

## **Sea-floor spreading and deformation processes in the South Atlantic Ocean: An evaluation of the role of mantle hotspots**

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Recent improvements in our ability to enhance the resolution of satellite-derived marine gravity data (Geosat and ERS1) from 30-40 km down to ~10 km wavelength, has provided a unique opportunity to look in detail at the complex tectono-magmatic processes involved in the opening of the South Atlantic Ocean. This improvement in resolution has been achieved by innovative research and development funded by an oil industry consortium study conducted by the Leeds University spin-off company GETECH [1-3]. Application of new methodologies, developed as part of the above research, can significantly improve our understanding of oceanic crust-forming processes, particularly the role of near-ridge mantle hotspots and intra-plate deformation, hitherto impossible to resolve fully with current datasets.

Our current knowledge, based on existing research, indicates that slow-spreading mid-ocean ridges such as the Mid-Atlantic Ridge are strongly segmented along their axes by transform faults (Fig. 1). In the South Atlantic these transform faults are typically spaced some 50-100 km apart, reflect the relative plate motion directions of the newly formed crust and occur at offsets of the normal faulted median rift valley that marks the axis of the ridge. The sites of these active transforms are regions of decreased magma generation, resulting in the transform zone being starved of volcanism and expressed as a deep trough in the oceanic crust. At greater distance from the ridge crest, the transform motion ceases. This change occurs at the adjacent ridge offset; between the ridge offsets the transform separates different plates while beyond the ridge offsets the transform separates older (or younger) crust belonging to the same plate. Beyond this transition the transform fault is referred to as a fracture zone or flow line. The starved nature of the flow line and the differing age of the oceanic crust across the flow line generates a distinct bathymetric and gravity feature (Fig. 2) that can be traced for large distances away from the ridge axis and preserves evidence of former plate tectonic processes and movement vectors.

Studies by Silveira & Stutzmann [4] indicate that there are significant differences in S wave velocity structure beneath the northern and southern Mid-Atlantic Ridge (MAR). In the northern MAR negative S-wave anomalies occur down to 150 km depth, whereas in the South Atlantic these extend to 300 km depth. This difference can be related to the presence of hotspots along or close to the ridge axis in the South Atlantic, which locally generate trails of volcanic islands and seamounts as the plate migrates over the hotspot. These hotspot trails strike at an oblique angles to the flow-lines suggesting deeper processes are in operation than those that formed the flow-lines. These hotspots have traditionally been linked to upwelling convective instabilities or "mantle plumes", originating from thermal boundary layers at the base of the upper mantle (670 km discontinuity) or even the core-mantle boundary (2,900 km). The seamount trails may provide an important record of the local linear absolute velocity of the African plate in the hotspot reference frame. Additionally, establishing the processes which form these trails of South Atlantic hotspot volcanism can provide important insights into the role of mantle plumes in continental break-up and the subsequent evolution of the ocean basins.

Within the South Atlantic there are a number of distinct hotspot traces (see Figure 1) in the form of linear aseismic ridges (e.g. Rio Grande Rise, Walvis Ridge) and chains of seamounts and oceanic islands (e.g. St. Helena Seamounts). The two best developed hotspot trails have been explained by the upwelling of deep mantle plumes since the onset of continental break-up in the Early Cretaceous – the St Helena Seamount chain and the Walvis Ridge, linked to the St Helena and Tristan mantle plumes respectively [5]. The geometry of the St Helena seamount chain is, however, complicated at the continental end by the Tertiary-Quaternary volcanic activity of the Cameroon Volcanic Line (Fig. 1) which straddles the continental margin and appears to represent reactivation of this lineament. The Walvis Ridge extends from the continental margin of Africa to the active volcanic islands of Tristan da Cunha and Gough. The

SW end of the hotspot trail consists of a ~ 400 km wide region of scattered seamounts, small ridges and islands, similar in morphology to that of the St Helena Chain. The Rio Grande Rise is considered to be the conjugate of the Walvis Ridge on the South American plate, although its geometry is far less regular.

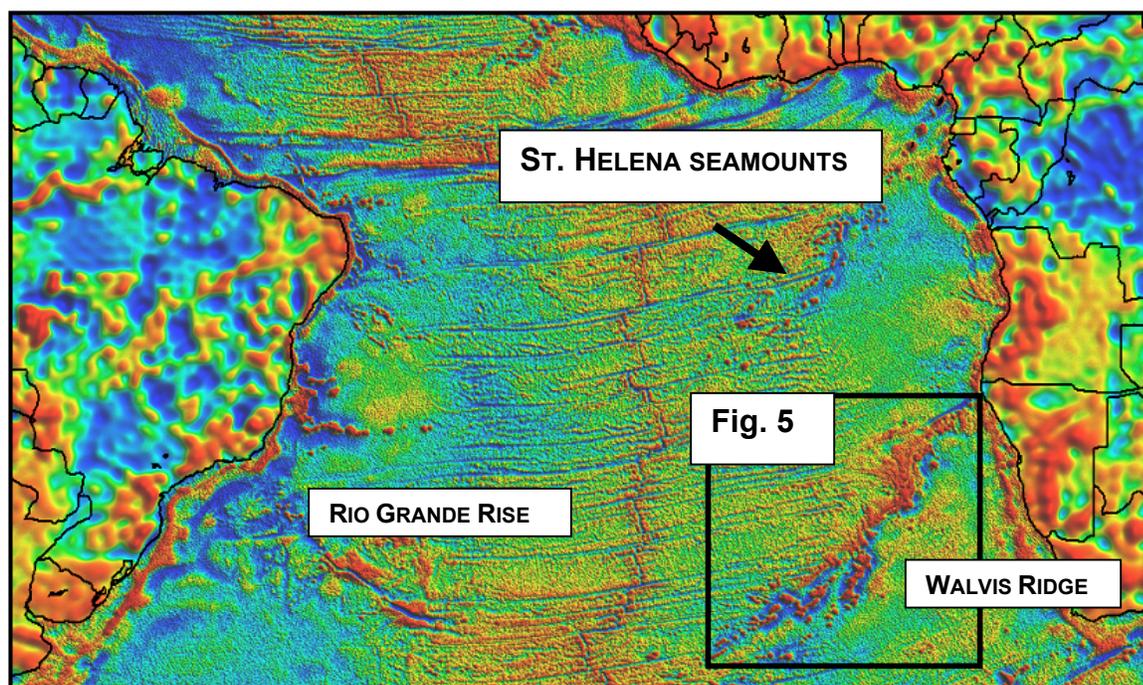


Figure 1: The satellite free air gravity of the Central, Equatorial and South Atlantic Oceans. Inset boxes indicate the location of Figures 6 and 7.

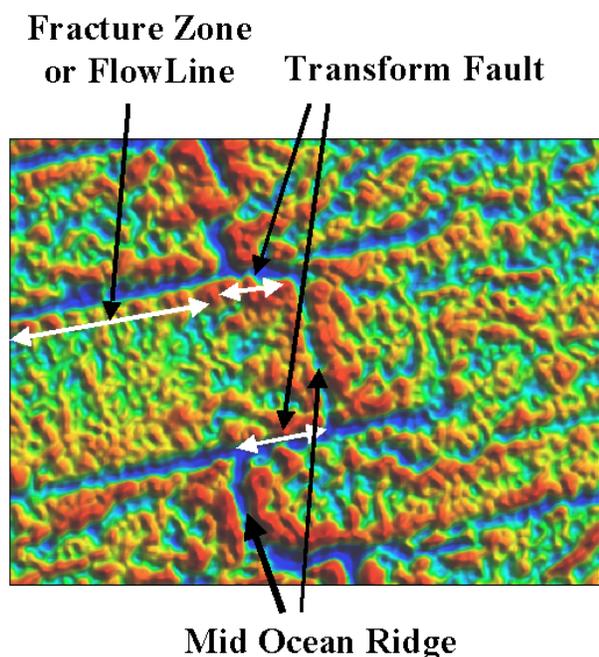


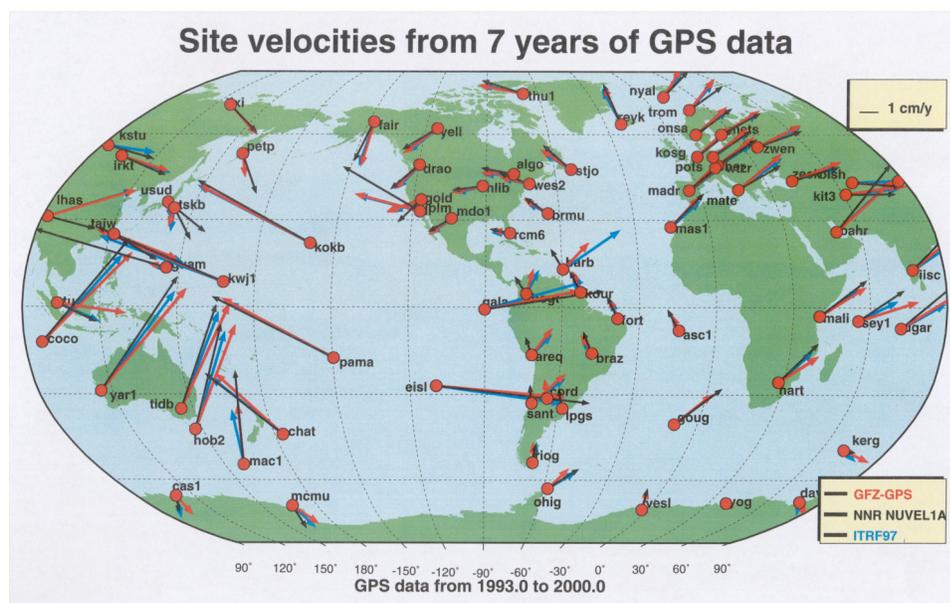
Figure 2: Gravity Image of the mid South Atlantic mid-ocean ridge

O'Connor et al. [6] have demonstrated (by Ar-Ar dating) that individual seamounts in these hotspot chains probably form very rapidly, in less than 1 Myr. These authors suggest that the migration rate of volcanism along the St Helena seamount chain has slowed significantly in the past 19 Myr to about  $2 \text{ cm yr}^{-1}$  which they relate to a 33% reduction in the absolute motion of the African plate. Such a slow-down could be

related to the collision between Africa and Eurasia which began at about 38 Ma. It could also be linked to an upsurge of hotspot-related volcanism within continental Africa since ~ 25 Ma.

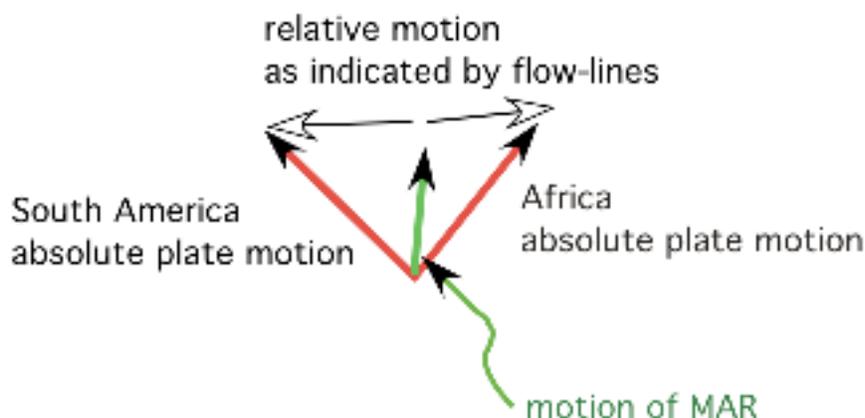
A new map of spreading asymmetries in the South Atlantic (Müller et al., [7]) shows that asymmetries in the spreading corridors close to St. Helena have increased since chron 13 (~ 33 Ma) and close to Tristan da Cunha became more pronounced between chrons 13 and 6 (~ 20 Ma). This correlates with an increase in hotspot volcanism linked to changing African absolute plate motion. O'Connor et al. [6] have suggested that the changes in the oceanic hotspot trails are related to the interplay between changing lithospheric stress, in response to the deceleration of the African plate, and enhanced heating of the lithosphere due to slower plate motion over hotter regions in the mantle (i.e. mantle plumes). Changing lithospheric stresses due to plate deceleration could have triggered hotspot-related volcanism in new areas located over relatively broad hot zones within the asthenosphere. This could explain the existence of numerous sub-parallel seamount trails on the ocean floor, each of which may provide a faithful record of the direction of African plate motion at the time they were volcanically active.

New data for global absolute plate motions based on plate tectonic (NUVEL 1A), GPS and astronomical studies (ITRF97) (Fig. 3) indicate that the African plate is presently moving to the NE whereas the South American plate, east of the Andes, is moving to the NW. These directions of motion are consistent within both oceanic and continental domains. For example, within the South Atlantic Ocean the oceanic island of Ascension (asc1 in Fig 3) lies just to the west of the Mid-Atlantic ridge and moves along the same vector as South America, whereas the oceanic island of Gough (goug in Fig.3) lies to the east of the ridge axis and moves with the African plate.



**Figure 3: Absolute plate motions based on GPS data (red arrows) from GFZ Potsdam, Germany for the period 1993-2000 compared to directions of motion predicted by the NUVEL 1A model (black arrows).**

If a vector diagram of the African and South American absolute motions is constructed (Figure 4) then the relative motion between Africa and South America is essentially E-W and this is what the transforms and flow lines reflect. Slight changes in flow line direction indicate changes in the relative motion of the plates brought about by the consequence of plate interactions/collisions elsewhere e.g. Africa colliding with Europe and India colliding with Asia. The South Atlantic ridge axis will have an absolute motion equivalent to the mean between the African and South American vector directions. This dictates that the ridge axis is moving due north. Thus magmatic processes that are independent and deeper than the flow line geometry will be influenced by absolute plate motions rather than relative motions. Combining these phenomena, if data resolution permits, will provide vector controls on the absolute and relative plate motions at any given time in the past. This has not been previously exploited in unravelling past relative and absolute plate motions.

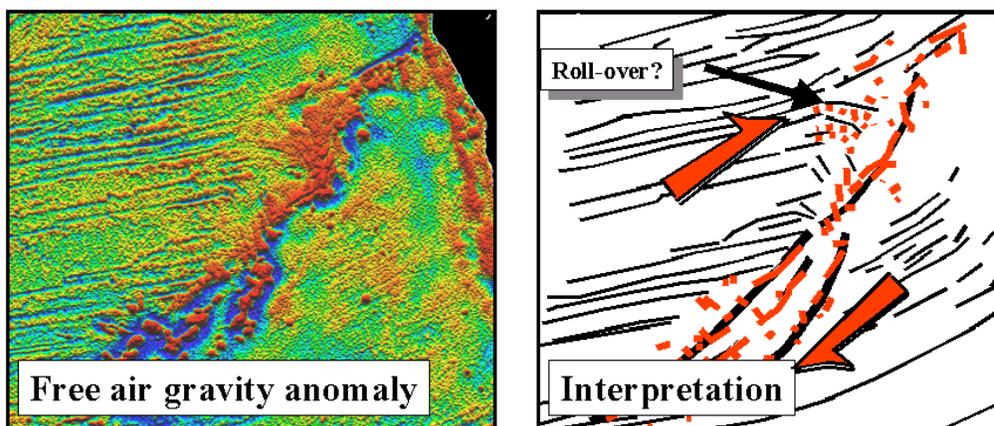


**Figure 4: Vector diagram showing relations between absolute plate motions, relative motions and motion of the mid-ocean ridge (MAR)**

The absolute plate motion results indicated on Figure 4 are based on the simple assumption that there is no net-rotation of the lithosphere (i.e. using a reference frame that yields zero for the integral of  $\mathbf{v} \times \mathbf{r}$  over the Earth's surface, where  $\mathbf{v}$  is the plate velocity at position  $\mathbf{r}$ ). The GFZ-Potsdam GPS data (red arrows in Fig.3) are considered to be the most reliable. For a given plate the motion should conform to rotation about a Euler pole. For South America (east of the Andes), as noted above, the plate motion is consistently to the NW with an Euler pole located at approximately 25.4 °S and 126.4 °W. For South America west of the Andes the motions to the NE are consistent with the subduction of the Nazca plate beneath the Andes.

#### KEY OBSERVATIONS

- That the absolute plate motion directions of Africa and South America have been consistent since the opening of the South Atlantic Ocean commencing in the Early Cretaceous (ca 126 Ma).
- That plate motion direction strongly influences fault tectonics (within both continents and oceans) on both micro- and macro-scales. Faults parallel to the direction of plate motion should be more susceptible to reactivation, whilst faults orthogonal to the direction of plate motion should remain locked. This may have important implications for the localisation of kimberlites and other centres of alkaline magmatic activity within Brazil and central-southern Africa.
- That the concept of “hotspot traces” is over simplistic and that a model involving the periodic release of plate stresses in the form of shear/wrench faulting is more appropriate.
- That the fabric of the ocean crust records relative (shallow phenomena related to flow lines) and absolute (deeper phenomena related to mantle hotspots) motion vectors that can help trace absolute plate motions back in time.
- That intra-plate deformation has an important role during sea-floor spreading. Deformation appears to be quite common within the South Atlantic oceanic crust and may be the controlling factor in the development of the Walvis Ridge and Rio Grande Rise aseismic ridges. These ridges appear to have developed as a response to periodic changes and release of intra-oceanic plate stress. This has resulted in wrench and shear movement and deformation along these features (Fig.5).
- The aseismic ridges appear to have had a controlling influence on periodic stress release within the oceanic parts of the plate as well as on the adjacent continents.
- Stress release within Africa and South America may have resulted in localised decompression melting of the mantle, evidenced by the presence of alkaline volcanic complexes and kimberlite diatremes that are younger than the main phase of ca 135 Ma flood basalt volcanism (Parana-Etendeka provinces) that pre-dates continental break-up.
- If the internal structure of the Walvis and Rio Grande ridges can be better resolved, we may gain fundamental new insights into the origin of these intra-oceanic plate structures and adjacent continental weak zones, leading to the development of generic models for other regions of the Earth.



**Figure 5. Gravity field of the Walvis Ridge and possible interpretation in terms of stress release at discrete times resulting in shear movement and deformation**

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