Earthworks

- global thinking in exploration geoscience

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Continental versus Oceanic: why is it a competition?

Introduction

An astronomer living on Mars might turn a modest telescope towards the planet Earth. With a little perseverance he or she might perceive, below the ever-changing cloud patterns, that the surface of the planet is divided in the ratio of about 1:3 between solid land areas and shiny, liquid-covered areas. The earthbound geologist, meanwhile, is well aware that describing all the many features of the earth's crust is a great deal more complicated than this. Why is it, then, that when earth scientists start trying to describe offshore geology they so aften revert to being Martian astronomers? Why has everything to be categorised rigidly as either 'oceanic' or 'continental'? Particularly along passive margins which have resulted from many years of rifting turning into crustal stretching and, eventually, growth of new ocean, is this really a useful approach?

The problem perhaps starts with the cross-sections of rift valleys often shown in geophysics text-books. These diagrams show, for example, a cross-section of an idealised rift and perhaps the gravity anomaly to be expected across it. Such a diagram may be accurate enough in itself but the reader (and perhaps even the author) may be misled into thinking that one cross-section describes a whole rift system, i.e. that the whole structure is perfectly two-dimensional or unchanging along strike. We only have to look at a map of the East Africa rift to see that this is not the case.

It is patently true that it takes only one 'weakest link' for a crustal plate to separate into two parts and that, as a result, a developing rift tends to become concentrated into a single, narrow topographic trough, often filled with a deep lake. But the deep lakes of Africa do not join up. It might, however, be instructive to imagine how this might happen in the future.

Take the example of Lakes Tanganyika and Malawi (Figure 1), each about 600 km long but separated by about 350 km and with an east-west offset of 250 km. Gravity and aeromagnetic coverage of the terrain between them (in Tanzania, Zambia, Malawi and DRC) shows major (sub-)parallel faulting across a NW-SE striking zone about 200 km in width. How might this develop into two passive margins?

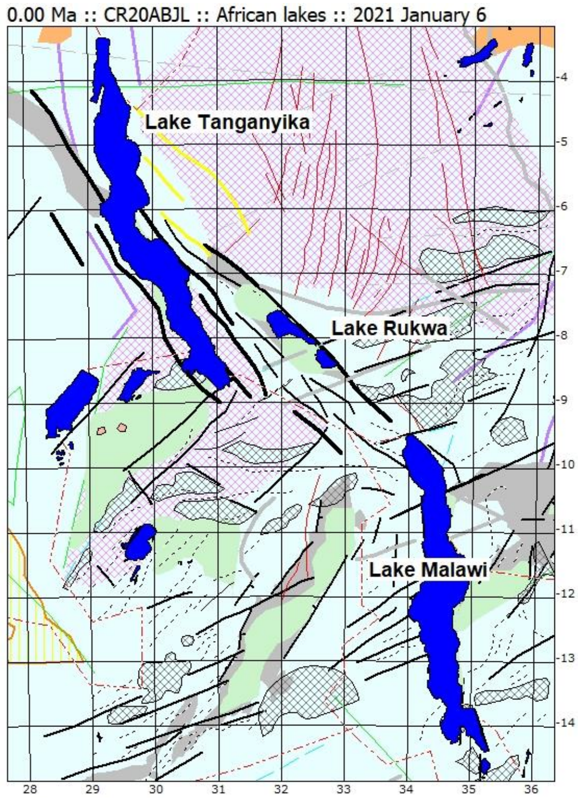

Figure 1. *Interpretation of aeromagnetic and gravity data around lakes Tanganyika and Malawi.*

Small continents

We may also look more regionally to the occurrence of what I call 'ambivalence' in the rifting process. For example, Madagascar is a substantial piece of unarguably continental crust that rifted off Africa while remaining part of East Gondwana. Later it became (and remains) part of the Africa plate after a second episode of rifting separated India from its east coast. Sri Lanka, another smallish but truly continental fragment, has a similar rifting history only with two rifting episodes much more closely related in time. It remained attached to Antarctica when India and Antarctica first started separating but later became fixed to India once a definitive, long-lived mid-ocean ridge was established between Sri Lanka and Antarctica. The Seychelles is an even smaller example of a piece of continental crust that has retained at least some of the properties of a full-sized continent, despite now being so remote from Africa and India. Were the East Africa rift system to develop fully into a new ocean, we can also imagine that the Tanzanian craton might form the bulk of a new small continent, several times the size of Madagascar, were both the east and west branches of the rift system both to remain viable candidates for lines of proto-ocean development. How might that play out between lakes Tanganyika and Malawi?

True continent, true ocean

Can we define rather more strictly what we think of as continental crust and ocean crust? Within Gondwana the continental areas are generally made up of Precambrian crystalline rocks, often overlain by younger (Proterozoic and Phanerozoic) continental sediments. Deep seismic soundings and global seismology indicate the moho to be at a depth of 35-40 km most often. MT studies suggest that some of the oldest (Archean) terranes (cratons) rest upon mantle material that has remained in place below them over time, extending in depth to 300-400 km.

By contrast, true oceanic crust is typically only about 8 km thick and lies beneath about 4 km of ocean water. This crust is made of basalt (including pillow lavas) and sheeted dykes emplaced close to the active mid-ocean ridge which acts as the source of magma that solidifies and moves away from the ridge in a 'double conveyor belt' as two plates progressively separate. Younger deposits above the basaltic layer are mostly pelagic sediments sourced from material within the ocean water column. Vast basalt outpouring, often subaerially, typify a number of significantly large oceanic plateaus, such as Kerguelen, associated with prolonged activity of plume heads in the mantle. Some areas of (deep) ocean floor also support an extensive area of sediment having its origin in the relatively small number of big rivers that drain the continents into deltas that can extend far out into the ocean basins. Considering that it occupies about 70% of the earth's surface, the geology of the oceans is remarkably simple, at least at a scale of 1:10 000 000.

Mid-ocean ridges

What is also remarkable is the self-replicating nature of mid-ocean ridges in terms of their geometry. Simple-mindedly, it might be expected that, over time, a mid-ocean ridge might simplify itself and become some sort of smooth curve down the middle of an ocean. In reality, the many right-angle bends where mature rift sections join ridge-offsetting transforms show remarkable longevity, the transform often leaving records of their history thousands of kilometres long, sometimes easily traceable from coast to coast across an entire ocean. Their origins can sometimes be attributed to pre-existing structural features in the continental crust, most obviously as accommodation zones in the original rift systems. In the rather simple ocean now developing between Australia and Antarctica (which is situated in the 'Euler tropics', about 90 degrees distant from the Euler interval pole that describes their relative motion and oriented nearly along a line of Euler longitude (great circle)) there are 13 clearly defined offsets in the ridge over a distance of 5373 km, thus with an average ridge length of 447 km between each transform. Repeating the calculation for the South Atlantic Ocean (also situated in the Euler tropics) gives 16 transforms in 5138 km for an average spacing of 342 km.

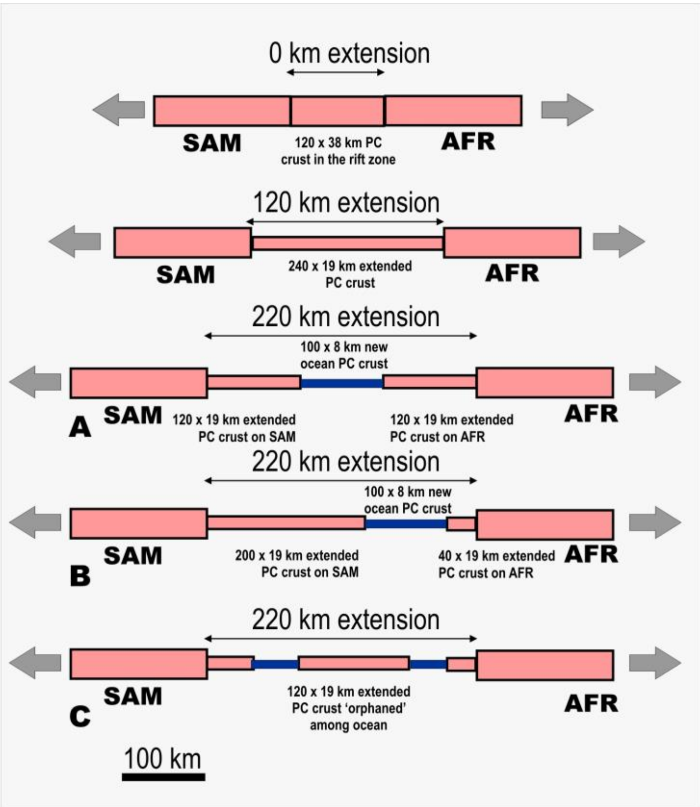

Figure 2. *Conceptual extension of continental crust as rifting turns to drifting. Initially a 120 km width of full-thickness Precambrian crust may be involved in rifting. This is reduced to half in thickness by 120 km of extension before the onset of ocean growth. The initial mid-ocean ridge may be (A) central or (B) off centre within the rifted zone. Two ridges may compete for a time leaving a fragment of stretched crust stranded in the ocean. 'Continental' crust may therefore be encountered (e.g. in an exploration well) hundreds of km offshore.*

The lakes Tanganyika and Malawi (each about 600 km in length) could then develop into simple mid-ocean ridge sections that would be fairly typical. At present, each lake has a significant number of accommodation zones, for example places where the rift is asymmetrical to the west joins the next section where it is asymmetrical to the east. So even a rift sufficiently well-defined to host a major, deep rift-lake still has to undergo significant simplification before the onset of ocean growth as evidenced in the deep oceans.

How much stretching?

Around most margins of the Gondwana continents there is a well-defined edge or shoulder to the outcropping or near-outcropping Precambrian rocks of the continental interior. If not seen in outcrop, this shoulder is usually clear in aeromagnetic survey coverage or offshore seismic surveys. These are the 'Precambrian' areas shown in pink in the various figures and animations produced here.

The separation between such conjugate shoulders that should be adopted in a Gondwana reconstruction is uncertain. For the South Atlantic Ocean, a separation of about 120 km (on average) gives a reassembly that is considered satisfactory to most authorities familiar with the offshore geology. This suggests that a ribbon of continental crust about 120 km wide was initially involved in the rifting process. An amount of extension of 120 km therefore would reduce this crust to half thickness (for a beta factor of 2.0). A beta factor of between 2 and 3 seems to be necessary before extension turns from rifting into the creation of new ocean (ref), by which time the original crustal ribbon would be 240 to 360 km in width. In Figure 2, the lower figure is adopted by way of an illustrative 'thought experiment'.

As with rifting, there is no guarantee that the process of ocean-growth onset is symmetrical or positioned centrally within the rifted zone. Figure 2 shows three representative cases. In case A, the successful mid-ocean ridge is indeed central, in case B it is much closer to one margin than the other while in case C there is some 'ambivalence' with two mid-ocean ridges initially competing. This might easily be the case along sections of margin where, as between Lakes Malawi and Tanganyika, the main locus of the rift is only defined late in the separation process.

It follows that the edge of *stretched* continental crust can be quite close inshore (e.g. the east coast of Madagascar), more than 200 km offshore or even that isolated fragments of undeniably 'continental' material occur even further offshore if 'ambivalence' is prolonged.

Not real continent!

What seems too often to confuse understanding of this basically simple situation is the binary argument (continental vs oceanic) introduced at the start of this piece. A single encounter of Precambrian material in an offshore well or a dredge sample, for example, is often taken as sufficient evidence that the location is 'continental' - with all that that implies. Is it full-thickness continental crust? Certainly not. Is the lithology typical of Precambrian rocks seen onshore? Quite likely. But, after the processes of crustal extension have run their course, listric faulting will have probably reduced such fragments to thin slivers surrounded by material of origin among much magmatic material and elevated mantle. With so much extension, the original 120 km width of original true continent can be spread over a large area - but often as only relatively tiny and isolated fragments.

The term 'continent-ocean boundary' (COB) has also passed into common usage to describe the oceanward edge of stretched continental crust. And such boundaries get drawn way offshore to include such tiny fragments as case C in Figure 2. And seismic data that indicate that the crust is thicker than the 8km typical of true oceanic crust also often invokes the term 'continental' for such anomalous areas.

More useful is the term 'transition zone' which implies not one but two boundaries: (1) the edge of the full thickness Precambrian crust, most often but not always inshore from the coastline and (2) the inboard edge of true oceanic crust produced by a mid-ocean ridge. At any given location the width of this transition zone can vary within a wide range. It should not come as a surprise that Precambrian material is encountered far offshore or even in fragments isolated far out in the ocean. This is simply a consequence of the complexity of the transition zone and its evolution.

The well-defined 'gravity margins' evident around the Gondwana continents discussed elsewhere (Research Update No XX) fall generally outboard of the outcrop 'shoulder' and have been used to assist satisfactory fits of the continents with a separation of about 50 km. This is consistent with the arguments presented here, though the precise origin of the gravity anomalies remains uncertain.

When rifts don't join up (at first)

Let us look in more detail at some of the processes at work during crustal extension. Two well-defined rifts, offset by an accommodation zone (pre-transform) that evolves into a transform to give the typical pattern of mid-ocean ridges may be the simplest – and perhaps not even the most common - way a rift turns into a mid-ocean ridge. Rifts are often symmetric half-grabens. In one section the main fault may be on the east side of a north-south rift, in the next on the west. Or two such sections may be separated by a third that is more or less symmetrical (Figure 3). As rifting progresses, the dominant fault to the east might propagate south into the central section while that to the west propagates to the north. If this situation persists, the central part of the middle rift section may undergo a counter-clockwise rotation. Should this occur towards the end of the transition from rifting to drifting (i.e. at the onset of true ocean crust formation) the rotated fragment is particularly prone to becoming isolated from one or both of its parent continental fragments; the stage is et for the type of 'ambivalence' discussed earlier.

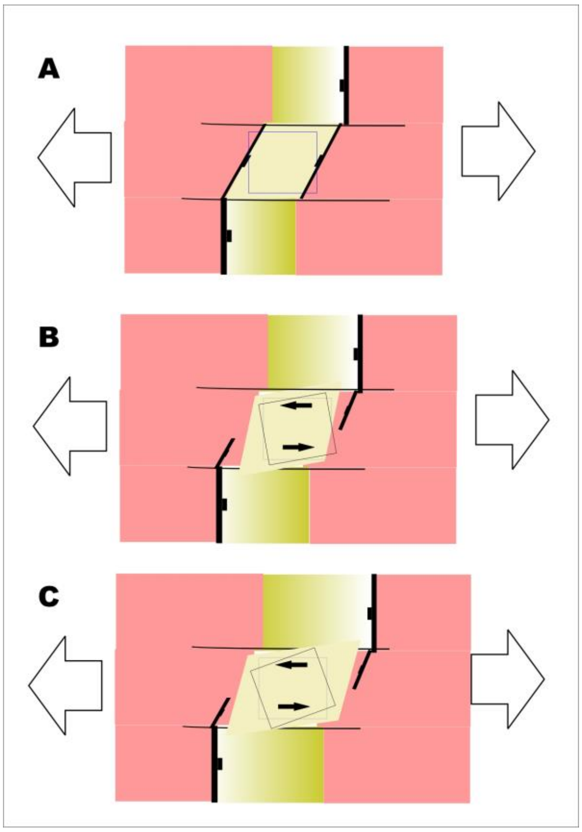

Figure 3. *A section of rift valley with an offset undergoing extension. The northern part has its main fault to the east and the southern part to the west. As these two faults penetrate further into the central part, there is a tendency for the central part of the rift floor to rotate.*

We can also envisage such a situation occurring on a relatively mature mid-ocean ridge when well-separated ridge sections have their origins some distance apart in global terms. The result may be a competition for dominance between the two established ridges in the region separating them. The result can be a section of (ocean) crust that changes allegiance from one plate to another as time moves along. There are several examples of this. We interpret this to have happened repeatedly with the Sao Paulo Plateau, and the two parts (east and west) of the Rio Grande Rise. Some or all of these (predominantly volcanic) features may well contain isolated fragments of continental material having origins in the original rifted zone prior to the initial mid-ocean ridge formation.

We can draw a parallel here with the situation between lakes Tanganyika and Malawi where the offset between them follows the trend of the Paleoproteroic Ubendian belt. In the same way, the main offset in the South Atlantic mid-ocean ridge follows the grain of the Neoproterzoic Ribeira belt in coastal Brazil. How we see this process unfolding is described in the following section.

What happened in the central section of the South Atlantic Ocean

The global geometry of the first 50 myr of South Atlantic opening is quite simple. The relative positions of South America and Africa at anomaly C34 time (83.64 Ma) is well-established and the alignment of the earlier transform traces recorded in ocean-floor topography through the Cretaceous Quiet Zone (KQZ) is quite clear. An Euler interval pole located at 36.7 deg N, 26.2 deg W (Africa coordinates) brings the north coast of Brazil against the coast of West Africa while leaving an embryo South Atlantic that tapers from 1000 km width immediately N of the FAFZ to 120 km off Gabon. Our pole to close this wedge-shaped gap is at 9.4 deg N, 4.6 deg E. In the present model we have the pole change timed at 117 Ma (though it is planned to make this several myr younger to conform with the 2020 GTS). At the latitude of Sao Paulo, the change in spreading direction at this time is quite substantial (about 25 degrees, WNW-SSE becoming E-W approximately) and can be expected to have had considerable effect on the stretched conjugate margins that still had not fully separated. North of Sao Paulo the salt basin had only just started to disrupt.

We see the well-established southern ridge propagating north from the Bouvet plume head close to the Brazil margin, separating the small 'continental' fragment (and its volcanic load) that is now the San Paulo Plateau (SPP) from the mainland. At the same time, the emerging northern ridge splitting the salt basin started to penetrate southwards between the SPP and Angola. By about 100 Ma, the more westerly of these two ridges became defunct. By this time the SPP had made a counter-clockwise rotation of about 90 degrees and was situated in its present-day position, about 500 km offshore, with a mid-Atlantic ridge that was to be long-lived lying immediately to its east.

Following this event, we see the two parts of the Rio Grande Rise lying astride the active mid-ocean ridge to the south of the SPP, much the way Iceland presently straddles the mid-Atlantic Ridge. These two fragments would, in turn, undergo a similar counter-clockwise rotation, first RGR-W, then RGR-E, as the active ridge moved to the east, not as two single ridge jumps but as opposing ridges caused rotation of the 'ambivalent' fragment separating them. The while process may be followed in the animation. XXXXXXXXX

The cause of the jumps, we suggest, is tha,t once the mid-Atlantic ridge became self-sustaining (e.g. about 117 Ma), its location drifted slightly westward of the Tristan plume head in our fixed hotspot reference frame. In the vicinity of the plume particularly there was a propensityy for a new ridge to form further to the east of the active ridge. This happened progressively with the consequent rotation of all three offshore fragments.

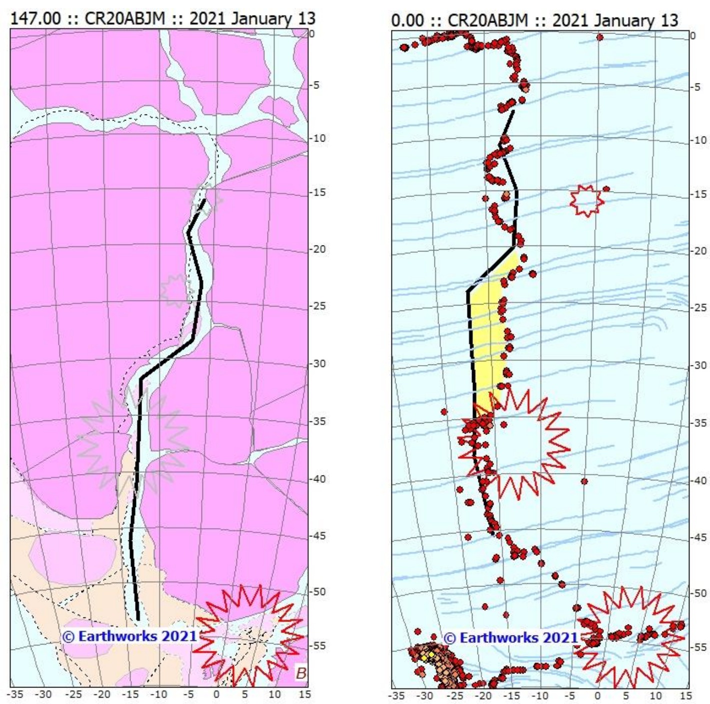

Figure 4. *(a) Idealised median line between continents Africa and South America at 'fit' position. (b) Same median line at half the subsequent rotation of South America, i.e. theoretical mid-ocean ridge position, showing the area between latitudes -20 and -35 degrees where the ridge has jumped eastwards by about 330 km. Not that this also about the amount by which the mid-ocean ridge has moved with respect to the fixed Tristan plume head.*

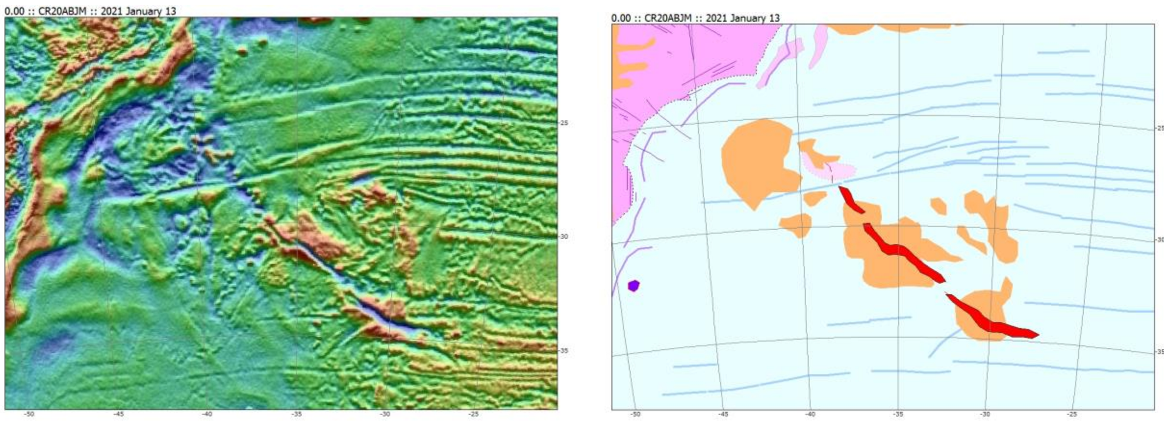

Figure 5. *(a) Ocean floor topography, Rio Grande Rise (courtesy of Geognostics). (b) Interpretation of (a). Pink = Precambrian areas; blue = transforms; orange = volcanic plateaus; red = extinct rift valley in Rio Grande Rise.*

Figure 4(a) shows a somewhat stylised location of the initial rift between South America and Africa. When this is drawn on the fragment we call the South Atlantic mid-ocean ridge (which undergoes exactly half the Euler rotation experienced by South America against Africa) and move to the present day situation (Figure 4(b) we see our initial ridge directly in comparison with present-day seismicity on the MOR. The yellow-shaded area shows an area equivalent to the fragments that have been progressively 'jumped over'.

Figure 5 shows the ocean-floor topography in the vicinity of the Rio Grande Rise (a) and its interpretation (b), including the trace of the failed rift which we interpret. Figure 6, finally, shows the position of this failed rift in relation to the initial (pre-rift) orientation of South America and Africa, according to our model.

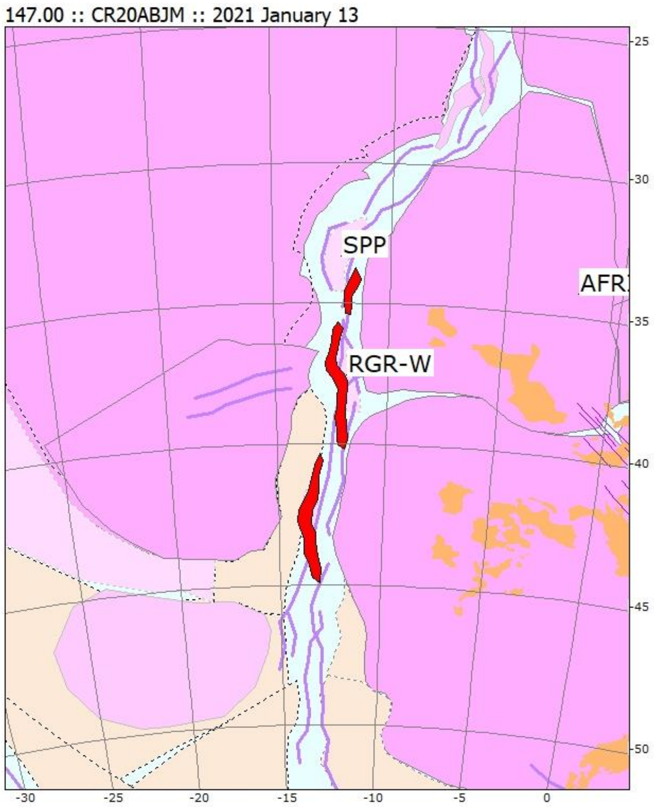

Figure 6. *The failed rift on the Rio Grande Rise in its Gondwana reassembly position (Model CR20ABJM).*

Conclusions

To conclude, we support the idea that the Walvis Ride is the trail of the Tristan mantle plume but consider that the same notion is too simplistic to explain the Sao Paulo Plateau and the Rio Grande Rise. Instead, we advocate that the two parts of the Rio Grande Rise existed as a time as the active mid-ocean ridge between Africa and South America and rode the ridge in an Iceland-like fashion until a new active ridge started to the east of it, penetrating southwards and causing the old, dying ridge to rotate through about 90 degree before being abandoned completely on the south America side of the active ridge. In this, the two Rio grande fragment followed the pattern already followed by the Sao Paulo plateau, following the marked change in spreading direction during Aptian time. All three fragments are likely to contain fragments of extended continental material amongst the volcanic matter that undoubtedly forms their bulk. This may be attributed to their prolonged existence within the extensional zone between two major continental plates. This does NOT imply that we should describe them as ‘continental fragments’ in their own right. We do, however, advocate that they had an existence as micro-plates that brought them to their present localities distant from the margin of South America.

Colin Reeves

Delft, 2021 January 13