, in conjunction with surface kinematic analysis, shows that the northwestern Grenville orogen is characterized by closely spaced ductile thrust ramps dipping uniformly through the entire crust (Green et al., 1988). This unusual mode of crustal shortening may have occurred where the lithospheric mantle was thin or absent as a consequence of prolonged asthenospheric upwelling.

Mafic dikes of the 1.27 Ga Mackenzie swarm extend across most of the central and northwestern Canadian shield. The swarm presents mechanical problems in accounting for over 1800 km of distributed extension if caused by lithospheric stretching, and thermal problems if the magma traveled horizontally for 2400 km from a hotspot in the Coppermine area (Fahrig, 1987). Alternatively, the dikes may represent leakage from melt ponds derived from the mantle upwelling. The southeastward-fanning configuration of dikes may record the contemporary intraplate stress trajectories (Féraud et al., 1987) that are generally related to forces imposed at plate boundaries (e.g., Cloetingh and Wortel, 1986). Accordingly, the dikes may parallel compressional stress trajectories related to the coeval(?) orogen bordering the Beaufort Sea (Cook, 1988). Similarly, the northwest trend of the younger (1.24 Ga) Sudbury dike swarm may be related to the onset of thrusting in the Grenville orogen (Green et al., 1988).

Seismic reflection profiling shows that the 1.1 Ga Midcontinent rift contains an extraordinary thickness (15–20 km) of basalt (Behrendt et al., 1988). The quantity of magma generated in rifts is critically dependent on the potential asthenosphere temperature (White et al., 1987). Accordingly, the great thickness of basalt in the midcontinent rift implies the existence of a mantle thermal anomaly (i.e., mantle upwelling) independent of that induced by the rifting process.

Middle Proterozoic breakup of the postulated Early Proterozoic supercontinent is difficult to prove because the margins of Laurentia were overprinted by subsequent events. However, if the 1.3–1.0 Ga renewal of orogeny in Laurentia is related to aggregation of a Late Proterozoic supercontinent, then the persistence of anorogenic magmatism in Laurentia until 1.1 Ga implies that Laurentia, like Africa today, remained above the mantle upwelling during the period of continental dispersal. Moreover, it implies that reassembly of a Late Proterozoic supercontinent occurred above a mantle upwelling, rather than a downwelling, as predicted in theory (Anderson, 1982; Gurnis, 1988).

TESTS OF SUPERCONTINENTAL EPISODICITY

If the tectonic evolution of Laurentia-Baltica from 2.0 to 1.0 Ga was governed by supercontinental aggregation, fragmentation, and reaggregation, then other continents should have participated in the same scenario. U-Pb geochronology is capable of testing the predicted correlations of orogenic and anorogenic activity with great precision. In Australia, the only other continent with sufficient U-Pb data, the parallels (e.g., widespread 1.9–1.8 Ga orogenesis, 1.8–1.3 Ga anorogenic magmatism, and 1.3–1.1 Ga orogenesis) are striking (Page et al., 1984; Wyborn et al., 1987). South America seems to have experienced a similar evolution, on the basis of less reliable Rb-Sr data. Globally, more data are needed and the real story will inevitably be more complex than the beguiling simplicity of the theory (e.g., arc-continent collisions occurred within the Tethyan embayment of Pangea—Sengör, 1984).

Paleomagnetism provides another test. Theoretically, rapid plate motions should precede supercontinental aggregation, anorogenic magmatism should be enhanced if a supercontinent is stationary relative to the underlying mantle (Pollack et al., 1981), and superswells should stabilize equatorially (Goldreich and Toomre, 1969). Paleolatitude variations for Laurentia (Irving and McGlynn, 1981) are consistent with the predictions: rapid variations are inferred from 1.9 to 1.6 Ga, a stable low-latitude position from 1.5 to 1.2 Ga, rapid variations from 1.2 to 0.9 Ga and, although data are sparse, an equatorial position from 0.9 to 0.6 Ga. According to the theory, similar patterns should be observed on other continents.

The model also makes testable predictions regarding changes in relative sea level, which should be highest during supercontinental aggregation and lowest prior to supercontinental breakup. This can best be judged by the presence or absence of marine platformal sediments preserved on nonstretched continental crust. The stratigraphic record in Laurentia accords with the predictions. There are numerous marine sequences, excluding foredeeps, indicating relatively high sea level between 2.0 and 1.8 Ga (Hoffman, 1988). High sea levels immediately following aggregation are suggested by the preservation of large intracratonic basins about 1.7 Ga in age (e.g., Baraboo, Athabasca, and Thelon basins). Outside of rifts, the Apache Group of Arizona is one of the few marine sequences in Laurentia between 1.5 and 1.1 Ga (the Grenville Supergroup may have been deposited far from Laurentia). Theoretically, secular stratigraphic variations in other continents should resemble those in Laurentia, except that continents which broke away from Laurentia during the Middle Proterozoic may record a relative sea-level highstand thereafter.

FIRST SUPERCONTINENT?

If superswells generated by supercontinents cause anorogenic magmatism, why was such magmatism more pronounced in the Middle Proterozoic than before or since? Consider that there has been a secular decline in mean mantle temperature and net growth of continental crust since the Early Archean. In order to promote mantle upwelling, a supercontinent must be sufficiently large that the mantle beneath its interior is not cooled by subduction at its periphery—the larger the supercontinent, the greater the insulating effect. Before 1.8 Ga, the total mass of continental crust may have been insufficient to form a true supercontinent. Next, consider that the volume of melt produced during upwelling increases with mantle temperature. Although supercontinents formed after 1.0 Ga could have been slightly larger than in the Middle Proterozoic, the mantle would have been cooler. Other things being equal, the first true long-lived supercontinent would have experienced the most intense anorogenic magmatism.

CONCLUSIONS

Widespread Middle Proterozoic anorogenic magmatism in Laurentia may have manifested a mantle superswell localized beneath a stationary supercontinent aggregated between 1.95 and 1.80 Ga. A superswell would have caused uplift of Laurentia, erosion of its lithospheric mantle, invasion of the continental crust by mantle melts causing extensive anhydrous partial melting of the lower crust, and eventual continental breakup. Orogeny along the southeastern and northwestern margins of Laurentia between 1.3 and 1.0 Ga may record the reassembly of a Late Proterozoic supercontinent. If so, the reassembly apparently occurred above a mantle upwelling, rather than a downwelling, as predicted in theory. Anorogenic magmatism was most pronounced in the Middle Proterozoic supercontinent; this may be because the mantle has cooled since that time and older continental aggregates were too small to generate superswells. The theory of supercontinental episodicity (the Sutton cycle) makes testable predictions regarding global tectonic correlations, paleolatitudes, and relative sea levels.

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Reviewers' comments

This is big thinking at its best; a bold attempt to pull together observations spanning vast stretches of geologic time into a relatively simple model of supercontinent episodicity.

Robert Detrick

This paper presents a new, exciting idea regarding anorogenic magmatism and, as far as I am aware, the first *NEW* model for such magmatism presented in many years.

Kent Condie
