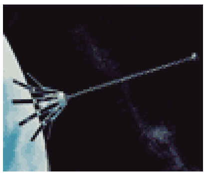
ERS-1

Sea-floor spreading and deformation processes in the South Atlantic Ocean: Are hot spots needed?



GEOSAT

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1. Introduction

The publication of the SEASAT satellite-derived gravity map of the world's oceans in the mid 1980s, with resolution of ~ 60 km and greater, by Haxby revealed for the first time the global fabric of plate tectonics, and resulted in a major advance in our understanding of Earth processes. In the mid 1990s *Sandwell & Smith* (1997) further improved the resolution of the satellite-derived gravity field using the combined geodetic mission data of GEOSAT and ERS-1 giving a resolution 30-40 km and greater. The enhanced detail of plate tectonic processes provided by these new data did not, however, result in such a dramatic advance as would have been expected. Hot spots and mantle plumes were by then firmly established concepts in explaining the observed linear chains of volcanic islands and in providing a super-deep mantle frame of reference (the hotspot reference frame) that was independent of plate motions at the surface.

Accumulating scientific evidence over half a decade and recent GPS-derived absolute plate motions suggest that both the mantle plume frame of reference and the age dependence along volcanic lineaments are not as strong as once believed. This article investigates the complex tectono-magmatic processes involved in the opening of the Central, Equatorial and South Atlantic Ocean and asks the simple question of whether there is an alternative tectonic model to explain the phenomena seen in the satellite gravity field. The case is made that hot spots or mantle plumes are not necessarily required to explain the volcanic lineaments and that most, if not all, features result from deformational processes during the evolution of the plates. Such a model has a range of implications which, hopefully, can be tested to further refine the model.

This study uses throughout the satellite data of *Sandwell & Smith*, which have resolution of 30-40 km and greater (*Sandwell*, 2002). To evaluate and develop the proposed model the resolution of the satellite gravity needs to be increased to about 10 km. This satellite resolution has been achieved using GEOSAT and ERS-1 geodetic mission data by innovative research and development funded under a ROPA award to the University of Leeds (1996-1998; to Prof. Derek Fairhead) and more recently, via Leeds University spin-off company GETECH of which Professor Fairhead is the CEO, by conducting two oil industry consortium studies to prove the technology and to implement it to map the world's continental margins (*Maus et al.*, 1998; *Fairhead et al.*, 2001a,b; *Green & Fairhead*, 1998). The need for such resolution is illustrated in this study and will significantly improve our understanding of oceanic crust-forming processes, particularly the role of magmatism and intra-plate deformation,

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2. The South Atlantic Ocean

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 (Figures 1 & 2).

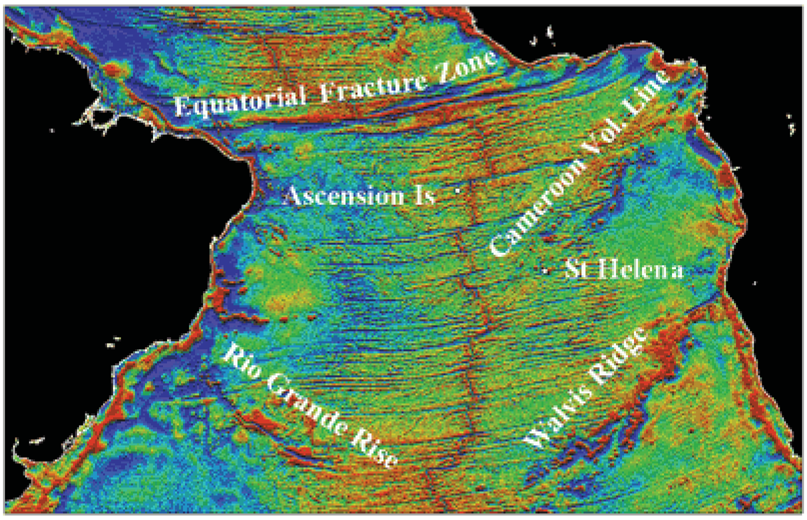

Figure 1: The satellite free air gravity of the Central, Equatorial and South Atlantic Oceans. Click on image for a larger version.

In the South Atlantic these transform faults are typically spaced some 50-100 km apart, reflect 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, which is expressed as a deep trough in the oceanic crust.

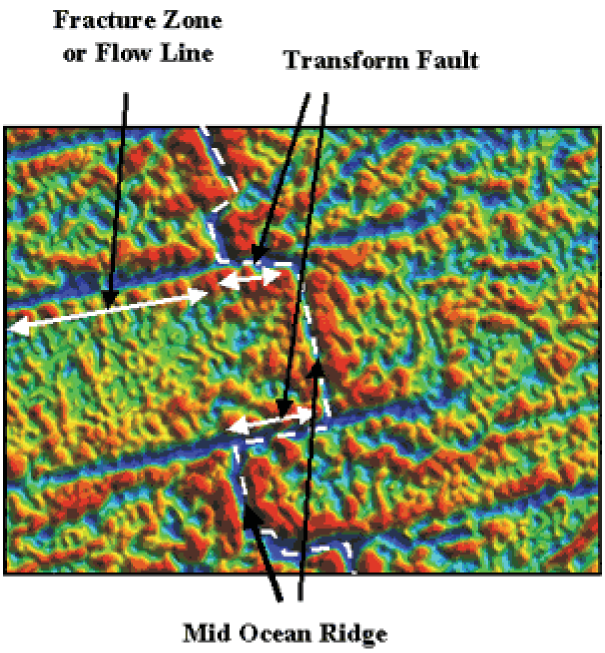

Figure 2: Free air gravity Image of a small part of the mid South Atlantic mid-ocean ridge.

At greater distance from the ridge crest, 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 it generates a distinct bathymetric and gravity feature (Figure 2) that can be traced for large distances away from the ridge axis and preserves evidence of former plate tectonic processes and movement vectors.

The hotspot concept for the evolution of the South Atlantic has generally been explained by active hotspot/mantle plumes being located along or close to the ridge axis, generating trails of volcanic islands and seamounts as the plate migrates over the hotspot. These hotspot trails strike at oblique angles to the flowlines suggesting deeper processes are in operation than those that formed the flowlines. These hotspots are traditionally linked to upwelling convective instabilities or “mantle plumes”, originating from thermal boundary layers at the base of the upper mantle (the 670 km discontinuity) or even the core-mantle boundary at 2,900 km depth. Assuming the hotspot reference frame is valid, the seamount trails would then provide an important record of past motion of the African plate.

Within the South Atlantic there are a number of distinct volcanic lineaments (Figure 1) in the form of aseismic ridges (e.g. Rio Grande Rise, Walvis Ridge) and chains of seamounts and oceanic islands (e.g. St. Helena Seamounts and the Cameroon Volcanic Line). These volcanic lineaments have been previously 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 (*Wilson*, 1992). The simplicity of the mantle plume and hotspot trails concept tends to raise more questions than it answers.

- When St. Helena should be the youngest volcanic centre, why should there be so much Tertiary-Present volcanic activity occurring within the Cameroon Volcanic Line (Figure 1) where it straddles the African continental margin?
- 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. Why does the conjugate Rio Grande Rise on the South American plate, exhibits a total different morphology?
- Why does the Cameroon Volcanic Line not have a conjugate volcanic lineament on the South American plate?
- Why should the South Atlantic plumes track the mid-oceanic ridge when the hotspot reference frame is independent of plate tectonics?

If we can establish the processes which form these trails of South Atlantic volcanism, then we can gain important insights into the role of mantle plumes or other mechanisms in continental break-up and the subsequent evolution of the ocean basins.

3. The Central and Equatorial Atlantic

The Central Atlantic is located to the north of the Equatorial fracture zones that dominate the bathymetric morphology and satellite gravity field between NE Brazil and the Gulf of Guinea (Figure 1). The Central Atlantic Ocean opened in the early Mesozoic separating Europe/Africa from North America (*Wilson*, 1997), whereas the South Atlantic Ocean

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opened later in the early Cretaceous and propagated northwards. The joining of these two independent spreading centres in the early-mid Cretaceous resulted in a major shear zone developing between West Africa and the northern margin of Brazil. Since the opening of these two spreading systems was different, differential motion was taken up as deformation predominantly in Africa and the Caribbean and least in South America. The change in flow line geometry north and south of the Equatorial fracture zones is shown in Figures 3, 4 and 5.

Figure 3 shows clearly defined flow lines with isochron ages for the Central Atlantic. Here the flow lines exhibit clear changes in direction indicating that the relative movement of the plates has changed due to plate interactions elsewhere on the globe e.g. India colliding with Asia and Africa colliding with Europe, resulting in the need for global adjustments in plate motions. Figure 4 shows the same isochrons for the northernmost part of the south Atlantic. When the flow lines and isochrons of Figures 3 and 4 are displayed together in Figure 5 there is immediate recognition that the flow lines are responding differently e.g. the curvature of the flow lines (marked as '+' and '–') is opposite to the north and south of the Equatorial fracture zone. This implies there are significant differences in relative plate motions to the north and south of the Equatorial fracture zone and this has resulted in deformation propagating into the Caribbean and Africa. Motion between Africa and Eurasia is shown in a different way in Figure 6 by tracking the motion of Africa with respect to Eurasia. The motion has been such that the tracks increase in length from northwest to east Africa. The amplification of the plate motion shows clear changes in plate motion at about 84, 65 and 37 Ma. Arrows indicate these changes for the movement of the Indian plate.

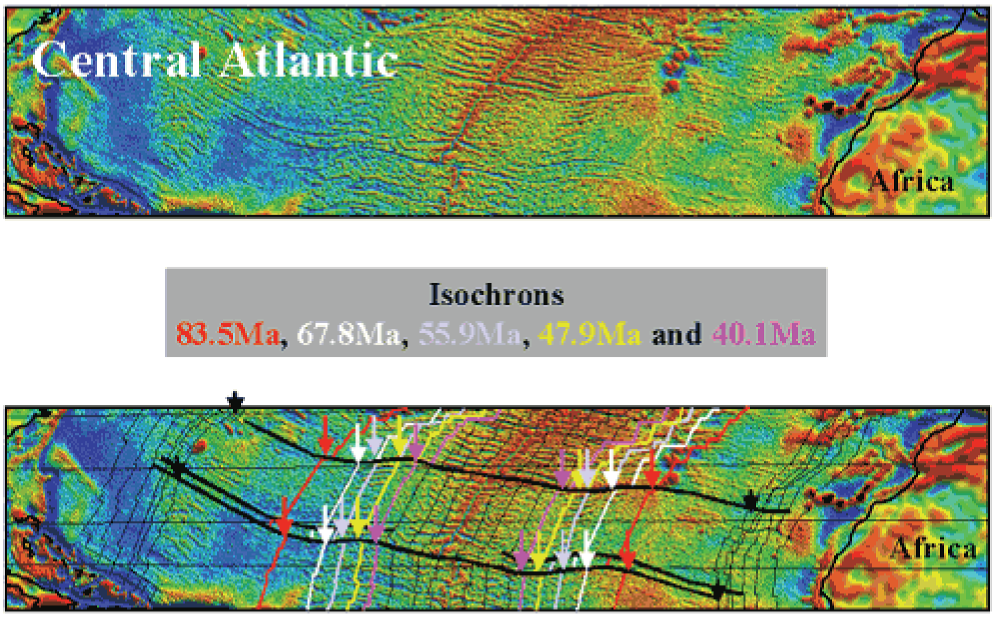

Figure 3: Free air gravity anomaly of the central Atlantic with flow lines and isochrons superimposed on the lower diagram.

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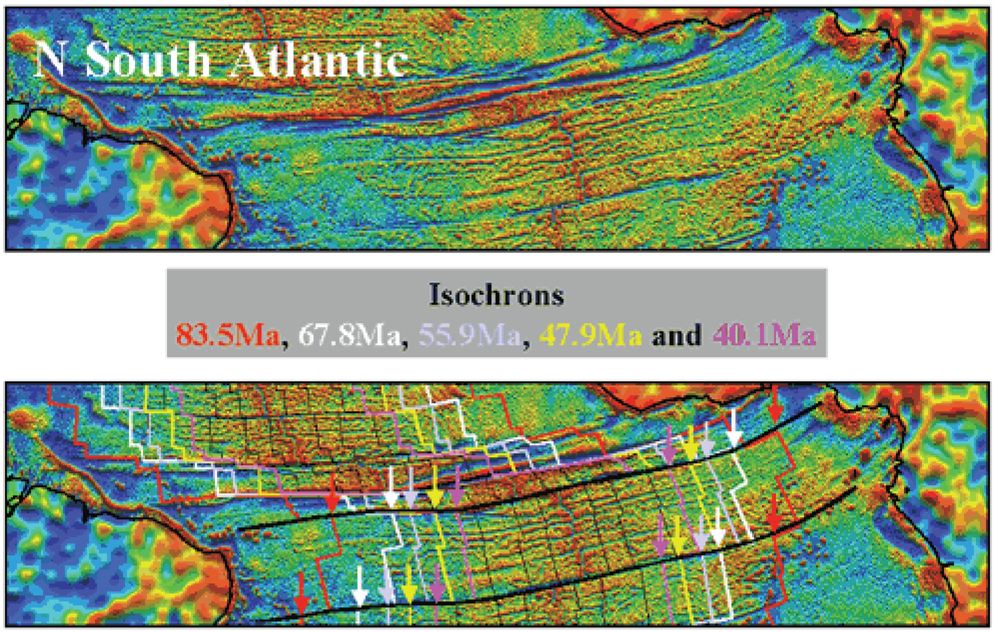

Figure 4: Free air gravity anomaly of the northern South Atlantic with flow lines and isochrons superimposed on the lower diagram.

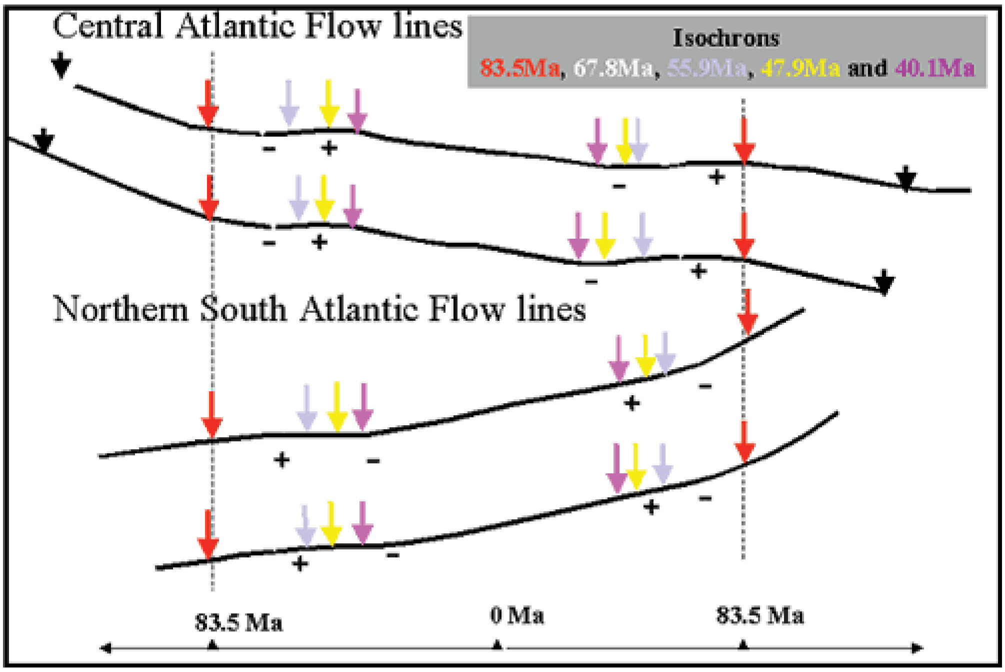

Figure 5: Comparison of the flow lines shown in Figures 3 & 4 (normalised to isochron 83.5 Ma) showing the distinct changes in relative plate motion highlighted by the '+' and '–' curvature signs.

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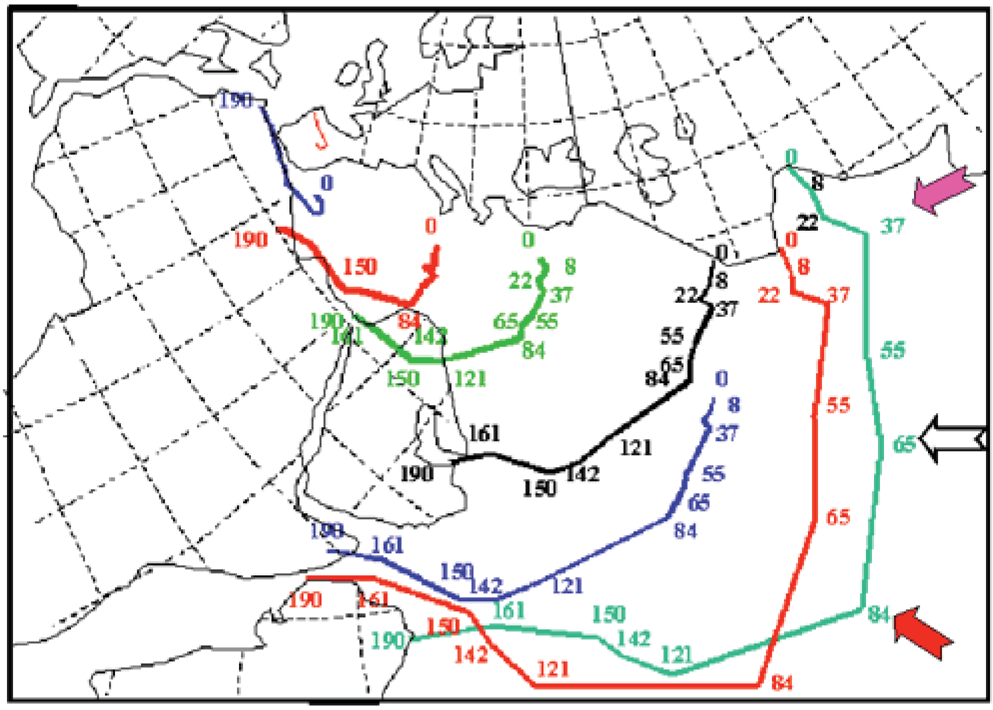

Figure 6: Relative plate motion between Africa and Eurasia and between India and Eurasia.

In Africa, this differential movement resulted in the development of major passive extensional structures (basin formation) and shear deformation (Figure 7). The stratigraphy of these internal African basins is a more sensitive indicator of stress changes. Detailed geological studies within the southern Chad basins reveals the poly-phase tectonic development of these basins, all affected in different ways, due to basin orientation, to changes in plate stress.

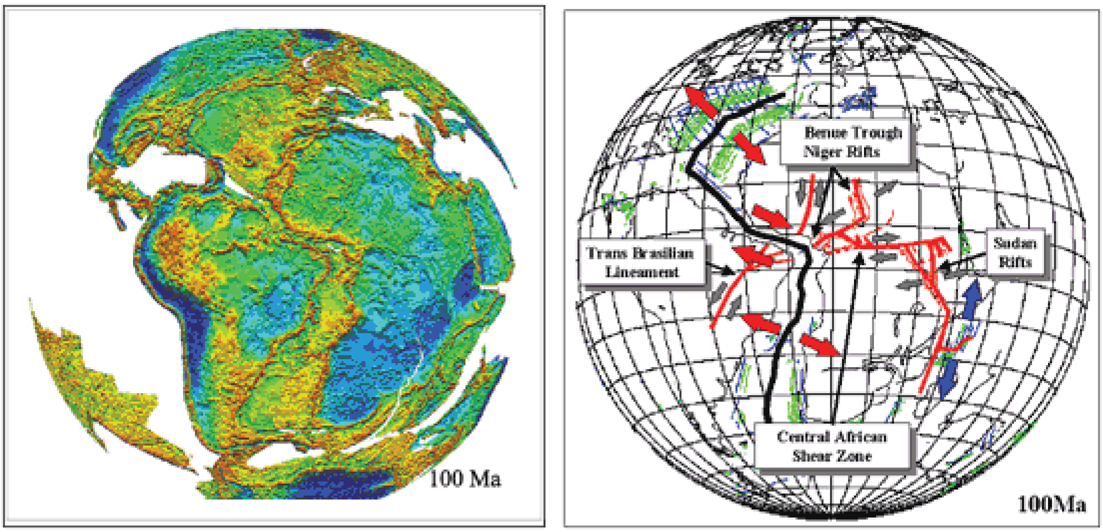

Figure 7: Plate reconstruction at 100 Ma using gravity data onshore and offshore and the associated deformation models for Africa and South America. Click on image to enlarge.

The principal stratigraphic events marked by arrows in Figure 8 indicate those events seen in the fabric of the ocean crust. Clearly the basin stratigraphy is more sensitive to smaller scale tectonic/stress change events than the ocean crust. Major inequalities in plate motion are expressed within the complex fabric of the oceanic crust. If the definition of the fabric was better resolved by having higher-resolution satellite gravity data then there is a real possibility that more of the complexity could be unravelled in terms of evolving plate motions and deformation that should link temporally and spatially with tectonics and deformation events within the rift basins of Africa as recorded in the stratigraphy and deformation of the sedimentary basins (*Fairhead & Green*, 1989; *Fairhead & Binks*, 1991: *Fairhead & Guiraud*, 2002). The stratigraphy of the basins clearly indicates the events we should be looking for in the ocean basins.

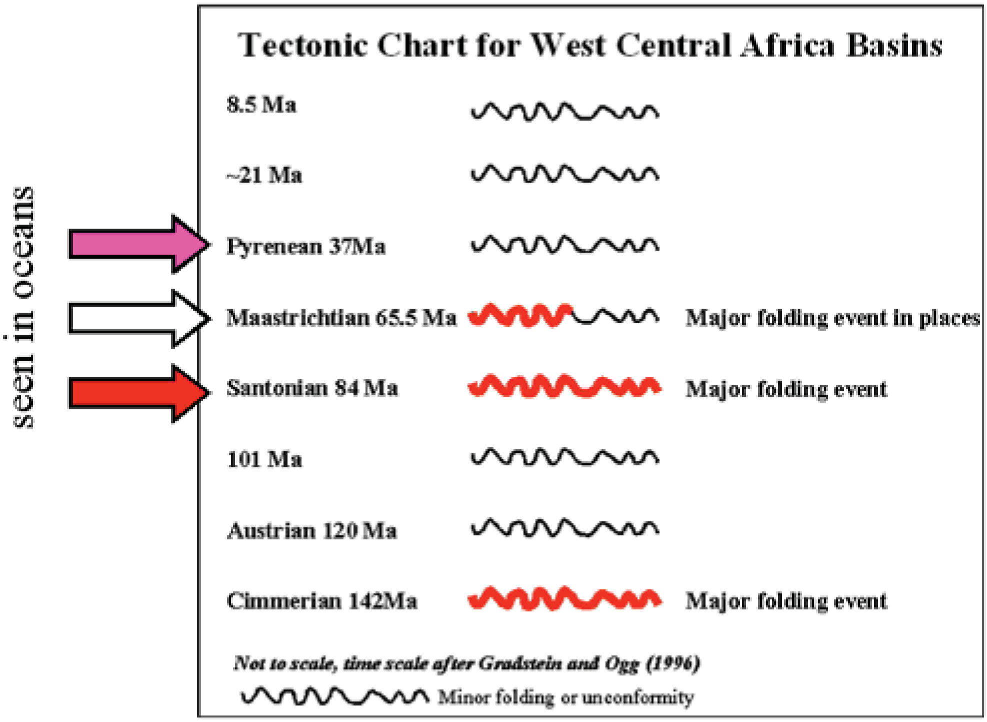

Figure 8: Generalised tectonic Chart for West Central Africa based on extensive geological and seismic interpretation. The arrows show the tectonic events seen in the fabric of the ocean crust.

4. Hypotheses that need testing

We have demonstrated above that changes in relative plate motion have resulted in stress changes in Africa that have been responsible for the development of a major rift basin system cutting Africa from Nigeria via Lake Chad to Algeria and from Cameroon through southern Chad, northern Central African Republic into Sudan and Kenya (Figure 7). New data for global absolute plate motions based on plate tectonic (NUVEL 1A), GPS and astronomical studies (ITRF97) (Figure 9) 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 (Figure 1) 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 Figure 9) lies to the east of the ridge axis and moves with the African plate.

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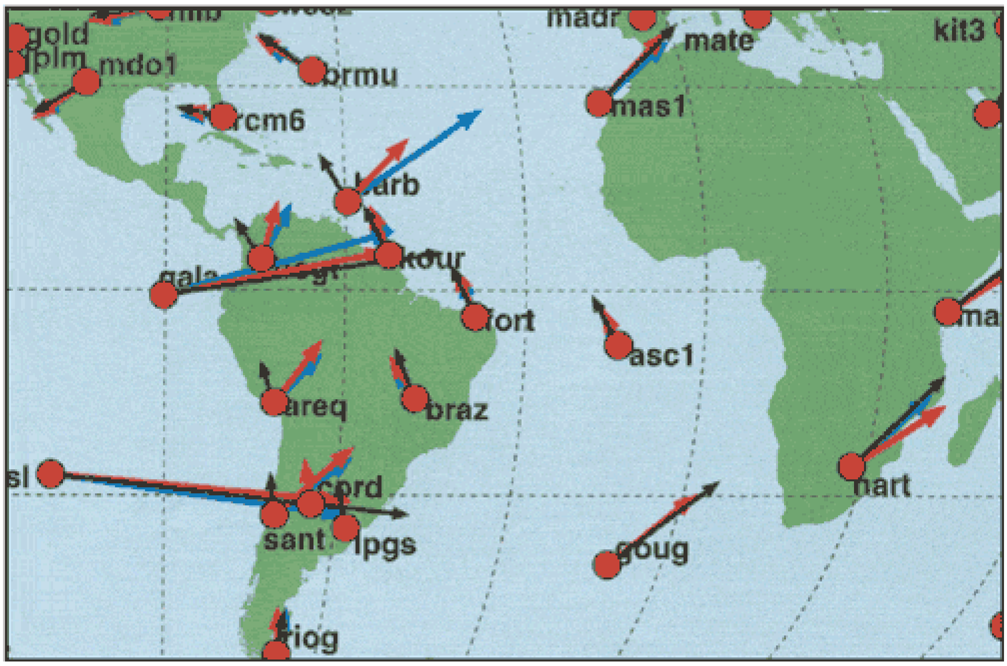

Figure 9: Absolute plate motions based on GPS data (red arrows) from GFZ Potsdam, Germany for the period 1993-2000 compared to directions of older estimates of motion predicted by the NUVEL 1A model (black arrows) and astronomic (blue arrows).

If a vector diagram of the African and South American absolute motions is constructed (Figure 10) 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.

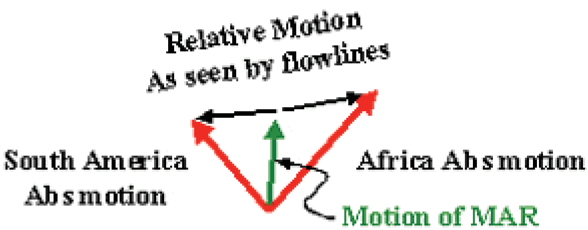

Figure 10: Vector diagram showing relations between absolute plate motions, relative motions and motion of the mid-ocean ridge (MAR) If we know the relative motions and the motion of the MAR then absolute motions can be deduced.

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 close to due north. Thus magmatic processes that are independent of, 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.

The absolute plate motion results indicated in Figure 9 are based on the simple

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assumption that there is no net-rotation of the lithosphere (i.e. using a reference frame that yields zero for the integral of *v* x *r* over the Earth's surface, where *v* is the plate velocity at position *r*). The GFZ-Potsdam GPS data (red arrows) are considered to be the most reliable. For a given plate the motion should conform to rotation about a given 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.

Evidence of this phenomenon can be seen in Figure 11 located south of the Equatorial fracture zone in the northern South Atlantic. Here the principal flow lines are parallel to each other but between these flow lines the fabric of the oceanic crust suggests a northward migration, with time, of rift axis volcanic centres, starting close to the southern flowline and moving progressively northwards along the rift axis, such that the volcanic centre is now close to the northern flowline. Since the oceanic crust is being generated at the mid-ocean ridge, the trace of the volcanic centres forms an inverted 'V' line symmetric about the oceanic ridge (shown by yellow lines in the lower diagram of Figure 11). This could imply that the magmatism is more associated with the absolute motion of the plate as discussed above. Improved satellite gravity resolution will help to define such phenomena better and to identify more of them. Knowing the opening rate of the MAR allows the relative and absolute motions to be determined.

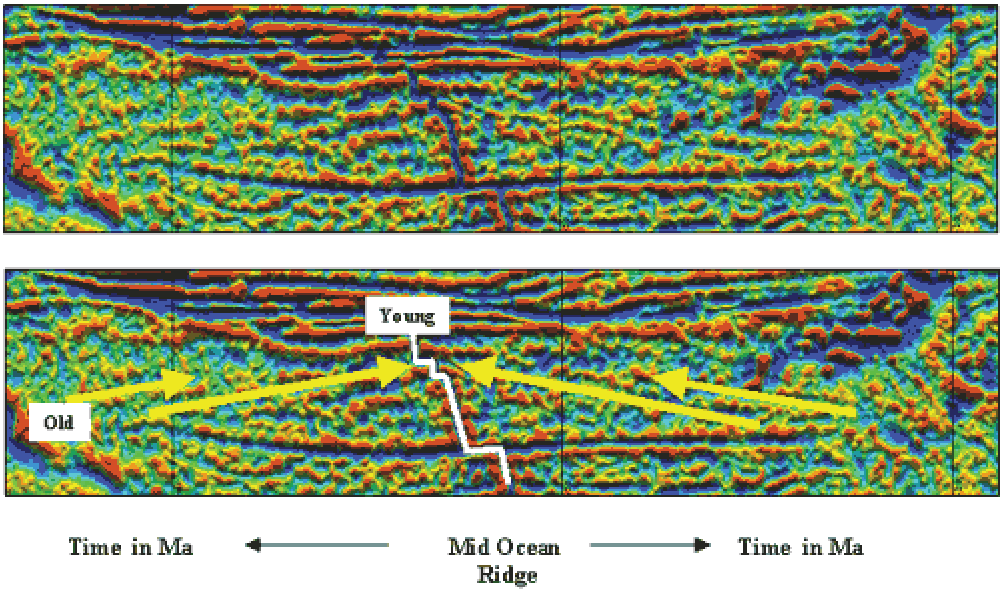

Figure 11: Structure of the mid-Atlantic ridge based on satellite-derived free air gravity showing migration of features (volcanic centres?) northwards with time within a ridge segment.

The origin of the volcanic lineaments needs to be reassessed now that the absolute motions of the plates are known (Figure 9). The absolute direction of plate motions is considered strongly to influence fault tectonics (within both continents and oceans) at 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. On a macro-scale this may have important implications for the early emplacement of Cretaceous kimberlites and other centres of alkaline magmatic activity within South America and Africa, and for the origin of the volcanic lineaments that closely parallel the absolute plate motion directions. On the micro-scale this same model concept may be a principal control on the timing of fluid flow along faults within hydrocarbon systems, i.e. faults paralleling the plate motion being more susceptible to

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fluid flow than orthogonal faults.

It is proposed that the concept of “hotspot traces” for the South Atlantic is over simplistic and that a model involving the periodic release of plate stresses in the form of shear/wrench faulting may be more appropriate. Closer evaluation of the Walvis ridge and Rio Grande rise tends to support such a model. The development of the Central African rift system already testifies that major changes in plate stress configurations, seen in the fabric of the oceanic crust, have been able to develop and propagate extensive passive rift systems throughout west, central and north Africa (Figure 7). Lesser stress changes also register within the stratigraphic record of these basins. It is not unreasonable to conclude that stress changes within the African and South American plates will be absorbed or dissipated wherever there is an existing plate/crustal weakness; the style of deformation will depend on the orientation of such weak zones. Inspection of the satellite gravity for the South Atlantic indicates that deformation of the oceanic crust appears to be quite common and may be the controlling factor in the development of the Walvis Ridge and Rio Grande Rise aseismic ridges. The evolutionary model that we propose for these ridges is a periodic response to periodic changes and release of intra-oceanic plate stress. This has resulted in wrench and shear movement and deformation along these features (Figure 12).

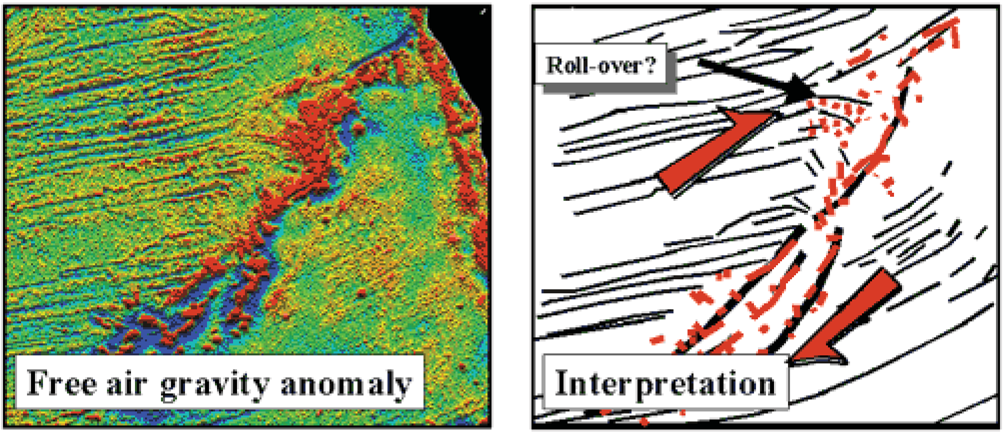

Figure 12: Free air gravity field of the Walvis Ridge and possible interpretation in terms of stress release at discreet times resulting in shear movement and deformation.

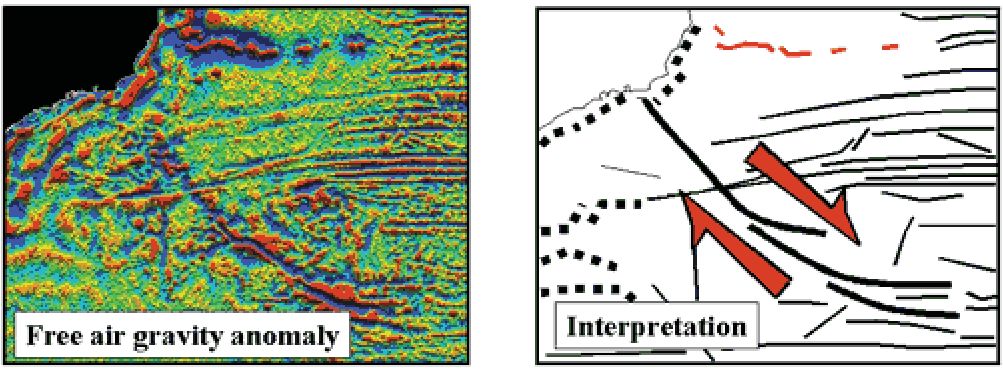

Figure 13: Image enhanced free air gravity anomaly with possible interpretation of dextral shear and extension in discrete segments along the Rio Grande rise.

We propose that stress within the African plate has been dissipated by wrench and shear movement as shown in Figure 12 at key times in the past. The stress release has emanated from the ridge axis and propagated into the African plate as shear and wrench displacement, as well as causing localised decompression melting of the mantle, resulting in short volcanic lineaments where the volcanic centres have the same age and terminate at the mid-ocean ridge of the same age. The formation of the volcanic lineament is thus not a continuous process but is repeatedly reactivated when the plate stresses become too great to be sustained. The previous event will have already weakened the lithosphere such that ensuing events reoccur along the same feature. This then provides a model for the Walvis Ridge of segments (illustrated as thick black lines in Figure 12) of volcanic activity progressively occurring along with the evolution of the oceanic crust of the South Atlantic Ocean. This model still predicts an age progression along the ridge, but this is not necessarily linear with distance as with the hotspot model. Evidence for deformation for the Walvis Ridge is strong in that there is:

- flow line deformation, identified as a 'roll-over' structure in Figure 12, suggesting dextral shear/wrench movement along the Walvis Ridge, and
- the orientation of the flowlines to the north and south of the Walvis Ridge are measurably different, consistent with such dextral motion.

A similar tectonic scheme could apply to the Rio Grande Rise (Figure 13). Its differing bathymetric/gravity morphology to the Walvis Ridge however suggests there has been a greater degree of extension across the segments.

The continental extension of the Rio Grande trend is associated with alkaline volcanic complexes and kimberlite diatremes which are younger than the main phase of ca 135 Ma flood basalt volcanism (Parana-Etendeka provinces) that pre-dates continental break-up. Such a correlation may indicate that the same model process as identified for the Walvis Ridge and Rio Grande Rise is occurring deep within the continents at the onset of the lithosphere disruption process. If the internal structure of the Walvis and Rio Grande ridges can be resolved better, 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.

5. Conclusions

The proposed models for the volcanic evolution of the South Atlantic could be considered to be radically different to the model proposed by 'hotspot' enthusiasts. The advantage of the model is that it can be tested in many ways since there are clear implications for the migration of volcanism along the axis of the MAR and for the deformation model for the formation of volcanic lineaments. The model has the potential to resolve the complexity of the evolving oceanic crust since the gravity field is able to image accurately the main tectonic events that have occurred within the oceanic crust; these can be related to the more sensitive indicator of sedimentary stratigraphy and associated deformation within the adjacent continental areas of the plate that have experienced the same changes in plate stresses.

The overwhelming problem that is limiting the advance of our knowledge is the resolution of the existing satellite gravity. Our ability to repick the altimeter radar waveforms to a higher degree of accuracy and to improve satellite data processing methodology using the geoid (or sea surface) to gravity rather than the traditional method of sea slopes to gravity has resulted in significant improvement in the data resolution that is able to resolve reliable isotropic signals down to 10 km wavelengths (or 5 km at half wavelength) in equatorial areas. Such technological breakthroughs in satellite technology still await the funds to allow the resulting products to be used by Earth scientists in new and exciting ways.

Additional related information is available from the Central Atlantic Magmatic Province webpage and the Africa webpage.

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