Lithospheric control of Gondwana breakup: Implications of a trans-Gondwana icosahedral fracture system

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Abstract:

Gondwana broke apart along a truncated-icosahedral fracture system that minimized total crack length and therefore required the least work to nucleate and propagate new fractures across the supercontinent. The fracture arrangement met conditions imposed by Euler's rule for ordering polyhedrons on a spherical shell. Linear grabens accumulated Permian rift facies along 10,000 km of the fracture system in east Gondwana. Large igneous provinces erupted more than 100 Ma later along these fractures. This suggests that widening of existing fractures rather than impingement of deep-mantle plumes triggered outbreaks of flood basalt. The tensile stress field that initiated the fractures was symmetrical with Gondwana and exploited pre-existing lithospheric suture zones. The stress field was also symmetrical about the African geoid bulge in the Permian locus of Gondwana. Tensile hoop-stress along the Gondwana boundary initiated radial fractures that defined the lateral edges of Australia, India, Arabia, Libya, and northwest Africa. Fractures then evidently propagated inward across Gondwana, spontaneously bending at critical lengths congruent with the tessellation. Fractures later branched outward from the bends to create triple-rift junctions. Plate tectonic processes later exploited the icosahedral fractures to separate the Gondwana daughter continents.

Keywords: Gondwana, supercontinent, icosahedron, hot spot, mantle plume

Introduction:

While it is generally agreed that supercontinents break apart and re-assemble in grand tectonic cycles, much controversy surrounds the causes of breakup (Foulger et al., 2005). Following an original idea by J.T. Wilson (1963) that Hawaii was caused by motion of the Pacific lithosphere over a fixed region in the mantle that he termed a 'hot spot', the deep-mantle-plume paradigm predicts that superadiabatic plumes rise from the core-mantle boundary to drive continental breakup (Morgan, 1971,1981; Campbell, 2001). The paradigm proposes the following sequence of events. Plumes impinge on the base of the lithosphere, forming broad domes (Storey et al., 2001). Plume heads erupt large igneous provinces (LIPs) from three-armed rifts that branch from the domes (Ernst and Buchan, 2001). Two of the rifts propagate outward and link up with older such rifts to break the continent piecemeal; the third rift may form a "failed arm", or "aulocogen" (Burke and Dewey, 1973). Continental fragments then calve away and seafloor spreading disperses them. Some active volcanic hot spots may represent lingering ascents of thin plume tails at fixed mantle locations (Morgan, 1981). In this paradigm, plume ascents and breakouts are episodic and depend upon deep mantle viscosity and instabilities along the core-mantle boundary (e.g. Steinberger, 2000).

Mantle tomography does not, however, unequivocally demonstrate that plumes cross the mantle transition zone (Foulger et al., 2000). DeWit et al. (1988), Anderson (2001, 2002b), and Hamilton (2003) argue that continental breakup and associated large igneous outbreaks and hot spots are controlled, top-down, by lithospheric processes, rather than by rising plumes. Anderson (2005) formalized this opposing view as the "Plate Paradigm". Continental breakup may be initiated by thermal expansion of ordinary sub-lithospheric mantle that becomes insulated beneath a sluggish supercontinent. For example, Anderson (1982) showed that the Atlantic-African geoid anomaly coincides with the Permian locus of Pangaea and may represent the residuum of thermally-expanded sub-Pangaean mantle. The thermal expansion placed the supercontinent under uniform layer-parallel tension. The supercontinent then rifted apart, with decompression-melt-driven outbreaks of large igneous provinces along rift zones, as fragments drifted off the thermal bulge toward retreating trenches.

Anomalous hotspot activity that continues at fixed mantle sites within the decaying Atlantic-African geoid anomaly is consistent with this model (Chase, 1979; Crough and Jurdy, 1980; Anderson, 1982; Phillips and Bunge, 2005).

Here I argue that a uniform tensile stress field, constrained by Gondwana geometry and boundary conditions, initiated the fracturing of Gondwana by Early Permian time in a manner that minimized crack length and therefore minimized the energy required to nucleate and propagate new fractures. Organization of fracture polygons depended on the strength of the Gondwana lithosphere and geometric constraints for tiling a spherical surface. Plate tectonic processes exploited the initial Early Permian fractures more than100 Ma later to widen rifts, release LIPs through secondary decompression melting, and disperse rifted fragments. This model argues against the deep-mantle-plume paradigm and favors Anderson's plate paradigm.

Gondwana fracture tessellation:

Figure 1 presents a standard reconstruction of Gondwana, adapted from DeWit et al. (1988), Golonka et al. (1994), and Lawver et al. (1999). The argument presented in this contribution derives from the recognition that much of the fracture architecture of Gondwana was closely congruent with a precise, energy-minimizing configuration, the truncated icosahedron (Sears et al., 2005; Sears, 2001). The truncated icosahedron comprises a polyhedron with 12 pentagonal and 20 hexagonal faces. The pentagonal faces are centered on the vertices of an icosahedron. The buckyball is a familiar example of a truncated icosahedron. Projected onto the Earth's surface, each tile-edge of a truncated icosahedral tessellation subtends 23.28 degrees of arc, or approximately 2600 km.

The Gondwana fracture tessellation included parts of three large pentagons and six large hexagons of the scale and arrangement of a truncated icosahedron at the Earth's surface (Fig. 1). The yellow dots in Figure 1 lie near rift triple junctions separated by 23 degrees of arc. The angles between adjacent arcs are 108 or 120 degrees, the internal angles of pentagonal and hexagonal plates, respectively. The tessellation is intolerant; establishment of a single triple junction defines the distribution of all others. Gondwana fractures with a cumulative linear distance >20,000 km define segments of some 16 edges of this truncated icosahedral tessellation, highlighted in Figure 1. Older lithospheric sutures were reactivated as rift zones along the Benue trough, the Transkei-Namibia line, the Parana zone, and east Africa (Jourdan et al., 2006; Tommasi and Vauchez, 2001; Vauchez et al., 1997; Vauchez et al., 1998). These rift zones are approximately congruent with the tessellation, implying that they exerted some control over the orientation of the stress field that initiated the breakup, as discussed in a later section.

The geometric congruence of many Gondwana fractures with a single, rigorously defined tessellation indicates that, rather than piecemeal, the fractures formed in a uniform, Gondwana-wide stress field prior to dispersal of any daughter continents. Fracture propagation began before Early Permian time. Some 10,000 linear km of grabens that folllowed the fracture tessellation across east Gondwana accumulated Permian coal measures. Harrowfield et al. (2005) mapped a relict Permian-Triassic rift platform from New Guinea, along the western coast of Australia and Antarctica, to southern Africa. Bordy and Catuneanu (2002) mapped late Paleozoic Karoo rifts across southern Africa. Hauser et al. (2002) traced the early Permian Karoo rifts north along the Arabia-India rift zone. Sengor and Natalin (2001) showed that many other Gondwana rifts that are part of the icosahedral pattern were active in Permian and Triassic time.

The Jurassic Karoo and Cretaceous Bunbury, Rajmahal, Godavari, and Parana LIPs all erupted into existing Permian grabens. Clearly, the LIPs did not cause the icosahedral fractures, but rather exploited them more than 100 Ma after they had appeared in the geologic record.

Hexagonal fracture systems:

The truncated icosahedral fractures recall the hexagonal tensile fracture patterns of columnar-jointed basalt. Hexagonal joint networks occur in basalt flow interiors due to isotropic layer-parallel thermal stress (Weinberger, 2001). A joint face results from many discrete fracture events as the basalt cools and shrinks and layer-parallel tension accumulates until it exceeds the tensile strength of the crystallized basalt layer (Ryan and Sammis, 1978). A detailed study of columnar joints by DeGraff and Aydin (1988) showed that cracks propagate to a critical length, and then commonly bend at 120 degrees. New cracks then propagate either toward or away from the bends to create triple junctions. Each new crack bends when it obtains the critical length and, together with similar cracks, joins a network of hexagonal columns of surprisingly uniform sizes. A propagating crack will intersect an existing fracture orthogonally because the older fracture forms a free surface for which the principal stresses are parallel and perpendicular (Suppe, 1985).

Hexagonal fracture systems develop in an homogenous material undergoing uniform layer-parallel tension because they provide the greatest stress relief for the least work to nucleate and propagate cracks (Jagla and Rojo, 2002). A regular hexagonal pattern requires the shortest total crack length to pave a given area and provides the most stable triple-junctions, and hexagonal close-packing of fractures best relieves strain between neighboring domains. The energy used for the work of propagating cracks is stored as elastic strain within the volume of the layer.

Stronger layers crack into arrays of larger hexagons having a shorter total crack length. More strain energy is required to initiate the fractures, but because the layer is stronger, it stores more energy before failing. If polygons are sufficiently large to reflect the curvature of a spherical shell, Euler’s rule for convex polytopes becomes evident; pentagonal polygons will occupy the 12 vertices of an icosahedron, with intervening hexagonal polygons. As shell strength increases, the sizes of the polygons will increase and the number of hexagons will decrease in a stepwise fashion so as to pave the closed geometry of the sphere. The stepwise nature of the permissible tessellations means that layers having wide ranges of strengths may fracture in similar patterns; threshold strengths must be surpassed before the next-sized fracture tessellations are achieved.

The truncated-icosahedral fractures evident across much of Gondwana represent the largest hexagons permitted on a spherical tessellation. Gondwana occupies only a portion of a sphere, so has parts of only 3 pentagons and 7 hexagons of the full tessellation. Near its edges, Gondwana fractured into smaller polygons; the discontinuity between the larger and smaller polygons may represent a threshold strength related to thinning of lithosphere toward the Gondwana margin.

Gondwana stress tessellation:

A tensile stress field that induces an hexagonal array of cracks defines a triangular tessellation, with the vertices of the triangles at the centers of the hexagons (Hills, 1963). The triangular array defines the dual tessellation of the fracture array. (Edges of dual tessellations bisect one another orthogonally, and vertices of dual tessellations occupy the faces of one another.) The vertices of the triangles form null points in the medium; strain increases outward from them to the distance at which the material cracks.

Columnar joints result from shrinkage, whereas Gondwana fractures may have resulted from thermal expansion of the underlying mantle (Anderson, 1982). Both situations induce layer-parallel tension. By analogy with columnar basalt, the stress tessellation for the Gondwana fracture tessellation was its dual, the icosadeltahedron (Fig. 2). This triangular tessellation obeys Euler's rule for convex polytopes; pentamers, with five nearest neighbors, occupy the vertices of an icosahedron, while hexamers, with six nearest neighbors form the remaining vertices .

Figure 2 shows that the icosadeltahedral stress tessellation followed the Gondwana margin and was surprisingly symmetrical across Gondwana. This configuration provided the most balanced stress distribution and indicates that the intrinsic shape of Gondwana organized the geometry of the tensile stress field. Furthermore, the stress configuration best accommodated existing lithospheric suture zones within Gondwana, opening the East Gondwana, Transkei-Namibia, Parana, and Benue fractures. Those ready-made weak zones could accommodate tensile stresses back to adjacent vertices of the stress tessellation without requiring new fractures. New Gondwana fractures that cross-cut basement grain at high angles were nearly perfectly congruent with the ideal truncated icosahedral tessellation.

Tensile hoop-stress paralleled the periphery of Gondwana, so that most fractures intersected the margins of Gondwana perpendicularly (Fig. 2). These fractures separated New Zealand, Australia, India, Arabia, northwest Africa, and Central America. Tensile hoop-stress forms in response to expansion of an enclosed region, consistent with a uniformly-expanding Gondwana. These observations are consistent with the hypothesis of Anderson (1982) that Gondwana insulated the underlying mantle, leading to thermal expansion and shell-parallel extension.

Cracking spherical shells:

Experiments with drying clay shells provide insight into the formation of polygonal fracture patterns on spherical surfaces (Sears, 2006). Cracks initiate at re-entrants in the edge of a drying clay shell. One of these becomes a master crack that zig-zags across the shell in segments whose lengths are related to the thickness and strength of the clay (Fig. 3 A, B). Branch cracks then propagate from the bends in the master crack to form triple-crack junctions (Fig. 3 C). The branch cracks may continue to propagate and bend at the critical length to outline polygons. The cracks in Figure 3 approximated a dodecahedral tessellation.

The cracks result from uniform tension in a drying clay shell. The cracks are Mode I tensile fractures; they must initiate orthogonally to the edge of the shell and also to earlier formed cracks because they constitute free surfaces. Tensile hoop stress follows the margin of the shell, and intensifies at re-entrants because the sides of the re-entrants draw apart as they shrink. Stress concentration at the tip of a crack enables it to propagate. As it propagates, it releases strain energy stored on either side. Once a free fracture surface exists it forms an expansion crack that can resolve tensile stresses on either side out to a distance that is a function of the strength of the shell.

The tip of a propagating crack bends at about 120 degrees so as to resolve strain in the adjacent region and continues to propagate in the new direction. A bend in a crack forms a re-entrant that concentrates stress and initiates a new crack that propagates outward from the bend. The concept of a propagating master crack with secondary cracks branching from bends in a spherical shell fundamentally differs from the paradigm that three-armed cracks form above domes and link together into rifts that eventually separate continents.

For Gondwana, a master crack may have begun at a re-entrant along the Cimmerian shelf of north Gondwana between Australia and greater India, and zig-zagged from west Australia across to southern Africa, with a branch propagating along the Godavari trough of India. A separate crack may have propagated into Gondwana from a re-entrant along the Cimmerian shelf between greater India and Arabia, to intersect the other fracture at Sri Lanka. This second crack followed the east Gondwana suture, which required less work to split than the adjacent lithosphere. These fractures opened grabens in which Early Permian rift facies were deposited, but rifting was not accompanied by mafic igneous activity. This demonstrates that the rifting was not driven by the ascent of mantle plumes or emplacement of large igneous provinces. The Permian rifts generally paralleled the Permian Gondwanides trench, suggesting that trench-pull may have contributed to their opening. Fractures in west Gondwana opened in Jurassic and Cretaceous time, perhaps in response to trench-pull along the Andean margin.

LIPs and hot spots:

Nine large igneous provinces (LIPs) ranging in age from Early Jurassic to Early Tertiary erupted as Gondwana rifted apart and its daughter continents dispersed (Ernst and Buchan, 2001). When the continents are gathered into their Gondwana configuration, however, the future sites of the LIPs are congruent with vertices or edges of the fracture tessellation that was already evident in Permian time. This suggests that the fracture tessellation prepared the ascent routes for the eruptive sites, but that LIP outbreaks depended on later effects such as decompression melting as plate tectonic movements widened the fractures and opened conduits for LIP eruptions. Silver et al. (2006) proposed that flood basalts erupt from superheated accumulations of melt beneath continental lithosphere; such conditions may have evolved beneath Gondwana due to insulation, especially if subduction had decreased around Gondwana margins (e.g. Lowman and Gable,1999; Phillips and Bunge, 2005).

When Gondwana is reconstructed, the fracture tessellation may be superimposed on several major hot spots associated with Late Jurassic or Early Cretaceous rifts and LIPs. Heard, Marion, Bouvet, Gough, Tristan, St. Helena, Ascencion, and Fernando plot within a few degrees of the tessellation, mostly near vertices (Sears et al., 2005; Fig. 2). However, neither older hot spots associated with opening of the Central Atlantic Ocean nor younger hotspots associated with the Deccan or Ethiopian LIPs are congruent with this position of the tessellation. The congruent hot spots may record a time of drift stagnation of Gondwana that linked the sites in a fixed geographic framework.

Eruption of LIPs may have resulted from decompression melting upon opening of rifts along the fracture tessellation, perhaps augmented by thermal expansion of the upper mantle beneath the insulating supercontinent (e.g. Silver et al., 2006). Lingering hot spots may have been localized by alteration of feeder chimneys in the upper mantle beneath the original sites of the LIP eruptions. Fairhead and Wilson (2006) suggest, alternatively, that some hot spot tracks may be fractures that propagated due to stress instabilities in the widening plates. These considerations favor a lithospheric, rather than deep mantle, control for Gondwana LIPs and hot spots.

African geoid anomaly:

Anderson (1982) proposed that the Atlantic-African geoid anomaly marks the Permian footprint of Pangaea, the decaying remnant of thermally-expanded mantle that had been insulated beneath the supercontinent. Chase (1979) and Crough and Jurdy (1980) proposed that hot spot activity in the region demonstrates its increased thermal content. Rifting of the fracture tessellation may have coincided with periods of continental drift stagnation. Paleomagnetism shows that Gondwana moved slowly from 280 to 260 Ma, when it changed direction (Gordon et al., 1979). The Early Permian rift fill in the tessellation fractures correlates with this slow movement. Gondwana increased in velocity from 260 to 210 Ma, then slowed from 210 to 190 Ma (Gordon et al., 1979), when rifting was renewed and Gondwana began to break into daughter continents.

Figure 4 superimposes a contour map of the African part of the geoid anomaly on Gondwana in the mantle position that it may have occupied during Permian time (Golonka et al., 1994). If the geoid bulge was centered on Gondwana as shown, then the contours either paralleled or were orthogonal to the fracture and stress tessellations. Anderson (1982) suggested that Gondwana spread radially outward from the geoid high, consistent with the radial components of the stress tessellation. The outward spreading would also result in hoop-stress parallel with the geoid contours, consistent with the non-radial components of the stress tessellation. Evidently, when the combination of these stresses was large enough to overcome the strength of the Gondwana lithosphere, it cracked into the pattern that required the shortest total length of new cracks.

The icosahedron in nature:

Comparison of the Gondwana tessellation with other natural examples of icosahedral arrangements provides insight into the Gondwana fracture process. In nature, collections of particles or cells commonly surface a sphere in icosahedral patterns. These include fullerene molecules, blastocysts, colloids, quasi-crystals, florets, gumball seedcases, and numerous icosahedral viruses, including wart, herpes, polio, and HIV (cf. Anderson, 2002a). Because the pentamers form shorter, stronger bonds, viral capsids burst along hexamers (Zandi et al., 2005). The cracks zig-zag along polygonal boundaries much like those on fragmenting supercontinents.

Icosahedral configurations solve the classic Thomson problem of minimizing the energy of an array of mutually repulsive coulombic charges on a sphere (Altschuler et al., 1997). The lowest energy configurations produce truncated icosahedral strain gradients closely similar to the rift patterns seen on Gondwana.

Conclusions:

The self-organized Gondwana fracture tessellation is consistent with Anderson's (1982) hypothesis that the supercontinent drove its own breakup by insulating the underlying mantle. The thermally-expanded mantle lifted Gondwana, placing it under uniform layer-parallel tension. When tension exceeded the strength of the Gondwana lithosphere, it fractured into a symmetrical polygonal pattern commiserate with its strength and conforming to the geometric restrictions of a sphere and to the boundary conditions of the supercontinent. The Permian marine lowstand (Haq, 1995) may record the culmination of Gondwana thermal expansion and uplift (see Anderson, 1982). Likely, the fractures propagated in zig-zag fashion across the supercontinent, bending and branching at critical lengths. The fractures relieved the tension and separated the supercontinent into tiles that could move independently under the influence of plate tectonic processes. Separation of tiles opened rift valleys and ocean basins and drove decompression melting of the thermally expanded mantle, leading to outbreaks of LIPs and injection of dike swarms. These secondary effects were diachronous and depended on global plate tectonics to exploit the icosahedral fractures.

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Figure Captions

Figure 1. Gondwana reconstruction at 200 Ma, after Golonka et al. (1994), Lawver et al. (1999), DeWit et al. (1988). Heavy dashed lines define truncated icosahedral tessellation that is congruent with many Gondwana fractures. Black zones are Permian rifts with coal measures, after Harrowfield et al. (2005); Bordy and Catuneanu (2002); and Stampfli et al. (2001). Yellow dots are at vertices of precise truncated icosahedron, separated by 23 degrees of arc and at angles of 10 and 120 degrees. P-pentagon, H-hexagon

Figure 2. Relationship of Gondwana rift tessellation (heavy dashed lines) and its dual, the icosadeltahedral stress tessellation (thin solid lines) such that vertices of stress tessellation occupy faces of fracture tessellation, and vice-versa. Tessellations cross one another orthogonally. Black vertices are pentamers having five nearest neighbors and exactly occupy vertices of icosahedron at Earth-scale, as required by Eulerís rule for convex polytopes (see text). Blue vertices are hexamers having six nearest neighbors. Note that stress tessellation follows northern margin of Gondwana, implying it was free surface that guided tensile hoop stress. Thus, Gondwana split on radial fractures along northern rim. Note symmetry of stress tessellation across Gondwana. This provided shortest total fracture length and thus required least work to break up Gondwana. Yellow stars are major hot spot volcanoes in modern co-ordinates indicated by lines of latitude and longitude. Gondwana is restored so that fracture tessellation best fits hot spot tessellation. Red areas are LIPs with eruption dates shown. Note that although dates range over more than 100 million years, most LIPs erupted from fractures that restore to single tessellation that is congruent with Permian rifts (black areas). This implies that coherent tessellation dates to before oldest LIP (205 Ma), and that LIPs erupted from fractures diachronously as later plate tectonics opened fractures.

Figure 3. Crack propagation across a drying spherical clay shell. Sketched from photographs. A, B Master crack zig-zags across spherical shell. C. Branch cracks propagate from bends in master crack. Some of these also propagate and bend to define polygons. Crack pattern approximates dodecahedron.

Figure 4. African geoid anomaly superimposed on Gondwana in its Permian position. Note that contours of the geoid anomaly are generally orthogonal or parallel to stress tessellation, and that anomaly is centered on Gondwana. This is consistent with Anderson (1982) hypothesis that geoid anomaly marks paleoposition of Gondwana, and that Gondwana spread outward from anomaly as it broke apart.

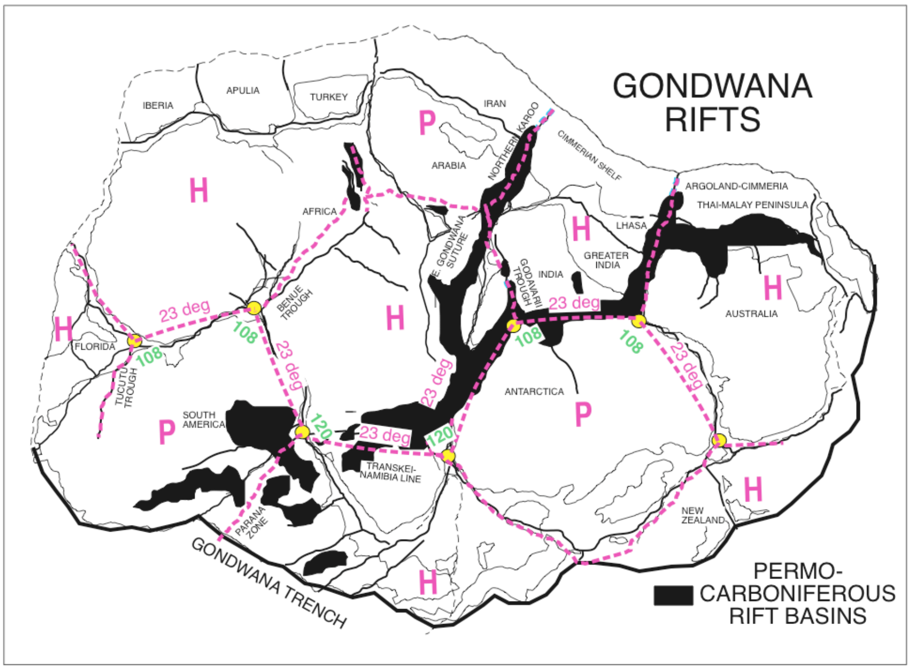
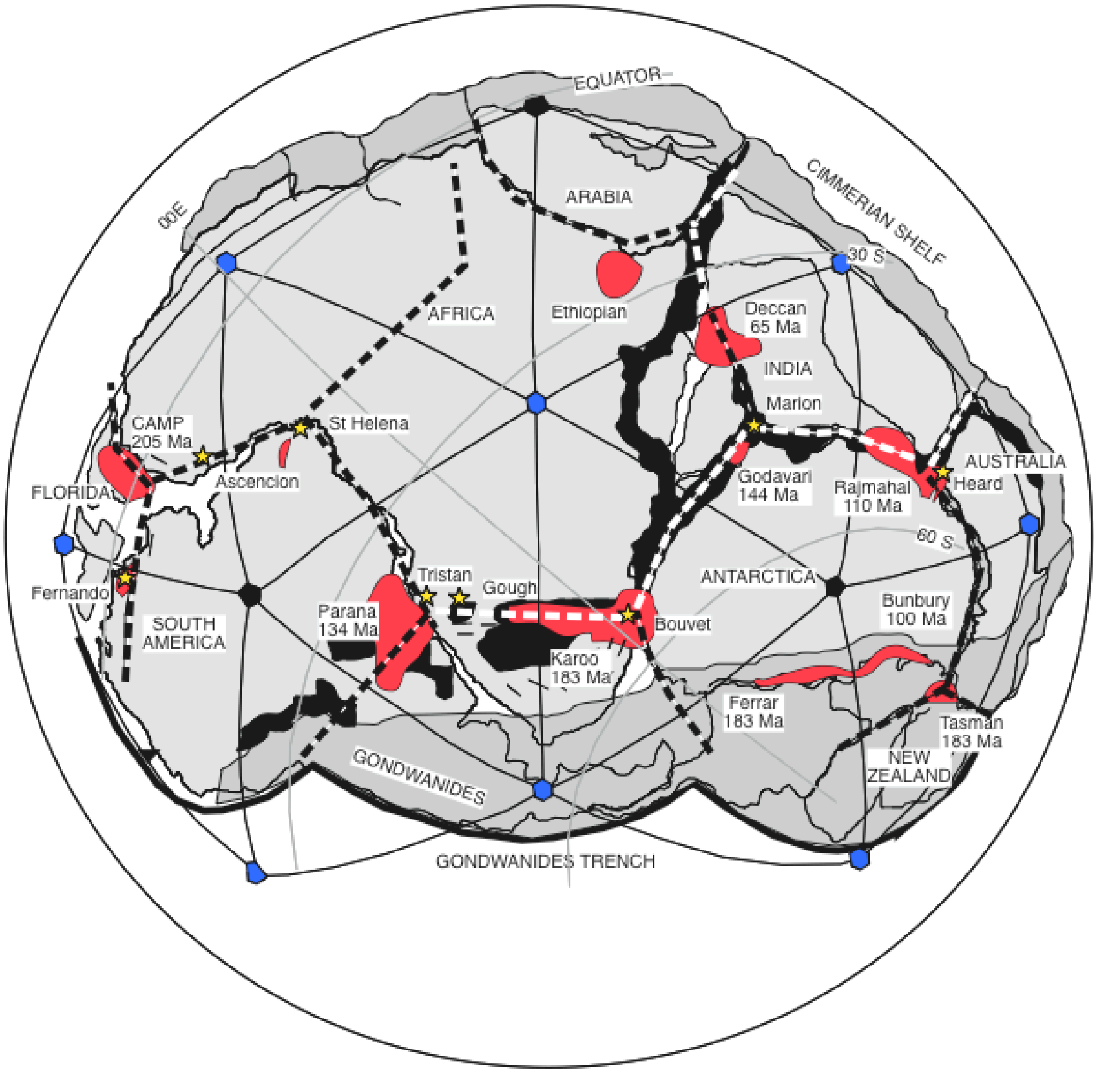

GONDWANA
RIFTS
IBERIA
APULIA
TURKEY
IRAN
ARABIA
AFRICA
NORTHERN KAROO
CIMMERIAN SHELF
ARGOLAND-CIMMERIA
THAI-MALAY PENINSULA
LHASA
GREATER
INDIA
INDIA
E. GONDWANA
SUTURE
GODAVARI
TROUGH
AUSTRALIA
BENUE
TROUGH
FLORIDA
TUCUTU
TROUGH
SOUTH
AMERICA
ANTARCTICA
TRANSKEI-
NAMIBIA LINE
PARANA
ZONE
NEW
ZEALAND
GONDWANA TRENCH
23 deg
108
120
H
P
PERMO-
CARBONIFEROUS
RIFT BASINS

Figure 1



EQUATOR
CIMMERIAN SHELF
00E
30 S
60 S
ARABIA
AFRICA
Ethiopian
Deccan
65 Ma
INDIA
Marion
CAMP
205 Ma
St Helena
Ascencion
FLORIDA
Godavari
144 Ma
Rajmahal
110 Ma
AUSTRALIA
Heard
Fernando
SOUTH
AMERICA
Tristan
Gough
Parana
134 Ma
ANTARCTICA
Bouvet
Bunbury
100 Ma
Karoo
183 Ma
Ferrar
183 Ma
Tasman
183 Ma
NEW
ZEALAND
GONDWANIDES
GONDWANIDES TRENCH

Figure 2

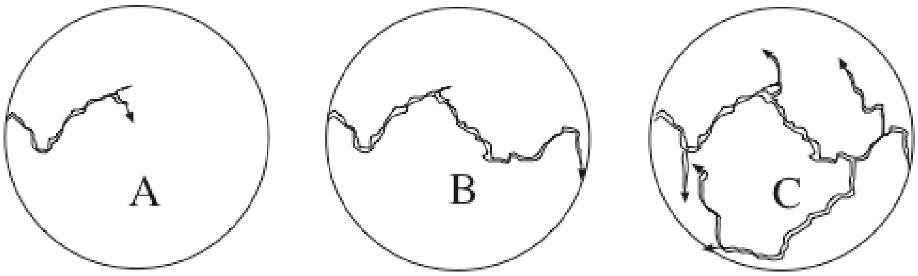


Figure 3

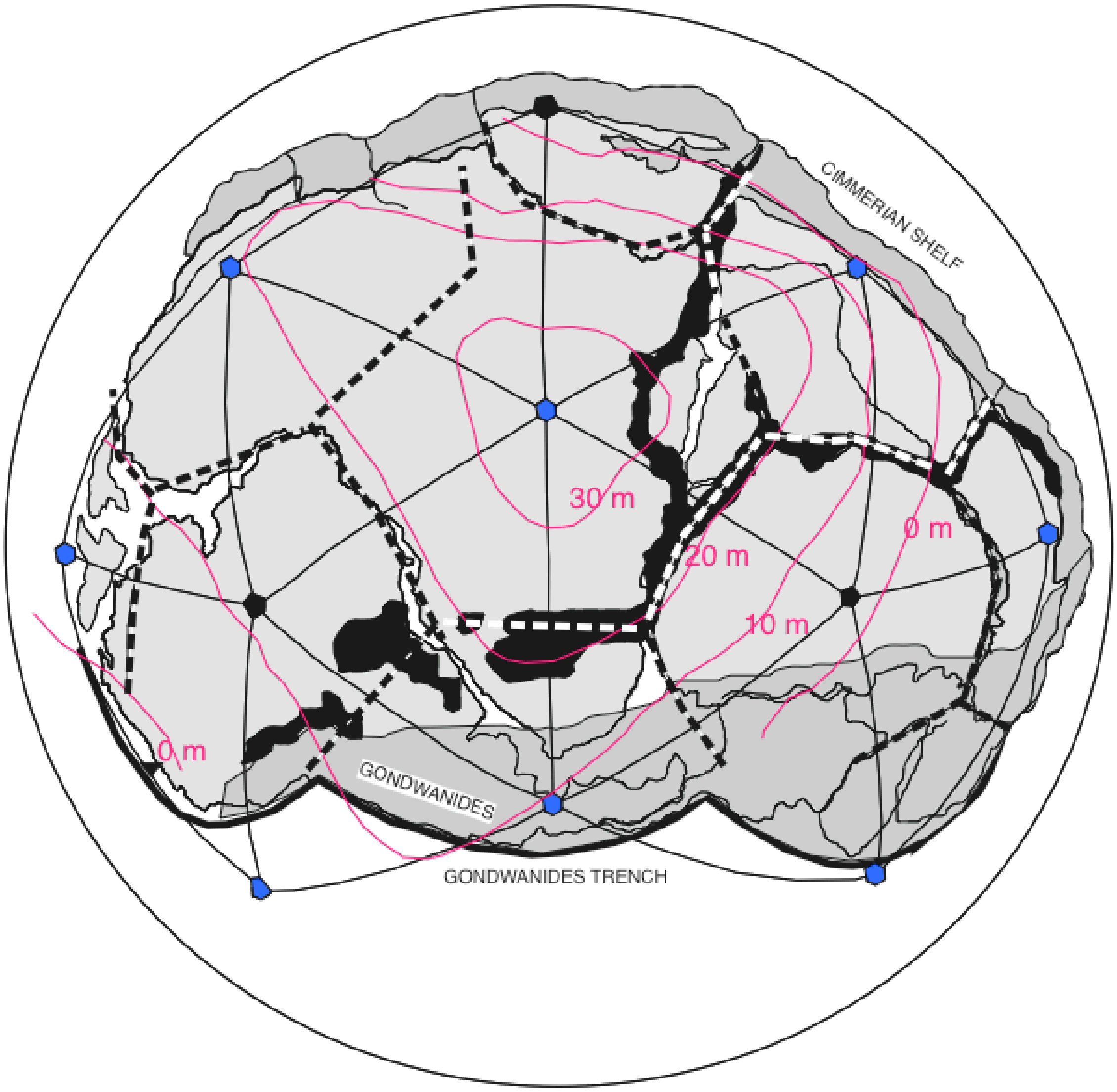

CIMMERIAN SHELF
30 m
20 m
10 m
0 m
0 m
GONDWANIDES
GONDWANIDES TRENCH

Figure 4