Toward the global tectonic model: A new hope (part 2)

Neil Hodgson[1*] and Karyna Rodriguez[1] continue to investigate the consequences for prospectivity of a revolutionary convection model of the mantle, by exploring the implications for shelf stability, distribution of source rocks and the geology of the rifting process on the passive margins.

Introduction

We all sense that ultimately 'nature' knows best. While we have tried to impose simple models and ordered processes on the world's geology, we actually continue to encounter nature's myriad uniqueness. As a result, we have grown comfortable with the butterfly effect of multiple influences randomly expressed at any scale from hand-sample to plate. We observe subsidence occurring offshore Argentina or Somalia while uplift occurs offshore Namibia and assume this is due to local tectonics acting ineffably and unconnectedly. That a sequence is deposited in a stable depositional regime in Angola while shelf collapse and instability produces the geology observed offshore Namibia is more troubling, but such contrasting tectonics acting simultaneously is again an expression of local plate stresses acting on local geology with non-linear results. This is our experience, so we understand our basin geologies on an isolated basin scale. With no common glue of a process we rely on an understanding of local basin tectonics. And this works but are we missing something?

There is hope of finding a glue to hold together our basin models. In the preceding article published in *First Break* (March, 2017), Hodgson and Rodriguez suggested that the potential for an overarching control on passive margin stability lies in the underlying convection patterns in the mantle. A revolutionary method for identifying present-day convection patterns in the mantle has been identified in an extraordinary paper by Hoggard et. al., 2016, which proposes to use deviations of the depth-to-oceanic crust of a given age from a model subsidence curve to indicate crust being uplifted or depressed by underlying convecting mantle. Their observed convection varies dramatically from previous mantle models. In this second article, we explore the potential consequences of this rebel mantle convection model for changing our understanding of geological processes on all the world's passive margins.

Hoggard et al.'s model proposes that uplift of oceanic crust, above the model depth it should lie at for a given age of crust, measured as a positive (+ve) residual, indicates upwelling hot(ter) mantle. They also show that depression below the modelled depth for crust of a given age, reveals a negative (-ve) residual indicating underlying down-welling cold(er) mantle. This mantle controlled dynamic topography is mapped by Hoggard et al., over the Earth's sphere to create a global convection cell model (Figure 1).

The vertical relief of the crustal uplift can be up to 2 km, and while this seems insignificant in comparison to the height of the convection cells themselves – 650 km deep (or more), an uplift of this scale in a basin will have huge implications for the geological systems, creating uplift and erosion of shelf areas or moving facies belts, creating flooding events that do not match global eustatic changes etc. Observations of dynamic changes to geological processes in basins that are 'elevational' rather than related to global sea level or local tectonics have been recognized for some time within the field of Dynamic Topography. Yet perhaps the most extraordinary conclusion of the Hoggard paper was the size of the convecting cells. These may be as small as 1-2000 km in diameter so that along any given passive margin one basin may be being inverted while the basin adjacent to it may be being depressed.

The consequence of the appearance of such phenomena on the stability of the sedimentary section being deposited is plain to see. If one assumes that sediments are deposited on the margins of a given basin in a stable angle of repose, then, were the sea bed of the basin floor 50 km from the shelf to lie at 3 km, if it were to be depressed by 1km, then the overall gradient or basin slope would be steepened by approximately 1 degree. This would destabilize sediments in equilibrium repose and one would expect to see shelf collapse, megaslides (i.e. gravitationally driven fold and thrust belts) and Mass Transport System (MTS) sediments

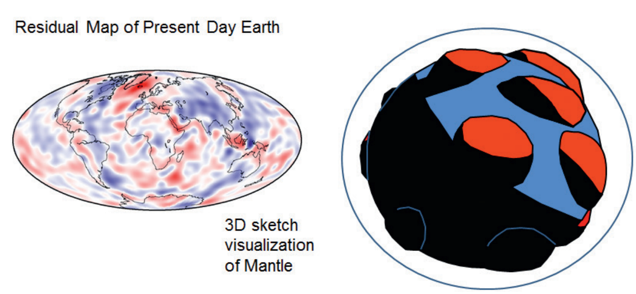

Figure 1 Left-hand side, Hoggard et al. (2016). Spherical harmonic model residual map of the earth. Right-hand side, sketch of 3D implication of Mantle topology. Both, red = +ve residual, blue = -ve residual.

[1] Spectrum Geo
[*] Corresponding author, E-mail: Neil.Hodgson@spectrumgeo.com

deposited in the lower slope and basin floor. Alternatively, were the basin floor to be uplifted by 1 km, the dip of the slope is reduced by more than 1 degree and therefore one might expect to see little shelf/slope collapse, and conformable or parallel bedded sediments in the deep basin, with little evidence of instability.

The sedimentary sections in the Orange River Delta of Namibia and Juba Lamu Delta of Somalia were compared in our preceding article. In Namibia the Cretaceous basin floor sediments are the products of an incredibly unstable shelf, which becomes more stable at the KT boundary (instead of MTS formation there is just the slower megaslide collapse of the shelf) and this transitions to deposit a Tertiary section that is very stable. Other factors like sediment supply rate and intra-clastic wedge high TOC shales have been over printed by a mechanism to create a stable system (Butler and Taylor 2010; Scarselli et al., 2016). By contrast in Somalia (particularly the north) much of the Early-Mid Cretaceous is very stable yet in the Late Cretaceous and Tertiary the sedimentary section is very unstable – developing MTS and stacked Mega-slides. Comparing the sedimentary stability to the present-day residuals, Namibia (stable shelf today) is currently over a positive residual, while Somalia (unstable shelf today) is currently over a negative residual. The change in stability of each basin may be accounted for by assuming that the sense of the underlying convection cell in each basin flipped at the end of the Cretaceous. In such a model Namibia's Orange Basin sediments would be underlain by a Cretaceous down-welling convection cell, which changed direction in the Tertiary and became up-welling. The reverse would be true of the Somalian stability pattern. However, it is absurd to think of a convection cell just changing sense of flow, for any reason, and fortunately we do not need to contemplate that because it is the movement of the African plate (broadly rotating anticlockwise around a pole through the Cape Verde Islands) that has moved these basins over the underlying mantle fabric — the Namibian margin was lying above a downward flowing part of the mantle convection cell, but migration of the plate to the North East drew it over the upward flowing part of that cell. The reverse would be true of the Somalian margin, and both transitions would be expected by rotation over a mantle cell pattern similar to that seen today.

And this is an interesting observation as one aspect of the mantle convection cells that is not well understood is how stable such cells are – do they stay in one place for millions of years or move laterally, coalesce etc? If we can replicate the stability history of basins by following the plate migration paths over the observed mantle convection cell pattern, it would be reasonable to postulate that the cells have remained stable for a long period of time – perhaps hundreds of millions of years. If this can't be done one might take this as evidence that the cells have a shorter stability period. If we can demonstrate long-term stability by back tracking plate movement over known geometry in the mantle, there would be a mechanism for understanding basin stability on a plate scale back through time. From chaos and localism comes hope of a new order.

Over the last year the stability profile of the Atlantic's basins have been steadily catalogued and compared to post-rift drift tracks of Africa and South America. Broadly, the stability of sediments in the Atlantic Margin basins are consistent with a stable pattern of DT residuals – allowing for complications from interaction with the deeper rooted mantle plume network and subduction zones. The expression of this is that some basins have moved rapidly over a heterogeneous set of mantle convection cells and this is recorded in a multiplicity of unconformities on the shelf, and in the basin a varied pattern of sediments related to stability and instability. Other basins appear to display few unconformities on the shelf, and in the deep basin displays few sediments appear related to shelf or slope instability. Such basins have tracked paths that have kept to one style of cell circulations – i.e. Angola/Congo tracking a NE path along a continuous downward convecting cell wall.

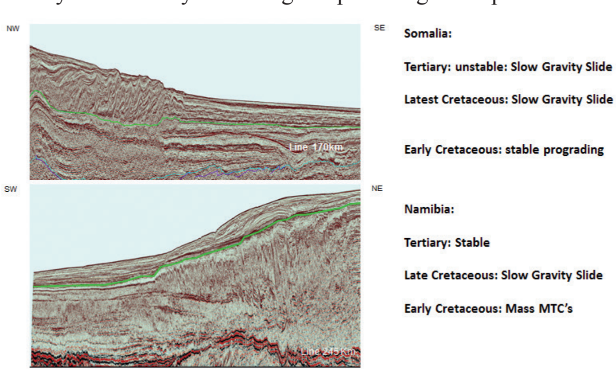

Figure 2 Comparison of Namibian and Somalian seismic data. Shelf stability, and the onset of instability are opposite on these two margins.

Implications of mantle convection cells on rifting.

Dynamic topographic studies onshore have been used to explore the mechanism behind drainage system changes (river piracy), and variations in rates of sediment supply, and even climate. However, the existence of a fabric in the mantle, with associated variation in heat flow to the overlying crust, is likely to have even more fundamental influences on continental plate dynamics.

Irrespective of their longevity, these relatively small diameter mantle circulation cells, much smaller than either continental or ocean plates, are distributed all over the globe, only modified perhaps by proximity to stable lower mantle plumes (such as Hawaii and Cape Verde) and the largest subduction zone systems (the Andes/Rockies at the Pacific rim). The small scale of the cells suggests that the generally accepted mechanism for moving plates may be in difficulty, as below any large plate there are numerous convection cells trying to move the plate in different directions. If mantle circulation drove plate movement it would be a surprise if plates moved at all. Fortunately, earth models that suggest plates are moved by trench drag and ridge push, and are just lubricated by the underlying mantle, are already well discussed (see for example Conrad and Lithgow-Bertelloni, 2002).

The passage of continents over the residual fabric brings heterogeneous stresses and heat flows to the base of the crust. To observe the wavelength of the residual textures, consider the distribution of residuals along the present day Atlantic mid-ocean ridge (Figure 3).

Here we see that +ve and –ve residuals along the ridge path with a wavelength of 1-2000 km over-prints even the adiabatic mantle up warp that feeds the spreading centre. Let us then assume then that a fabric of this order underlay the Gondwanan

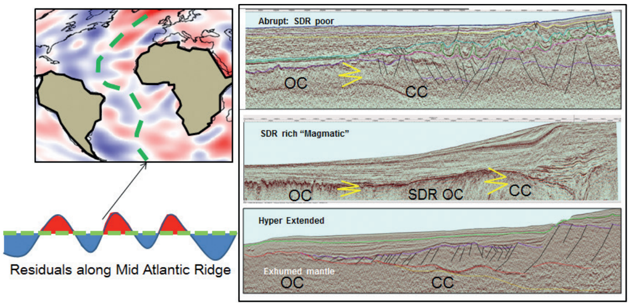

Figure 3 Residuals along a spreading centre are heterogeneous and asymmetric > These relate to Ocean-Continental boundaries that are abrupt (above top: South Gabon), SDR rich (magmatic) (above middle: Namibia) or hyper extended (above lower Somalia).

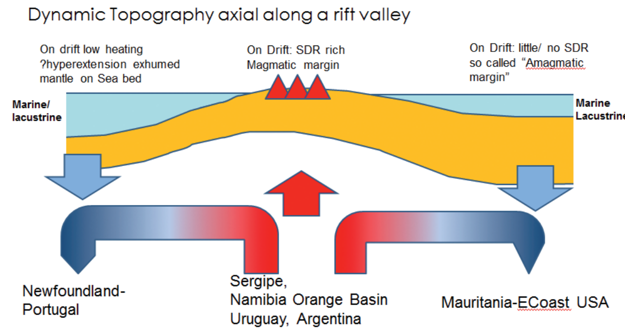

Figure 4 Relating a margins 'magmatism' to upwelling cells in Mantle.

continent at the end of the Jurassic period. As the great N-S rift that tore Gondwana apart opened, the rift would have been exposed to uplift and subsidence along its length reflecting the mantle signature as a dynamic topographic effect. Where the rift lay over a downward convecting cell, the rift valley floor would be low – a likely place for early lake formation and the site of the earliest marine transgression. The anoxic deeper parts of such restricted lakes and marine embayments, of course controlled by extensional faulting along the rift, could be good sites for the deposition and preservation of organic materials, i.e. potential source rocks, and in an alternative scenario of marine transgression the restricted marine boundaries that allow salt deposition basins to develop could again represent the edges of underlying topology modifiers. Parts of the rift on positive residuals would initially be subaerial, only inundated later in rifting by marine transgression. As the rift develops it can migrate over the underlying convecting cell fabric generating an opportunity for developing a diachronous source rock at the base of the drift sequence.

However, just as important to structural geologists studying the development of the geologies of the Atlantic margin might be the consequences for the initiation of drift. There seem to be two main tropes in structural geology that one might begin to address by consideration of the mantle fabric (Figure 3).

Firstly, a set of observations on passive margins concerns the magmatic or amagmatic nature of margins as they enter the drift phase. Some Margins are celebrated as being magmatic as they are regaled by thick seaward dipping reflector (SDR) packages comprised largely of continental flood basalts. The Continental crust often thins rapidly at such a margin. However, we shall come back to hyper-extension in a moment. Namibia and Argentina are well known as magmatic margins while other continental-ocean boundaries appear not to be associated with SDRs and are therefore 'amagmatic' (i.e. South Gabon). However, oceanic crust is made of volcanic basalt – extruded at the sea bed or emplaced as dikes. So to call such a margin amagmatic seems odd. It has been clear for nearly 20 years that flood basalts that comprise the SDRs are deposited sub-aerially (Jackson et al., 1999). An SDR-rich margin is therefore one where volcanism associated with drift occurs sub-aerially, while an SDR-poor margin is one where volcanism occurs sub-aqueously. If the underlying mantle, unconnected and 'disinterested' in the rifting process can modify the rift topology by +/- 2 km, the possibility is that variations in the presence, dominance and longevity of SDRs through the rifting process is simply a reflection of the underlying mantle convection pattern along the rift. A positive upwelling keeps a rift above sea level allowing flood basalts to be erupted during early drift. A negative down welling of mantle rapidly brings the rift below sea level – either allowing marine transgression or creating an inland lake. Basalt erupted below water quenches preventing SDR formation, and generating oceanic crust sensu 'mid ocean ridge basalt' (MORB), (Figure 4). Removing the issue of the 'magmatic nature' of the rift/drift in this way not only removes the requirement for a 'transitional crust' term (because SDRs are oceanic crust), it also allows us to consider the more compelling question of rifting: why some passive margins appear very abrupt, and on others the continental margin is drawn out, extended or hyper extended?

The formation of the Atlantic margin salt basins is also worthy of discussion at this point. The Early Cretaceous Salt deposits of West Africa and Brazil are related to early marine transgression of the Atlantic rift. Such deposits are not ubiquitous along the Atlantic, but neither are they uncommon, indicating that the controls on salt basin formation are not local and specific and indicate an early rift geology of multiple semi-isolated lakes with restricted access or periodic to the global ocean. Often the subsequent deformation of the salt deposits makes the nature of the continental-ocean boundary cryptic. However, there appears to be little lateral room in the salt basins to hide an extensive SDR-rich 'magmatic margin' between continental crust and oceanic crust. So it seems likely that such salt basin margins represent a normal response of a margin to neither being on the apex of upward welling cell (SDR-rich margin) nor the nadir of a downward convecting cell (hyper-extended crust), but somewhere in between.

An abrupt passive margin has thick continental crust rapidly thinning to oceanic crust over perhaps 50 km lateral distance, while a hyper-extended passive margin thinned continental crust extends over 200 km. These hyper extended margins are usually devoid of basaltic SDRs. Indeed beyond the hyperextended crust, the mantle is exhumed at sea bed. Exhuming and serpentenizing of the mantle has to occur below sea level and is therefore a version of a non-magmatic margin i.e. a rift segment that has been rapidly drawn below sea level and sits over downward convecting mantle cells. Such cells provide a lower heat flow to the base of the crust allowing extension in the lower crust to be expressed by elastic or ductile stretching. The corollary is that the more abrupt margins that are uplifted (+ve residuals), rich in magmatic

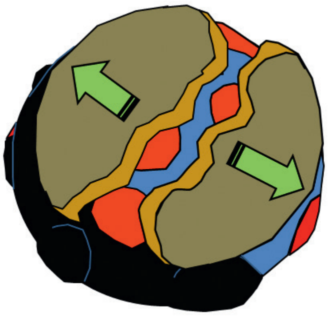

Figure 5 Sketch of plate-rifting over underlying residual fabric. Conjugate rift margins swiftly become asymmetric in their development.

SDRs, located above upwelling mantle cells have additional heat flow that prevents crustal stretching; they just burn through the crust abruptly. A simile for this might be that just as gently heating a glass plate with a burner allows it to be gently stretched, overheating it just melts through the glass creating an abrupt termination. We have seen examples of this type of behaviour elsewhere – high heat flow causing abrupt continental margins in the Indian ocean where 'normal' rifting has separated West India from Madagascar, then as West India subsequently drifted over the reunion hotspot the additional heat from the plume melted off a substantial part of the West Indian syn-rift to leave the Seychelles and the Mascarene Plateau behind.

The consideration of heat flow contribution from the mantle is worth noting. Currently heat flow in basin models used to predict hydrocarbon generation from the burial history of organic-rich rocks is (unless constrained by well data) assumed to correlate to an understanding of the radiogenic component of the underlying crust comprising a basin. Continental crust is assumed to have high heat flow owing to the high levels of Potassium and Uranium (etc), while oceanic crust is considered to have low heat flow owing to low levels of these lithophile elements that has been produced as a result of multiple large-scale melting events in the history of the mantle. While this is correct, recent drilling in deeper water off both the west and east coast of Africa is suggesting that heat flows of thinned continental crust and oceanic crust are more complex, and are picking up heat contributions from either 'hot-spot' lower mantle plumes or the upper mantle convection cells. We have been unable to confirm thermal signatures on oceanic crust as the data is either too sparse or dominated by thermal decay away from spreading centres. However, where oceanic crust has moved rapidly over the fabric of convection cells, the residuals appear to have a subtle elongation in the direction of movement. This may be an expression of the variable heating pattern imparted on the overlying crust creating thermal striping.

A last point to make is the nature of rifting on passive margins, in that underlying the rift at any time will be an irregular pattern of convecting cells such that it is very likely that one side of the rift will be being affected differently to the other (Figure 5). Only in unusual circumstances will each side of the rift be affected by the underlying convection cells equally. The implication is that not only relative uplift (or subsidence) can be heterogeneous across a rift, but also heat flow on the lower crust. The rule might be that most passive margins should not be identical to their conjugate partners, so differences between the early stage formation of conjugate basins should be no real surprise (Lentini et al., 2010). One might also expect in extreme cases hyper extension on one margin and abrupt termination to continental crust on the conjugate, although frankly the implications for the complex transition between these two margins has probably not been part of the interpreters tool to date. At Spectrum, we are constructing an atlas of continental-oceanic boundaries to examine this phenomena across conjugate margins.

Conclusion

The geologic history of passive margin basins can be related to the underlying mantle convection pattern, and the passage of continental margins over this fabric. If this is so, then the previous memes that consider the dominant forces on basin geology to be local and unconnected to adjacent or remote geologies are redundant.

Although first indications suggest that the present-day residual map of Hoggard et al. (2016), represents a good, first-pass, model for the mantle topology that interacted with continental plate margins back to the Jurassic period, it has not yet been proven that the mantle's convection cells are actually static and long lasting. Yet even if they are not, by testing the stability sequences of basins we have a tool to build paleo-residual maps of the mantle. While currently there is only darkness, with such a model we can explore the connectedness of basins, perhaps understanding basin processes in a new way. The work is not complete, yet its pursuit using the Hoggard et al. (2016), mantle convection map as a platform gives us hope of finding a unifying model into which each branch of geology — basin structure, sedimentology and hydrocarbon exploration — can be found to fit. It is still only a hope, yet that is all you need to start a revolution.

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