Principles of Global Tectonics

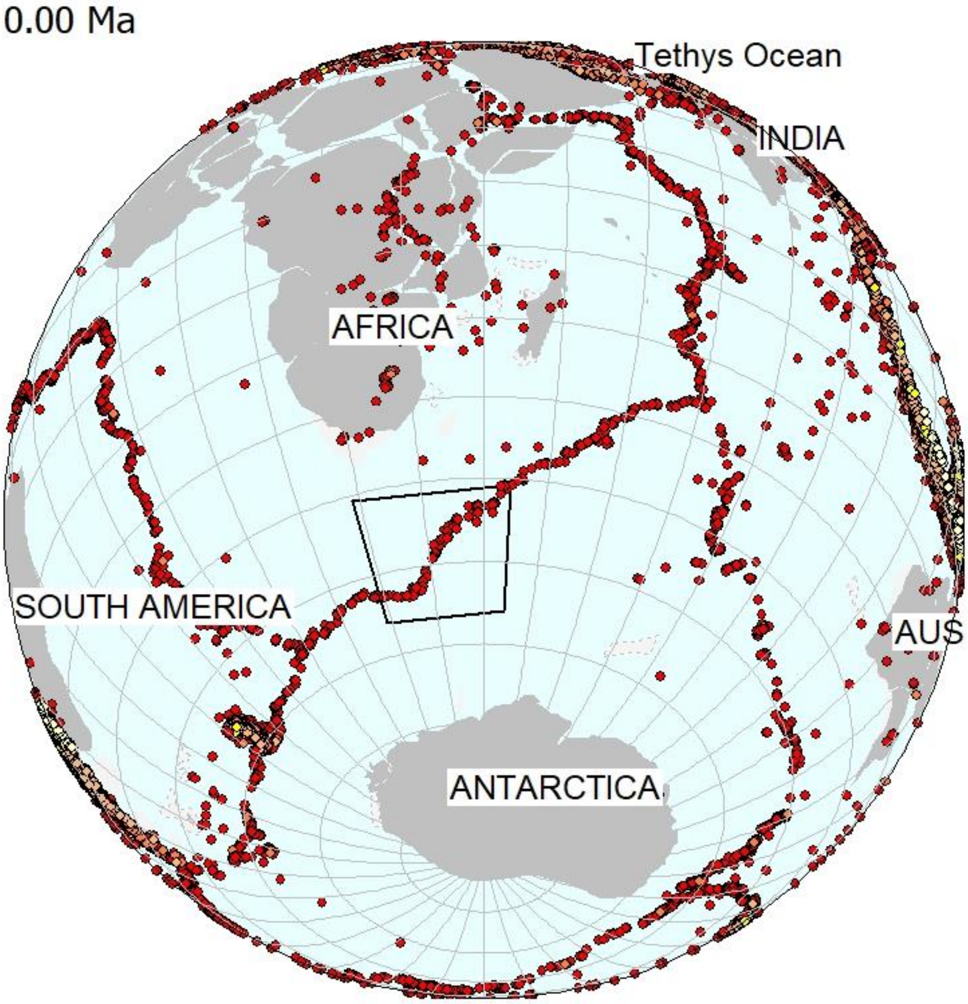

Figure 1. Earthquake epicentres in a view centred on the SW Indian Ridge. The two largest plates derived from Gondwana are Africa and Antarctica. The South America plate lies to their west and the Indo-Australia plate to their east. Note that the East Africa rift is rather modest in scale and ill-defined in comparison to the well-defined rifts of the global mid-ocean ridge system.

Our Dynamic Earth

The configuration of the continents on our globe has been steadily changing over geological time. Today's familiar world map of continents and oceans is just a snapshot of a continuous process of movement that has been going on for thousands of millions of years. Rates of movement are typically only a few centimetres per year but these are frequently brought to our attention by the occurrence of the earthquakes and volcanoes that, for the most part, are confined to the narrow marginal zones that separate the present ten large tectonic plates (Figure 1).

During much of Phanerozoic time, i.e. from about 540 Ma (million years ago) when the Precambrian came to an end, the present southern continents made up a single stable ‘supercontinent’ known as Gondwana. From about 185 Ma, however, this entity started to rift and fracture and new oceans began to form between the resulting fragments. These oceans – the South Atlantic, Southern and Indian Oceans – now occupy almost half of the world’s surface area.

Global tectonics discovered

It is only relatively recently (1960s) that earth scientists have realized that it is the growth – and eventual consumption – of such oceans that is central to the long-term evolution of the earth’s crust through global tectonics (Livermore, 2018).

Ocean crust itself is relatively short-lived; no substantial areas of ocean crust exist today that are much older than the start of Gondwana disruption. The lighter, more buoyant continents, by contrast, contain a geological record that goes back to the oldest known rocks, in excess of 4000 million years (4.0 Ga) in age.

It was only even more recently (late 1990s) that technology could map in detail the topography of the ocean floor (Figure 2), from which the precise pattern of ocean creation with time could be worked out in considerable detail (Smith and Sandwell, 1997).

Ridges, transforms and the growth of oceans

New crustal material is generated at mid-ocean ridges, often called accretionary margins, where the two adjacent plates are pushed or pulled apart, making room for new crustal material to be emplaced between them. A ridge is made up

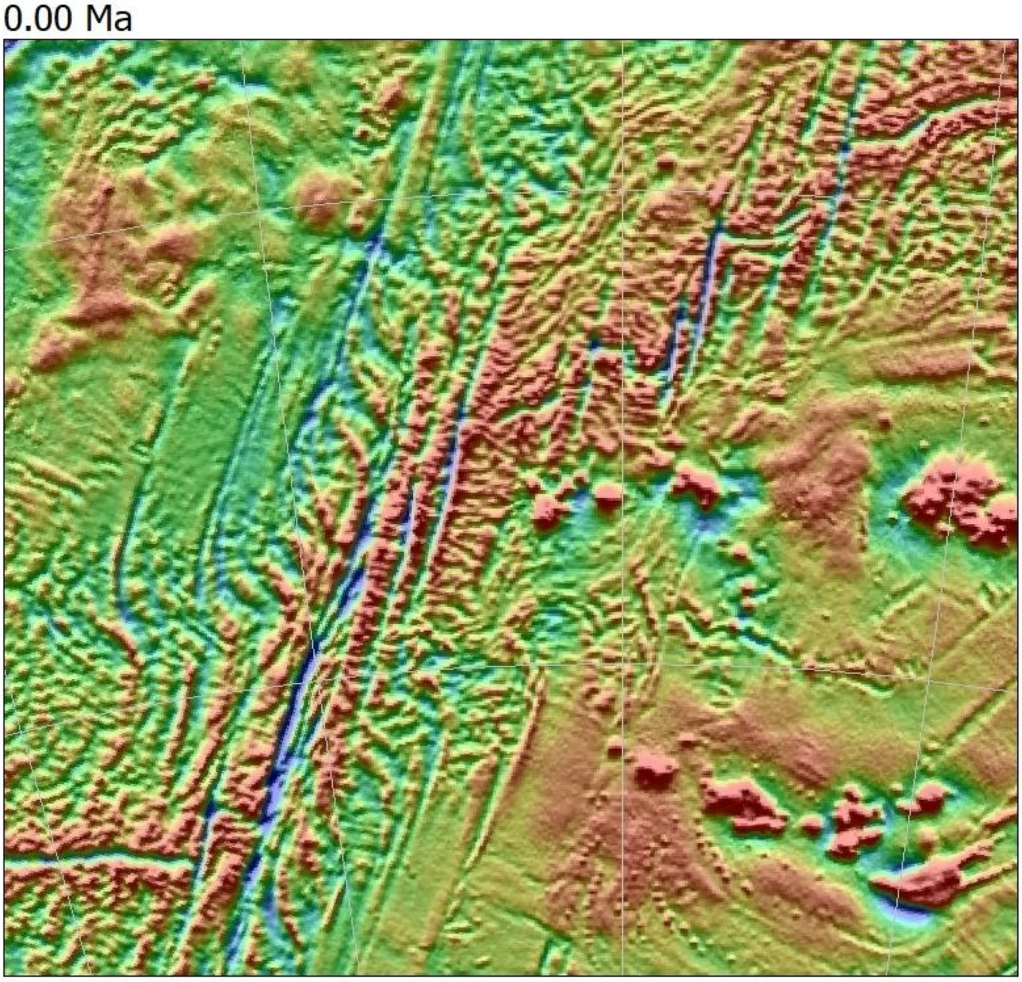

Figure 2. Topographic detail of the SW Indian Ridge showing central rift valleys and parallel 'transforms' that offset the rift sections. The area shown is outlined in Figure 1 and measures about 1700 km square. Image courtesy of Geognostics.

of ***rift*** sections, where the sides move apart normal to the length of the rift, and ***transforms*** where rift-offsets are joined by faults perpendicular to the rift sections across which relative movement is strike-slip.

Remarkably, the pattern of rift sections and transform offsets making up a complete ridge is seen to be almost perfectly self-replicating. As a result, even those parts of transforms that are no longer seismically active are often continuous for thousands of kilometres either side of the present mid-ocean ridge, sometimes even extending as far as the conjugate shorelines.

Maintaining the opposing sides of such features coincident and collinear during their development is a powerful constraint on modelling the earlier positions of any pair of continental fragments. This enables precise working, backwards in time from the present situation, to predict the positions of continents at times in the past (Reeves & de Wit, 2000).

The geomagnetic time scale

The earth's magnetic field as a whole has reversed its polarity at irregular – and often quite frequent – intervals over geological time. Magnetisations of opposite polarity, acquired by the newly-solidified ocean rocks, therefore follow each other in the ocean crust. This results in a distinctive pattern of stripes, something like a bar-code, appearing mirror-imaged either side of the mid ocean ridge (Figure 3).

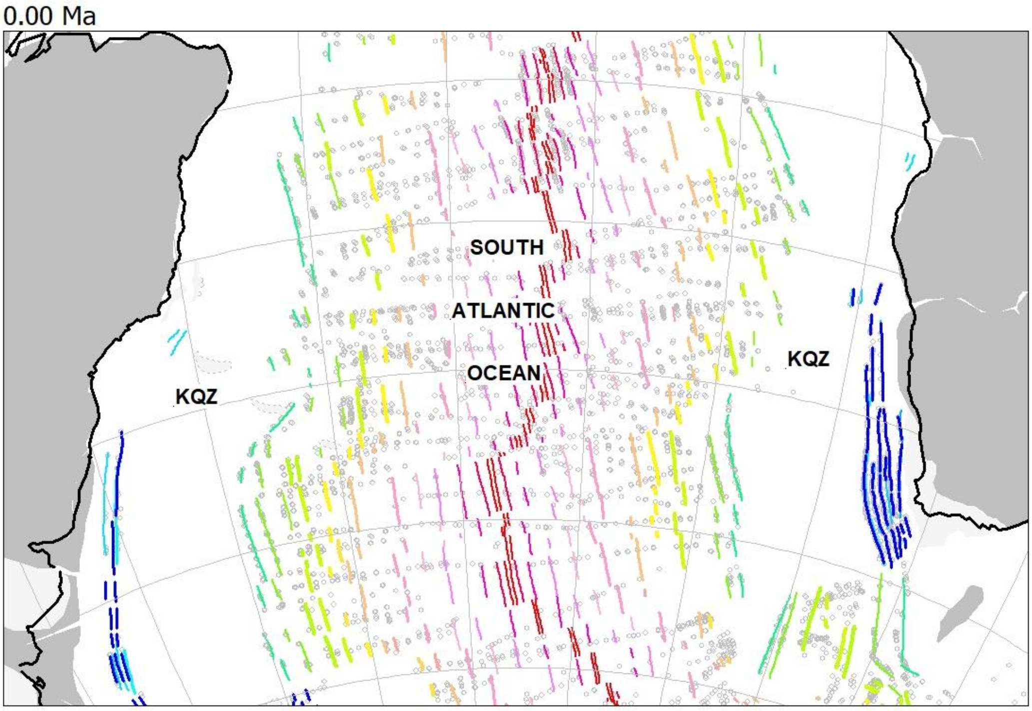

Figure 3. Marine magnetic anomalies attributable to geomagnetic reversals in the South Atlantic Ocean. The Cenozoic series of anomalies is given spectral colours from red to green. The older 'M-series' anomalies dating from before the Cretaceous Quiet Zone (KQZ) are coloured blue. They are found only in the southern part of the South Atlantic.

These oceanic magnetic anomalies allow the whole process of ocean creation to be calibrated against an absolute time scale. Unfortunately for studies of Gondwana dispersal, the

Cretaceous Quiet Zone (KQZ or Cretaceous Normal Superchron) that is devoid of such reversals occupies about 20 per cent of the time period of interest. Furthermore, the Indian Ocean (particularly) is only sparsely covered with the marine magnetometer tracks that can map these magnetic anomaly features precisely.

Economy of Hypothesis

Incomplete datasets are commonplace in earth science. Where no evidence to the contrary exists, it has been assumed in the present work that continental movements remain steady over long periods of time. In building animations, this means that interpolation across gaps in the data can be made. The smoothness of the modelled continental movements is then, in itself, a constraint on unnecessary or unjustified hypothesis.

A further constraint is that the destruction of oceanic crust, once formed, appears today to be confined to a limited number of global-scale subduction zones. This implies that there is a considerable threshold to be overcome before ocean crust, once created, can be consumed back into the earth's mantle. This is an additional constraint when trying to model the relative movements of the fragments of Gondwana since activities at the plate margins predicted by the model should then always be either constructive (ridges) or conservative (transforms), never consumptive (subduction zones).

Moving progressively backwards in time from the present day situation (the only certainty!) and removing older and older ocean has led to a robust model of Gondwana dispersal (see Homepage animation) that agrees with all data presently to hand and is subject to refinement (within the limits of error) as new data become available.

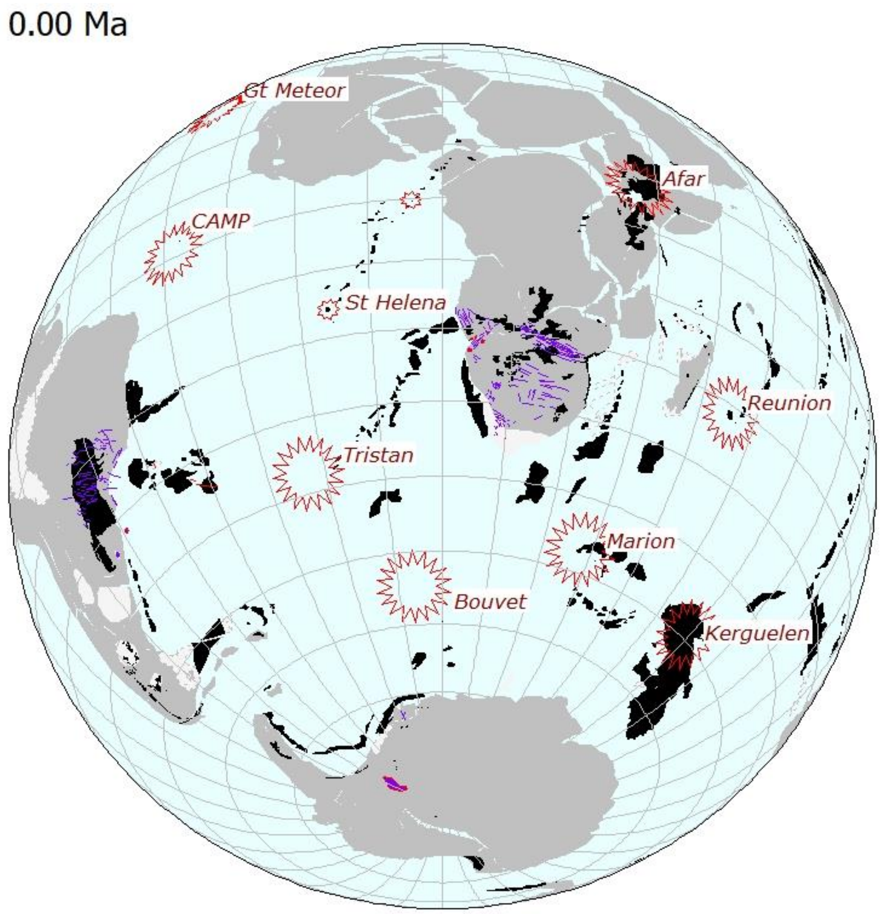

Figure 4. The mantle plumes that separated Gondwana, shown by the red stars. The main accumulations of igneous material associated with each of them – including some very large submarine plateaus –- are shown in black and some dyke swarms in purple.

Mantle Plumes

The movements of continents recorded in the ocean crust are **relative** movements that may, of course, be ‘chained’ from one continent to the next. Relating this whole system to a fixed rotational axis for the planet has been achieved using what is known as the Hotspot Reference Frame.

A number of ‘plumes’ are thought to arise from deep within the earth’s mantle, probably even coming from the surface of the molten core. They are recognised to have been active over the time interval that covers Gondwana dispersal and may even have been responsible for the instigation of this dispersal when they first reached the surface. All the evidence suggests that, within a few hundreds of kilometres, these plumes have been fixed both in their relative position and with respect to the earth’s rotational axis.

When a mantle plume ‘strikes’, its initial impact tends to be quite abrupt and often gives rise to copious amounts of basalt and dyke injection in continental areas (such as the Deccan Traps in India and the Parana basalts in Brazil). But by far the largest part of their output is generally piled onto the pre-existing ocean floor at later stages (Figure 4). In this way several large (now) submarine plateaus have been created over time (e.g. Kerguelen).

The activity level of the plumes appears to decline over many tens of millions of years, but most are still in evidence in the form of small oceanic island volcanoes such as Reunion and Bouvet. Watch the animation on the Homepage and see if you can find any relation between the breakup of Gondwana and the impact of these plumes. It looks very much as though global tectonics is less about continents moving than it is about mid-ocean ridges staying in the same place with respect to the constellation of plume heads (Figure 4).

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References

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