

Fractured Earth



The surface of our planet has changed over the years, oceans come and go. Our understanding of the forces driving these changes is largely based on the breakup of Gondwana. But what does it take to generate the forces that split continents? Findlay Craig investigates.

The surface of our planet is not stable. Continental drift theory, first proposed by Alfred Wegener in 1926, and accepted by the geological community in the 1960s, provides a model for how tectonic plates move and interact. Most of the evidence plate tectonics is based on comes from the breakup of Gondwana, the supercontinent that began to stretch 210 million years ago (Ma) and break apart ~180 Ma. After this the continents assumed their familiar configuration. While plate tectonics is now an accepted theory, and modern observable systems are reasonably well understood, the processes that drive supercontinent breakup remain poorly understood, and thus there are large areas of plate tectonics that are... fuzzy, at best. In this article I will examine a few of the models proposed, and what implications each of these has in relation to Gondwana breakup.

Below is an up-to-date ‘tight fit’ model produced in 1999. Tight fit models are reconstructions that attempt to take into account all the crustal deformation before, during, and after breakup, as well as factors such as major delta systems at the mouths of large rivers, that change continent outlines.

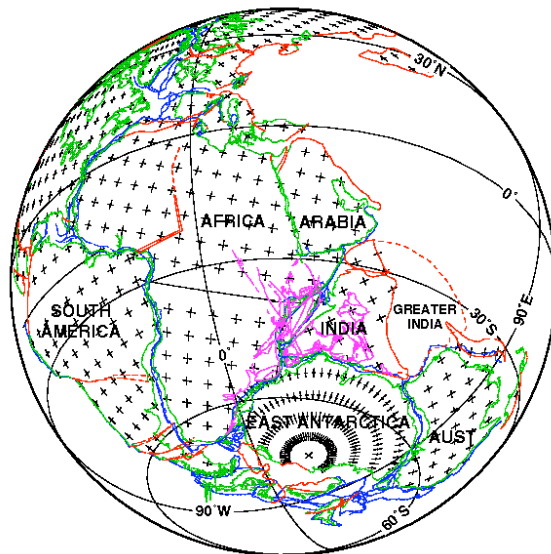


Figure 1: Tight fit model of Gondwana, showing how the continental plates fit together.

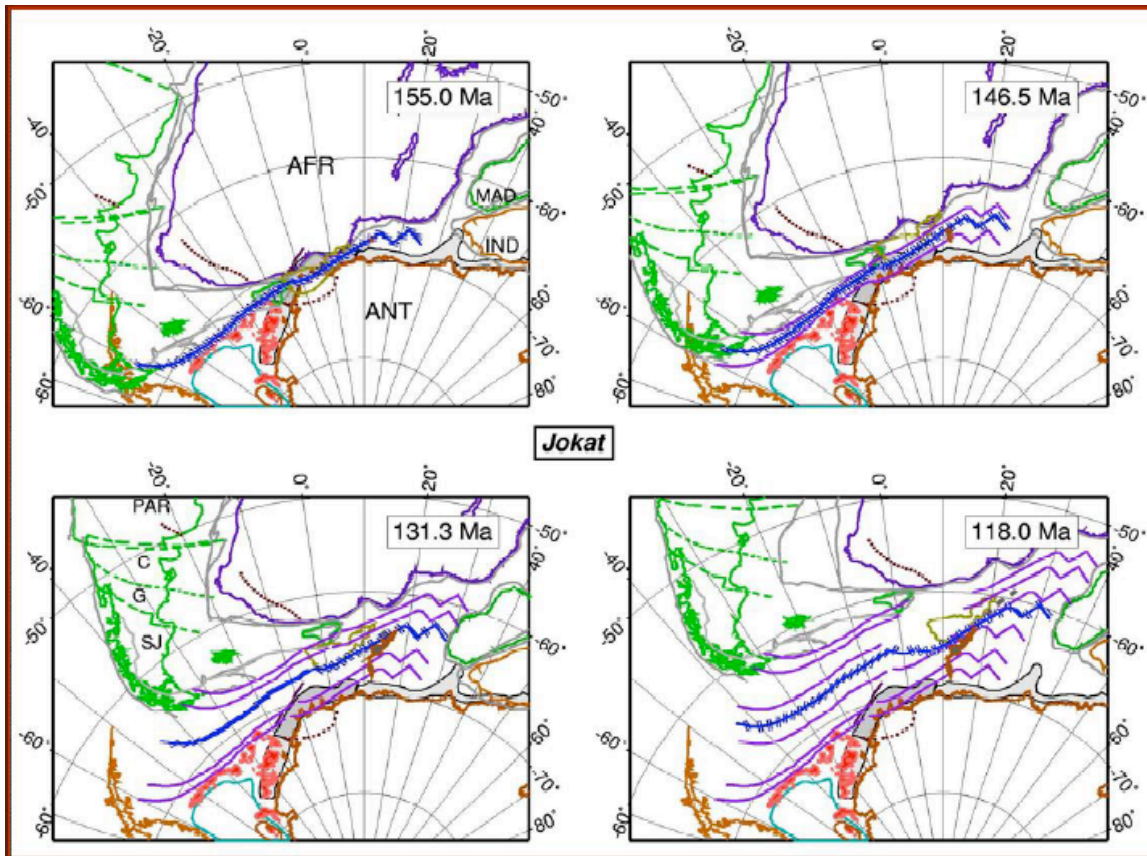


Figure 2: Relative positions of continental plates through time as SW Gondwana rifted apart.

Period	Time (Ma)	Event	Basin development
Late Permian- Early/Middle Triassic	>210 Ma	Gondwana supercontinent relatively stable. Laurasia moved off to N. as Pangea broke up.	Most of Gondwana, with the exception of the Gondwana fold belt covered with low relief basins.
Late Triassic- Early Jurassic	210	Gondwana begins to undergo local extension, stretching apart and thinning certain areas of crust.	Shallow basins develop as lithosphere thins, followed by rapid basin deepening with the onset of brittle deformation and faulting.
	183	Karoo Large Igneous Province (LIP) erupted. Rifting of Africa and S. America from Antarctica	
Middle to Late Jurassic	-	Continued rifting and opening of new ocean basins.	Ocean crust developed in Weddel Sea, what are now full blown ocean basins continue to deepen.
Early Cretaceous	134	Parana-Etandeka LIP erupted. Rifting of S. America from Africa. Madagascar LIP erupted. Rifting of India from Antarctica.	Basins develop on margin of continents. Basins in Argentina and S. America form oblique to present coastline in response to oblique extension starting in S. Atlantic.
	110	Rajmahal LIP erupted S. of India. India begins to speed North.	
Middle Cretaceous	-	Continued rifting and opening of new ocean basins.	'Thermal sag' of continental edges causes the sea to flood some continental margins.

Table 1: Events during Gondwana breakup.

The evidence from the rocks is not in debate, rather, geologists now use different breakup models to explain these observations. Later on I will examine what models are presently being proposed to explain the breakup. But first, it is simpler to examine the observational data. What is it we are trying to explain?

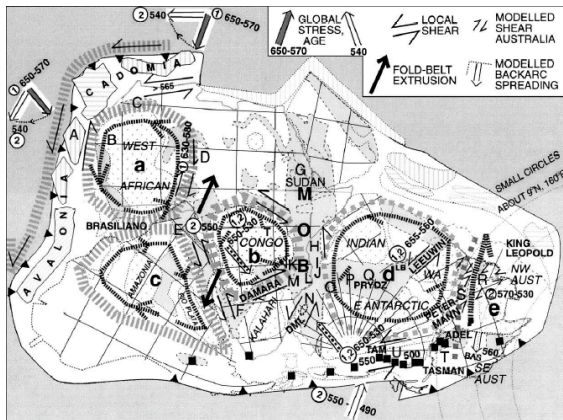


Figure 3: Map of Gondwana showing various tectonic forces acting on the super-continent.

Above is a series of time-slice maps, showing the initial movements of the continents as Gondwana broke up. The text box also contains details of events during Gondwana breakup.

Before Gondwana broke apart, the continent was under both extension and compression. That may sound like a paradox, but does in fact make sense. With the detachment of Laurasia, which moved north, the western and southern coasts of Gondwana were active subduction zones, where oceanic crust sank beneath continental crust. The net effect was to compress the continent as a whole, but to cause areas of local extension around the margins. The extension occurred because as oceanic crust slides below continental, it tends to pull the continental edges, creating a back-arc basin. Some of these weakened

areas would later develop into full-blown rift zones.

There are four distinct processes that are arguable causes of breakup. Probably the simplest to explain is the concept of pre-existing lineations. Proponents of this model, argue that Gondwana had areas, or zones, of pre-existing weakness, perhaps related to how Gondwana originally assembled. These lines of weakness were later exploited, possibly by mantle plumes, and were the lines along which the continents separated.

Another relatively simple model relies on forces generated by subduction around Gondwana, as well as a 'thermal cap' created by thick continental crust insulating the mantle and increasing the geotherm, to drive breakup. I have already discussed how the edges of the continent under subduction generated tension; the argument relies on the inherent instability of supercontinents, and argues that breakup was inevitable from the moment Pangea accreted.

One of the most hotly debated theories just now is whether or not breakup was driven by mantle plumes. The concept of mantle plumes is well established in the scientific literature, but has, over recent years been challenged. Mantle plumes (according to this argument) originate at the core/mantle boundary, before rising through convection, and impacting on the base of the crust. Subsequently, the plume spreads out, uplifts and thins an area of crust, which then splits, and as it subsides back to its original position, rifts open. The plume, which is hotter than the surrounding mantle, and also melting due to decompression, produces a vast amount of igneous material, a Large Igneous Province, or LIP. To give some idea of scale, the Karoo LIP,

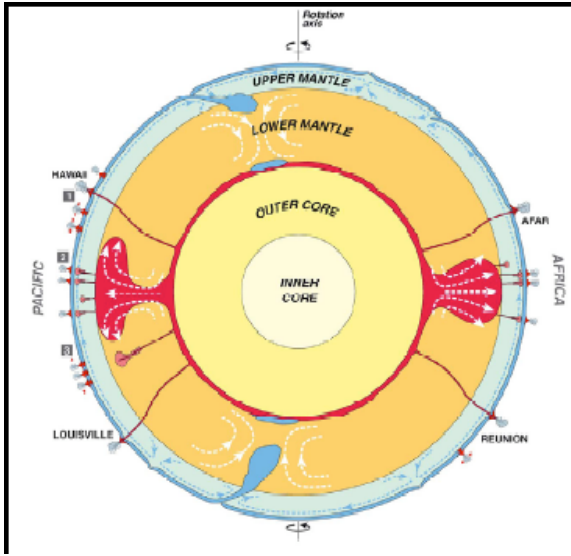


Figure 4: Simplified model of the plume system.

mentioned above, produced more than $2 \times 10^6 \text{ km}^3$ of lavas on the surface.

There is a suite of variations on this theme. For example, some proponents argue that mantle plumes caused the breakup of Gondwana, but they would have been unable to do so had the crust not already been thinned by extension, or had pre-existing lineations not existed.

Although this is a neat model, it is perhaps the most controversial one presented here. To be blunt, there are many geologists who question even the existence of mantle plumes. Instead, they argue for a 'plate model' that does not rely on mantle plumes, but rather on forces generated by the plates themselves. In this model LIPS are produced from simple decompression melting of the mantle during rifting, and the location of volcanism is fixed by stresses in the crust causing failure, rather than a rising body of hot foreign material.

The last model presented here is the 'self organisation' model, a model which appeals because it is very neat. This model is by far the most abstract, and attempts to look at 'big picture' processes, rather than individual events.

James Sears noticed that Gondwana fracture patterns made regular polyhedra. These polyhedra obey Euler's law, forming a regular arrangement of pentagons and hexagons, in exactly the same arrangement as you will see on a

Eulers Law:
 Euler's law states that $V+F-E=2$, where V is the number of polyhedron vertices, E is the number of polyhedron edges, and F is the number of faces. This equation allows us to test whether an object is a true polyhedra (ie, composed of a regular pattern of repeating shapes or not).

football. The reason for this particular arrangement is that a system of regular hexagonal cracks minimises the amount of energy required to create fractures, generates the shortest crack length, and provides the most stable triple junctions. When this arrangement is projected onto a sphere it produces pentagonal plates between the hexagons. The exact same process occurs when other homogenous materials such as basalt cool, forming hexagonal pillars (for example, the

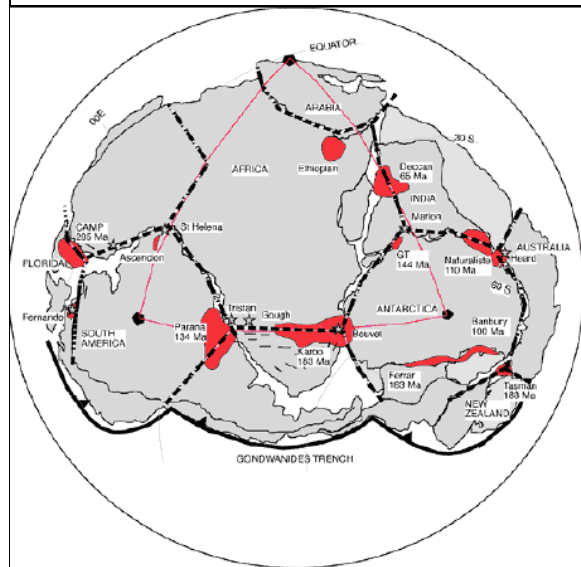


Figure 5: Eulers law super-imposed on Gondwana.

Giants Causeway in Ireland).

On the right is a map showing the African Geoid anomaly, a topographic high created by excess heat caught beneath the supercontinent. On the right is a map showing both the geoid anomaly and the stress patterns it produces. The contours are either parallel or orthogonal to the fracture and stress tessellations. When Gondwana was uplifted, its curvature increased, putting it under additional hoop and radial tension. Eventually the combination of these forces overcame the continent, and it tore apart.

In this model breakup is initiated by stresses created by the existence of the supercontinent; again, breakup was inevitable.

So with a number of different models, how do we decide which is most appropriate, bearing in mind that it must explain all the observed evidence?

Certain things are reasonably well accepted; for example the role that pre-existing lineations played. But in contrast, the 'plate' and 'plume' camps are mutually exclusive and cannot both be right. Are the forces required deep-rooted in the Earth, or shallow-generated near the surface?

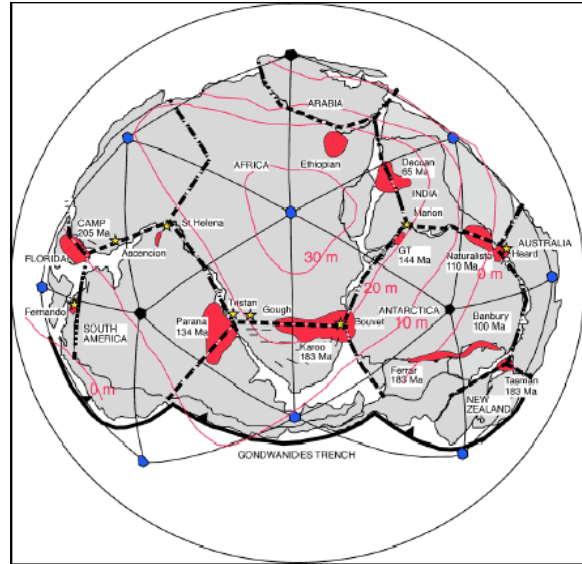


Figure 6: Eulers law and stress patterns super-imposed on Gondwana.

Even the origin of LIPs remains ambiguous. Is a plume needed to generate so much melt, or is simple decompression in an extending area enough?

The answer may not be known soon, but an unbiased outsider can see merit in all the models proposed. The most likely answer, as with most scientific debates, may lie in some combination of the models. More study will resolve the debate, so for now, watch this space.

References:

Lawyer, L.A., Gahagan, L.M., Dalziel, I.W.D., A tight fit-Early Mesozoic Gondwana; A plate perspective, in Motoyoshi, Y. and Shiraishi, K. (editors), *Origin and Evolution of Continents: Proceedings of the International Symposium Origin and Evolution of Continents*, 13-14 October, 1997, Tokyo, Memoirs of National Institute of Polar Research, Special Issue, No. 53, 214-229, 1999.

<http://www.mantleplumes.org/>

McDonald, D., Gomez-Perez, I., Franzese, J., Spalletti, L., Lawyer, L., Gahagan, L., Dalziel, I., Thomas, C., Trewin, N., Hole, M., Paton, D., 2002. *Mesozoic break-up of SW Gondwana: implications for regional hydrocarbon potential of the southern South Atlantic*. Marine and petroleum geology, 20, pp 287-308.

Sears, J., *Self-organised breakup of Gondwana*, <http://www.mantleplumes.org/EarthTess2.html>

Vaughan, A., 2007. *A new supercontinent self-destruct mechanism; evidence from the Late Triassic-Early Jurassic*, Journal of the geological society, London, 164, 2, pp 383-392