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Continental rift systems and anorogenic magmatism

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Abstract

Precambrian Laurentia and Mesozoic Gondwana both rifted along geometric patterns that closely approximate truncated-icosahedral tessellations of the lithosphere. These large-scale, quasi-hexagonal rift patterns manifest a least-work configuration. For both Laurentia and Gondwana, continental rifting coincided with drift stagnation, and may have been driven by lithospheric extension above an insulated and thermally expanded mantle. Anorogenic magmatism, including flood basalts, dike swarms, anorthosite massifs and granite-rhyolite provinces, originated along the Laurentian and Gondwanan rift tessellations. Long-lived volcanic regions of the Atlantic and Indian Oceans, sometimes called hotspots, originated near triple junctions of the Gondwanan tessellation as the supercontinent broke apart. We suggest that some anorogenic magmatism results from decompression melting of asthenosphere beneath opening fractures, rather than from random impingement of hypothetical deep-mantle plumes.

Keywords: Rift; Gondwana; Laurentia; Anorogenic magma; Plume

1. Introduction

The ultimate causes and controls of continental rifting and anorogenic magmatism remain controversial questions in geotectonics. Geodynamicists commonly model anorogenic magmatism as the result of impingement of hypothetical deep-mantle plumes on the lithosphere, with continental rifting as a secondary consequence of lithospheric doming above the plume head (cf. Wilson, 1963; Morgan, 1981; Bijwaard and Spakman, 1999; Campbell, 2001; Condie, 2001; Storey et al., 2001; Turcotte and Schubert, 2002). However, in a serious challenge to the deep-mantle plume paradigm, Hamilton (2002, 2003) asserts that the endothermic phase boundary at 660-km depth isolates lower and upper mantle convection, and that propagation of lithospheric cracks triggers anorogenic magmatism through decompression melting of ordinary asthenosphere. Similarly, Anderson (1982, 2001, 2002) takes a top-down tectonic viewpoint, in which a stagnant supercontinent insulates the underlying mantle, leading to thermal expansion, partial melting and a geoid bulge. The lithosphere then fractures over

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this bulge and anorogenic magma injects propagating rift zones.

Here, we show that continental rift zones and associated anorogenic magmatic provinces in some cases approximate a mathematically precise, large-scale tessellation, the truncated icosahedron. This quasi-hexagonal fracture pattern manifests a least-work configuration that minimizes perimeter, area and energy (cf. Anderson, 2002). The tessellation appears to be a brittle phenomenon organized within the lithosphere, and so favors the top-down origin for some rifts and anorogenic magmatic provinces.

2. Truncated icosahedron

The icosahedron has 20 identical triangular faces that meet in fives at each of 12 vertices. Truncation of the icosahedron creates pentagonal and hexagonal faces with equal edge-lengths (Fig. 1). Spherical truncation creates the familiar soccer-ball tessellation of regularly arranged hexagons and pentagons, for which each seam forms a 23° great-circle arc, and each triple junction joins two hexagons and one pentagon. The distribution of polygons is mathematically precise; establishment of a single pentagon fixes the entire tessellation. The truncated icosahedron incorporates the largest regular hexagonal tiles permissible on a tessellation of a sphere.

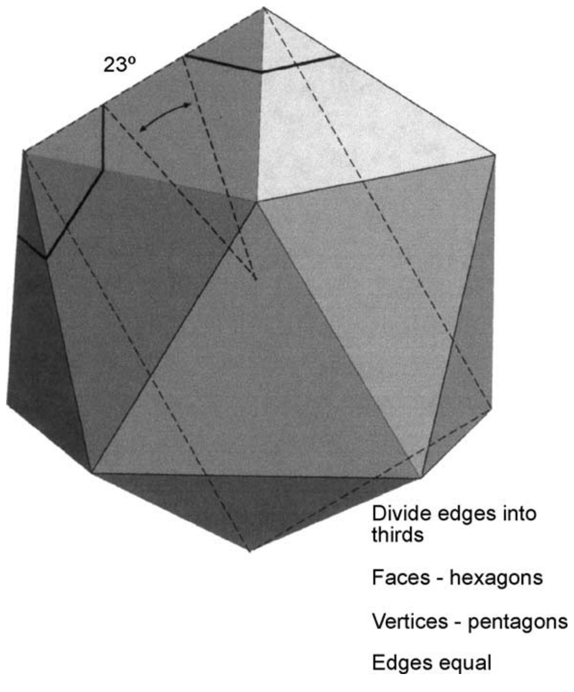

Fig. 1. Truncation of icosahedron divides edges into thirds and produces hexagonal and pentagonal faces with central angle of 23.28°.

Icosahedral structures typify many natural spherical equilibrium systems. Examples include fullerene molecules, wart and herpes viruses, radiolaria, tortoise shells, zeolites, quasi-crystals, clathrates, boron hydrates and foams (cf. Anderson, 2002). We propose that, under conditions of uniform horizontal extension, the pattern also characterizes fractures of spherical shells, such as the lithosphere, and associated emplacement of anorogenic magma.

3. Laurentia

Laurentia is a relic of a Paleoproterozoic supercontinent that likely included parts of Baltica, Australia, Siberia, China and other cratons (Sears and Price, 2003; Karlstrom et al., 2001; Hoffman, 1989). Mesoproterozoic and Neoproterozoic rift zones truncated Paleoproterozoic and Archean basement trends. Upon restoration of Cenozoic drift, the rifts approximate a hexagon and part of a pentagon of a precise truncated-icosahedral tessellation (Fig. 2). As detailed elsewhere (Sears, 2001), the edges of these tiles follow broad zones of Mesoproterozoic and Neoproterozoic anorogenic magmatism that include dike swarms, volcanic-sedimentary rift basins, and anorthosite, granite and rhyolite suites. The anorogenic suites are characteristically bimodal, A-type magmatic rocks having within-plate trace-element signatures (Van Schmus and Bickford, 1993). The rifts evolved into early Paleozoic passive-margin miogeoclines (Bond et al., 1984). Phanerozoic orogenic belts that compressed these miogeoclines now frame the craton and highlight the hexagon.

The Greenland, Arctic and western Canadian sides of Laurentia have arc-lengths of 23° and define three hexagonal edges. A fourth edge of this hexagon follows the Montana–Tennessee structural corridor, a >600-km wide zone of rifts, dike swarms, and anorogenic magmatism in the subsurface of the central United States (Hatcher et al., 1987; Paulsen

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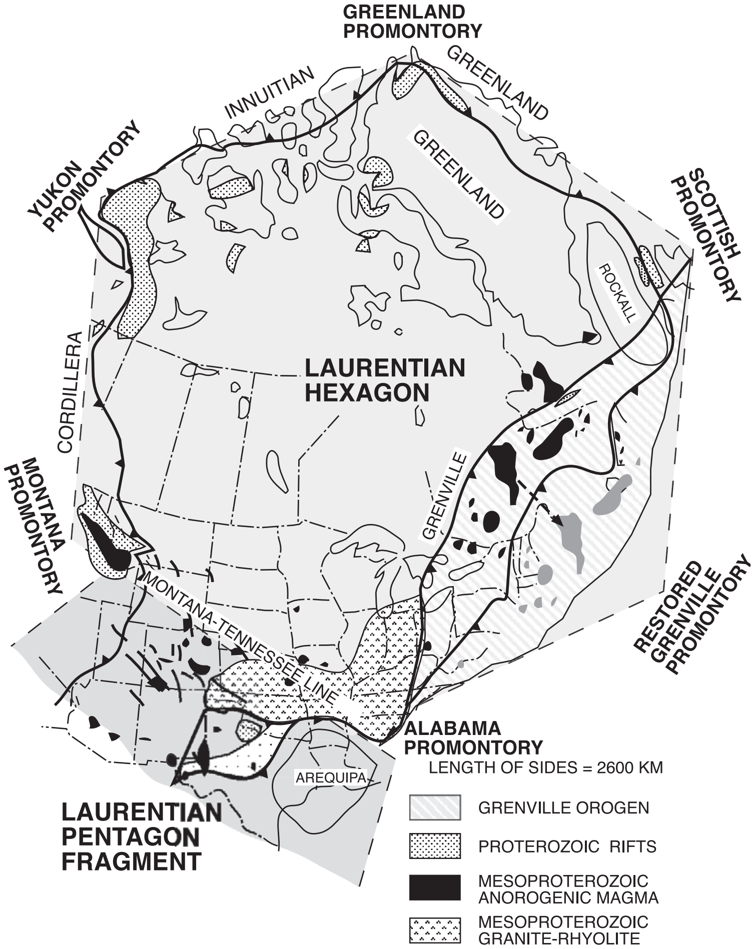


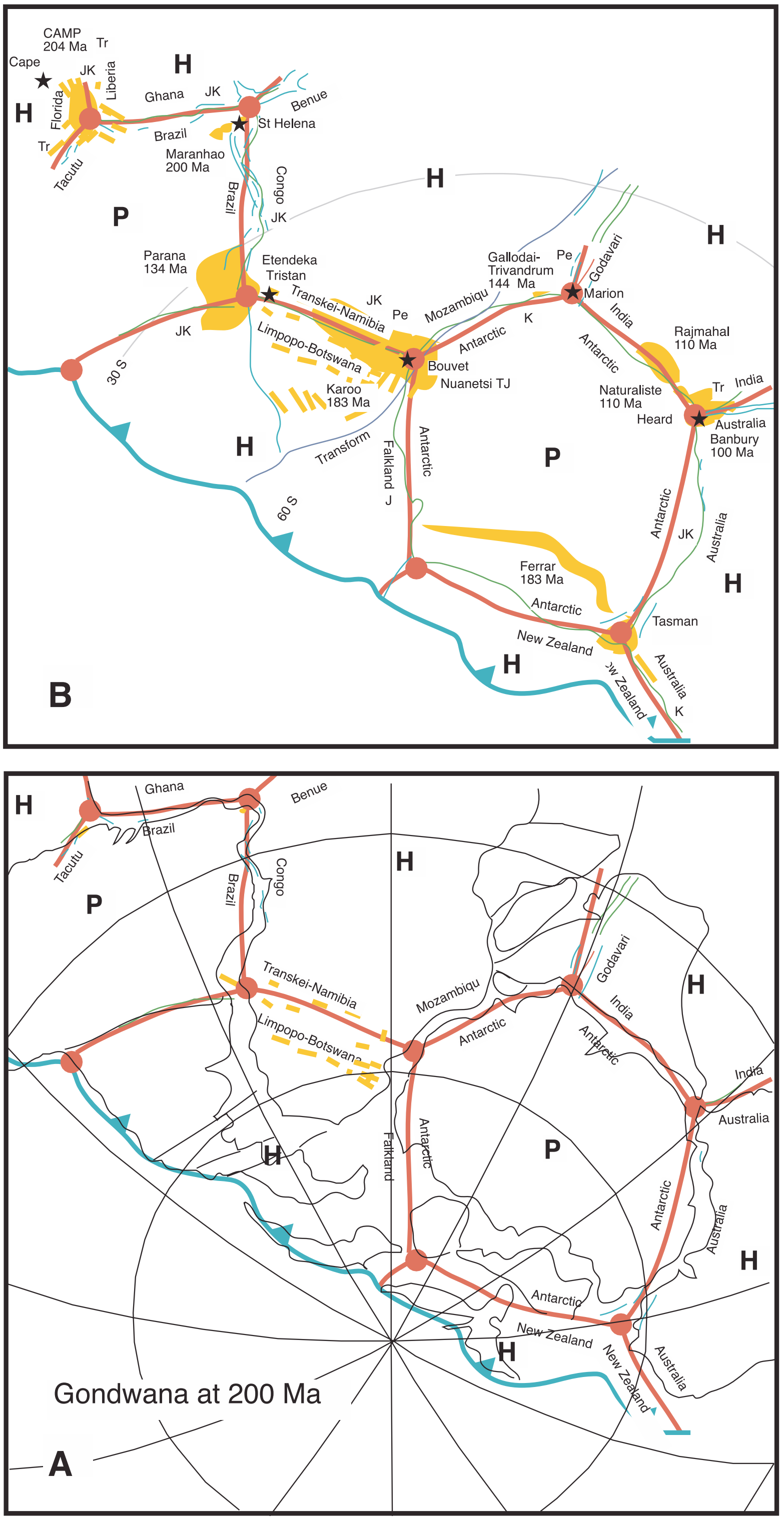
Fig. 2. Truncated-icosahedral fracture tessellation of Laurentia, after Sears (2001). Each side of hexagon subtends 23° of arc. Mesoproterozoic and Neoproterozoic anorogenic provinces occur along edges. Restored for Cenozoic continental drift.

and Marshak, 1994; Marshak et al., 2000; Sears, 2003). The Alabama, Montana, Yukon, Greenland and Scottish promontories are congruent with five vertices of the hexagon. This congruence satisfies two independent, precisely defined parameters of the truncated-icosahedral hexagon, the arc-length of edges (2600 km) and the turning-angles between edges (120°). The late Mesoproterozoic Grenville orogen may have tectonically collapsed the sixth vertex, as reconstructed in Fig. 2.

The tessellated rift zones initiated approximately 200 Ma after completion of tectonic amalgamation of Laurentia (Hoffman, 1989), when the supercontinent stalled in its apparent polar wander path (Elston et al., 2002).

4. Gondwana

Gondwana provides a Mesozoic example of truncated-icosahedral rifting and anorogenic magmatism. Fig. 3 restores Gondwana into its tight 200-Ma structural configuration, after Lawver et al. (1999), and illustrates the close congruence of Gondwanan rift zones and anorogenic magmatic provinces to the tessellation. The truncated-icosahedral tessellation is rigorous; Antarctica approximates a pentagon, the other polygons are dependent. More than 20,000 km of rifts followed 15 edges of this singular tessellation during breakup of the supercontinent. Triple-rift junctions are well established for Gondwana (Burke and Dewey, 1973). However, it has not previously


CAMP
204 Ma
Tr
Cape
JK
Liberia
Florida
H
Ghana
JK
Benue
St Helena
Brazil
Maranhao
200 Ma
Tr
Tacutu
Congo
Brazil
JK
P
H
Parana
134 Ma
Etendeka
Tristan
Transkei-Namibia
JK
Pe
Limpopo-Botswana
Karoo
183 Ma
Mozambiqu
Gallodai-
Trivandrum
144 Ma
Pe
Godavari
Marion
India
K
Antarctic
Bouvet
Nuanetsi TJ
Rajmahal
110 Ma
Antarctic
Naturaliste
110 Ma
Heard
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India
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Banbury
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Gondwana at 200 Ma
A

been noted that many of the triple junctions are separated by 23° of arc and fit the unique arrangement of the truncated icosahedron.

The following conjugate coasts correspond to tessellation edges (Fig. 3B): Florida–Liberia, Brazil–Ghana, Brazil–Congo, Falkland–Antarctica, Mozambique–Antarctica, India–Antarctica, Australia–Antarctica, New Zealand–Antarctica, Australia–India and Australia–New Zealand. The following branching rift zones, or failed arms, match edges of the same tessellation: Tacutu, Benue and Godavari (cf. Şengör and Natal'in, 2001). The discontinuity across central South America coincides with a tessellation edge (Fig. 3A). The Limpopo–Botswana and Transkei–Namibia mafic and kimberlite dike swarms (Hunter and Reid, 1987) follow a tessellation edge across southern Africa. The tessellated rifts mostly fractured relatively coherent Precambrian cratons within Gondwana. Gondwanan rifts that were discordant to the tessellation were those that reactivated older Gondwanan sutures. According to the compilation of Şengör and Natal'in (2001), the tessellated Gondwanan rifts mostly evolved in late Jurassic to early Cretaceous time, but some have Permian or Triassic ancestry (Fig. 3B).

Large anorogenic igneous outbreaks occurred along tessellation edges, near vertices. These comprise the CAMP (Central Atlantic mafic province), Maranhão, Paraña-Etendeka, Karoo, Gallodai-Trivandrum, Rajmahal, Naturaliste, Banbury and Tasman provinces. The igneous outbreaks were episodic from 204 to 100 Ma and are commonly considered to be plume eruptions (Ernst and Buchan, 2001).

Several volcanic "hotspots" are thought to represent continuing anorogenic magmatism at the approximate sites of the initial outbreaks of the Gondwanan igneous provinces; well-documented tracks of extinct volcanoes on the sea bed connect some of these active volcanic sea mounts to the provinces (Morgan, 1981). The following hotspot-igneous province links are possible: Cape Verde (or Fernando?) hotspot—CAMP, St Helena hotspot—Maranhao province, Tristan hotspot—Parana-Etendeka province, Bouvet hotspot—Karoo province, Marion hotspot—Gallodai-Trivandrum province and Heard hotspot—Naturaliste province. With the exception of Cape Verde, these hotspots conform rather closely to the vertices of a single truncated-icosahedral tessellation. Excluding Cape Verde, we determined a 1.5° mean angular distance between these hotspots and the triple junctions of a best-fit truncated-icosahedral tessellation (St. George, 2003). As shown in Fig. 3, the hotspot and rift tessellations are approximately congruent when Gondwana is restored onto the hotspot framework.

We suggest that the fracture tessellation propagated across Gondwana before late Jurassic seafloor spreading began to separate its parts. Fracture propagation may have begun in Permian or Triassic, because some of the rifts that fall on the tessellation are known to date from that time. The fractures relieved tensile strain within the lithosphere, but may not have erupted magma until the resulting tiles separated sufficiently to drive decompression melting. That is, although organization of the fractures may have been a passive, within-Gondwana response to tension, separation of the tiles and magmatic outbreaks may have depended on global plate-dynamics.

As observed by A. Luttinen, one of the reviewers of this manuscript, if the hotspots were indeed generated top-down, drifting of Gondwana during propagation of the fractures and opening of the triple junctions should have left behind a framework of asthenospheric hotspots that exhibit distorted rather than ideal truncated-icosahedral geometry. We suggest that initial opening of the Central Atlantic may have moved Gondwana and its fracture tessellation off the outbreak point of CAMP, so that the hotspot tessellation is displaced with respect to Cape Verde (or Fernando) hotspot. Furthermore, initial opening of the Mozambique Channel may have split the fracture tessellation between the halves of Gondwana, so that

Fig. 3. (A) Gondwana configuration at 200 Ma, after Lawver et al. (1999), showing congruence of Gondwanan rifts with truncated-icosahedral tessellation. Circles at truncated-icosahedral vertices (triple junctions) are separated by 23° of arc. (B) Simplified map of Gondwana on same base as (A), except Earth coordinates rotated slightly from Lawver's placement to demonstrate congruence of active hotspots associated with Gondwanan large igneous provinces and tessellation triple-junctions. Stars: active hotspots, names italicised. Yellow: large igneous provinces and dikes. Blue: Gondwanan rifts. Red: ideal truncated-icosahedral tessellation. P=pentagon, H=hexagon. Ages of rifts from Şengör and Natal'in (2001): Pe=Permian, Tr=Triassic, J=Jurassic, K=Cretaceous.

the modern hotspots are slightly dispersed from an ideal tessellation.

Despite these minor distortions, the approximate overall congruence of the hotspots to the tessellation implies that Gondwana was largely stagnant during late Jurassic–early Cretaceous magmatic outbreaks. This stagnation may be reflected in the late Jurassic–early Cretaceous loop in the Gondwana apparent-polar-wander path (De Wit et al., 1988) and is consistent with the De Wit et al. (1988) restoration of Jurassic and early Cretaceous Gondwana. It differs slightly from models of Golonka et al. (1994), Lawver et al. (1999) and Şengör (2001), however, in the position of southern Gondwana with respect to the hotspots.

Because the symmetry of sea-floor spreading is incompatible with that of the truncated icosahedron, Gondwanan plate boundaries evolved new ridge-transform configurations as the continental fragments dispersed. The incongruent southeast coast of Africa is one such transform boundary.

5. Discussion

The truncated-icosahedral fractures of Laurentia and Gondwana argue against a deep-mantle plume origin for some continental rifts, associated anorogenic igneous provinces and volcanic hotspots. The tessellated fractures better characterize brittle lithosphere than a chaotically convecting mantle. Although both Rayleigh-Bénard and Rayleigh-Taylor convection can adapt polygonal cells such as those of the truncated icosahedron under stagnant-lid conditions, such cells are unlikely to remain stable because high Rayleigh numbers (10^6–10^7) expected in the upper mantle lead to time-dependent convection and shifting cell patterns (Talbot et al., 1991). Worm-like ascents of hypothetical plumes from the mantle (Steinberger, 2000) argue against a geometrically rigorous hotspot distribution. The hotspot tessellation may, however, be consistent with the top-down tectonic models of Anderson (2001) and Hamilton (2003).

Anderson (1982) and De Wit et al. (1988) determined that a stalled supercontinent should insulate the mantle, and that the resulting accumulation of heat should partially melt and expand the asthenosphere. The increased radius of curvature of the lifted plate should then impose homogenous surface-parallel tensile strain on the lithosphere that should eventually fracture and disperse the supercontinent (Anderson, 1982). Anderson (1982) proposed that thermal uplift of Gondwana began in Permian, and that rift response began in Triassic–Jurassic; he hypothesized that the Atlantic–African geoid anomaly is a residual feature that is genetically related to the growth, stagnation and breakup of the supercontinent. We argue that the truncated-icosahedral fractures record the lithospheric response predicted by Anderson's (1982) model.

Jagla and Rojo (2002) demonstrated that cracks spontaneously self-organize into quasi-hexagonal tessellations in isotropic elastic media under conditions of uniform, layer-parallel tension, such as that proposed for Anderson's (1982) stagnant supercontinent. This is because the hexagonal pattern relieves the greatest strain energy for the least work invested in nucleation and propagation of fractures. Quasi-hexagonal fracture patterns emerge at several scales in natural materials; mud cracks and columnar basalt provide familiar examples. The scale of the polygons may be a proxy for the strength of the material; weaker and thinner materials, such as cornstarch, break into small polygons. The truncated icosahedron includes the largest hexagonal tiles permissible within a spherical tessellation; it may provide the most efficient configuration of fracture sets to relieve tension within large tracts of stiff Precambrian lithosphere. Geometry requires pentagons to alternate with hexagons on a sphere, leading to the truncated icosahedral tessellation.

Once a fracture tessellation has been established, the resulting lithospheric tiles are then free to passively separate above an expanding asthenosphere, much like sutures between hexagonal plates of a tortoise shell. Separation of the lithospheric tiles may then draw curtains of asthenosphere upward to grout the fractures, as a secondary process. Decompression-melting may then lead to injection of dike swarms along tessellation edges. Diapirs may rise to fill the larger openings that form at triple-rift junctions and erupt large igneous provinces. Injection of mafic magma into the lower crust may lead to secondary melting and formation of other anorogenic magmas, resulting, for example, in anorthosite massifs and granite-rhyolite provinces. Silicic anorogenic magmatism may be more typical where the fractures cross relatively young continental lithosphere, as for example in Laurentia, where large silicic provinces are more typical in Proterozoic orogenic belts than in Archean terranes. In Gondwana, mafic anorogenic magmatism is more common in Archean regions, but the large Chon Akie felsic province (cf. Ernst and Buchan, 2001) occupies the Phanerozoic Gondwanides. Perhaps fracture zones are more diffuse in younger, weaker continental lithosphere, leading to broader zones with more silicic magmatism. At the surface, grabens may evolve as lithospheric attenuation zones widen to 600 km or more, perhaps due to melting, eruption, sapping and separation of the tiles to accommodate continued expansion of the asthenosphere.

Resumption of plate motion may remove a supercontinent from the thermal bulge and arrest anorogenic magmatism, except for lingering asthenospheric hotspot plumes. However, should plate motion again stagnate and thermal expansion renew beneath the continent, established fractures may experience a resurgence of anorogenic magmatism, because significantly less energy is required to open existing fractures than to create new ones. Thus, as in Laurentia, several generations of magma may intrude the same fractures (Sears, 2001). Conversely, a second, discordant rift tessellation may begin to propagate. The East African rift system, which is discordant with the Gondwanan tessellation, may be such an example.

6. Conclusions

We conclude that a stalled supercontinent may fracture into a least-work, truncated-icosahedral configuration. Dike swarms may be intimately associated with the fracturing process, and magma injection may lead to melting of lower continental crust and further anorogenic magmatism. Continental drift may arrest anorogenic magmatism, but periods of stagnation may lead to recurrent anorogenic magmatism along established truncated-icosahedral fractures. Tessellated hotspots appear to herald lingering diapiric activity at the asthenospheric sites of the Gondwanan triple junctions on the eve of dispersal. They remain disposed within the Atlantic–African geoid anomaly, like hobnails in the footprint of Gondwana (cf. Anderson, 1982).

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