Solid Earth Discuss., 5, C103–C117, 2013
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Solid Earth Discussions

Interactive comment on "Kinematics of the South Atlantic rift" *by* C. Heine et al.

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Received and published: 30 April 2013

Response to comments Reviewer 1 (Anonymous)

We partly do agree with the comments regarding the style of the publication and would appreciate if Copernicus/EGU would provide a platform (or a system) to allow authors to link associated files to the publication in a more interactive way.

1. "... because very little of the background data for derivations of the quantitative restorations are shown"

   We have improved the paper and now provide more background information and data.

2. “The figures in this paper would really benefit from being made available in an environment like Google Earth”

We are making the individual figures available as vector based PDF maps on the DataHub site (see revised manuscript). Due to Google Earth not being able to place figures in geological time at reconstructed positions we see limited use in doing this. Only our Figs. 4 and 7 are at present day but cannot be easily transferred to Google Earth for reasons of projection. We will make data associated with the model available for download and visualisation in GPlates.

3. “another global capitalization typo: Pre-salt should be pre-salt like pre-breakup.”

Fixed.

4. *“P47:26 to p48 - [...]. A first comment is that the methodology used needs a lot more clarification.[...] The technique is fine, but what is lacking here is any discussion of how their 10 cross sections (Fig. 3) were used to constrain the restorations along the entire 14,000 km or so of the South Atlantic margins. The 10 cross sections are not located on a map, they are simply denoted by general area.[...] There are two that may be from the same area, one in the Kwanza Basin and another labeled as ‘GS Grid South”*

We apologize, the restored lengths of these sections are (and were) actually included in the reconstructions as thick magenta-colored lines (see Figs. 12, 15–20 in our discussion paper). The actual locations of the lines, apart from the two cross sections based on the gridded CongoSPAN data, were taken from Blaich et al. (2011) as explicitly mentioned in the manuscript. We have now included the cross section locations in an inset location maps in Fig. 3 in order to not add more information to Figs.1, 4 & 7. Furthermore, we are making the data files of the profiles available as GMT compatible files.

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Both CS Grid Central and South were "synthetic" crustal scale cross sections generated from gridded horizon interpretations using the CongoSPAN data set. The *Central* section is located in the Cabinda basin segment, whereas the *South* section is located in the southern Kwanza Basin. These *do not* conform to actual line locations but are arbitrary lines sampling gridded representations of Moho, Basement and seabed horions.

The restored sections were used to constrain our fit reconstruction. We have also added a methodology section to explain how we have constructed our plate model and at which point which data was used.

5. *"Although these would seem to be the same geographic area, the cross sections are very different. I would also expect the Kwanza section to look similar to the section in Unternehr et al. (2011), but it is very different. The Unternehr section has a large landward-facing scarp near the LaLOC, whereas the one in Fig. 3 has a large seaward-facing scarp near the middle of the line. Unternehr also postulates mantle exhumation, not shown in Fig. 3. Why the difference? "*

The assumption that "one in the Kwanza basin and another labeled as CS Grid South" are in the same geographic area is not correct and due to our mistake of not indicating the location. Section *CS Grid South* is in fact located in the southern Kwanza Basin. Section *CS Grid Central* is located in the Cabinda basin and hence one can expect it to look different to the one published by Unternehr et al. (2010). We have interpreted exhumed mantle in both of the CS sections presented. However, no exhumed mantle is interpreted in the sections of Blaich et al. (2011, "Kwanza" labelled section).

6. *"[...] it would seem that only 10 sections for the entire South Atlantic is very inadequate. More explanation and location of sections is very much needed. Some sections are restored to 36 km Moho depth, oth-*

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ers to 32 km, with no explanation for the difference."

The crustal thickness estimates were based on CRUST2 estimates for the onshore. This has been amended in the manuscript accordingly.

We would love to include more crustal scale cross sections covering more than the odd 4 margin segments of the 14000 km but unfortunately we are not aware of many more useful, georeferencable, crustal scale seismic data being available in the public domain for other parts of the conjugate South (and Equatorial) Atlantic margins.

We believe that covering 4 conjugate margin segments with restored crustal scale profiles represents a significant advancement compared to *all previously published* plate models in the South Atlantic – which incorporate *none* for their fit reconstructions and also do not contain estimates on margin extension.

7. *"A glaring omission is a cross section across the Santos Basin. The LaLOC in this area is more than 500 km from the coast (800 km if measured along the rifting direction, see Fig. 11), so restoration of extension here is key to fully understanding the South Atlantic.Some discussion of how this area was handled is essential."*

Yes, indeed. If the reviewer could provide us with a depth-converted, georeferenced, crustal scale cross section we would very much like to include it in our model. Unfortunately, there are no published cross sections at this scale available, which would allow us to construct a cross section which captures both extensional phases affecting this basin. The sections published by Zalán et al. (2011) or Gomes et al. (2009) cannot be located properly and are hence relatively useless in this context, whereas sections published by Scotchman et al. (2010) are in time and not in depth and sections by Contreras et al. (2010); Moulin et al. (2012) are not crustal scale and not oriented correctly with regard to our proposed opening direction.

On the point that the restoration of the Santos basin is a key to fully understand the plate tectonic evolution of the South Atlantic we have a different opinion to the reviewer. In our model a rigidly behaving South America with no intraplate deformation in the Parana Basin region will not have any major influence on the approximated plate motions in the Santos basin area, as we are fitting the southermost part of our rigid South America relative to Africa. While having more crustal scale data available here would certainly allow to better address many questions related to the formation of the Sao Paulo High, the influence of the Parana Hotspot on basin evolution and the kinematic evolution of the Santos basin itself. However, we are confident that our plate model robustly describes the kinematic framework of this basin.

8. *"The authors do assure us (p48:28) that their interpretation for the Brazilian margin matches that of Chang et al. (1992), but no visual confirmation is presented.[...] The Chang paper was also written before recognition of mantle exhumation processes, so this needs to be taken into account"*

A line representing Chang et al. (1992)'s restored COB is included in a revised set of plate reconstructions. Where possible, we have added regions of interpreted exhumed mantle in the reconstructions, cf. Fig. 20 in the outboard Santos basin features Zalán et al. (2011)'s interpretation of crustal types (compare LaLOC position vs. extent of extended continental crust). However, this goes back to the previous 2 points that there is no properly georeference-able crustal scale cross section for the Santos basin available.

9. *"Sections are shown for Pelotas, Walvis, Orange and Colorado, all of which cross volcanic margins with SDRs. How was the extent of continental crust across these margins determined?"*

As outlined in the text, the crustal scale cross sections are those of Blaich et al.

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(2011) including their interpretations of crustal type distribution. Here, our minimum, COB and maximum estimates are representing possible different interpretations of the extent of continental crust. The COB is that of Blaich et al. (2011), the “minimum” is the boundary inboard of the SDRs, the maximum/LaLOC is that outboard of the SDRs as interpreted by Blaich et al. (2011). We used various gravity derivatives and magnetic data sets (both proprietary and public) beyond available (propreitary and published) seismic data to construct the extent of the continental crust and our LaLOC. We follow previous authors in assigning the certain extent of the continental crust to proximal edge of the “G magnetic anomaly” and the large magnetic anomaly, and transitional crust inbetween there and the LaLOC.

10. *“On the reconstructions, Fig. 17 onward, the LaLOC is sometimes inboard of the SDRs, some- times within and sometimes outboard. Explanation needed.”*

We changed this in the revised version of the manuscript. The LaLOC is following the outermost expression of the seaward dipping reflector sequences as mapped by various earlier authors (Bauer et al., 2000; Stewart et al., 2000; Gladczenko et al., 1998; Sibuet et al., 1984). However, Reviewer 1 raises a valid question in the sense that the definition of extended continental crust (relevant to the plate kinematic modelling) and the onset of normal oceanic crust generated through seafloor spreading is difficult. Earlier works show different interpretations of a COB or the extent of extended continental crust along the Namibian volcanic margin.

Our revised model uses the following setup: our LaLOC traces the outer limit of the SDR sequences as presented by Bauer et al. (2000) for the Namibian margin and an envelope of the outer SDR sequences interpreted and generously provided by reviewer Dieter Franke (pers. comm.) for the Argentine Atlantic margins as well as the definition of SDRs for the Pelotas and Brazilian margin as presented in Bauer et al. (2000). The extended continental crust (present day) follows Gladczenko et al. (1998) along the Namibian Atlantic margin and a synthesis.

11. *"A final point about margin extension: the LaLOC is only shown on reconstructitons with oceanic crust. It should also be shown on older reconstructions as lines on each plate that track the authors' estimates of evolving extension on the conjugate margins."*

As the LaLOC stands for the "Landward limit of the oceanic crust" it would not be correct to show this boundary *before* oceanic crust is actually emplaced. While we agree on that such an overlap estimate would be interesting to show, it would also clutter the existing reconstructions. We cater to the idea of Reviewer 1 by releasing our continental outlines in a format which can be imported into GPlates or other reconstruction software so that anyone wishing to interrogate our model can do so with ease. In addition, Fig. 13 shows the amount of overlap at fit reconstruction time.

12. *"A general point about the references in this paper: This section 2.3 (p47:26) starts by referencing 13 papers that have apparently presented crustal-scale cross sections. [...] This results in many references that are simply there to acknowledge existence of the paper, which helps explain why there are nearly 200 total references in the bibliography. "*

We wrote in the paper "Where possible, we made use of these data to redefine the location of the continent-ocean boundary". So albeit each of these papers might only have contributed only a single data point in the construction of our COB/LaLOC, we have still used these papers hence we believe it is only fair to cite the appropriate publication this has been sourced from. We have re-phrased this sentence to "We made use of these..." to clarify this, but we've also tried to cut down a few references where possible.

13. *"What does 'M7 has been identified on both conjugate abyssal plains closed to the COB' mean? I don't quite see why, if M7 is identified on both sides, M4n is used as the oldest isochron. What has breakup-related volcanism got to do with it? If these chrons are on the abyssal plain, would there necessarily be associated volcanism? Also, another confusion – LaLOC is used earlier, now we're back to COB?"*

We have changed this portion of the text accordingly and updated the plate model to include anomaly M7.

14. *"P50:1 – this introduction to non-rigid continental plates is clumsily written. [...]"*

We like the suggestion and have implemented the new paragraph in the revised manuscript.

15. *"P50:18 – Africa. Again, far too many references. Do you really need 13, all the way back to 1974, to refer to WARS/East Niger?"*

Where possible we have cut down on the amount of references.

16. *"A more technical description is called for, describing what these authors saw to make you want to put in a plate boundary here. This same critique applies to the rest of this Africa section – a long list of references in each sub-section but very little to show why all the sub-plates are needed in the model. It is not the reader's job to burrow through, in the case of CARS (p51:4-6), 8 references to find out what persuaded the authors to include CARS."*

We agree that it is not the reader's job to do this, which is why we have included a whole section (3.1.1 Central African Rift System) to elucidate how these authors

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have convinced us to include the Central African Rift (or all the other deforming regions). The paper already presents a very extensive review of the tectonic structures which relate spatio-temporarily to the opening of the South Atlantic rift. We don't think it is necessary to provide excruciating detail why we have, for example, used Genik (1992)'s rift bounding faults from the Central African rift to delineate our deforming region. Instead we prefer to utilise the space for a description of our kinematic model and reconstructions.

The subplates are needed because sedimentary basins and rift structures document relative motions between otherwise relatively coherent and rigid tectonic plates. Figs. 1 and 4 show mapped rift structures active in the Late Jurassic/Early Cretaceous and total sediment thickness. We have listed the references in our *review* of the African intraplate extensional structures. The references *show* very well our reasoning why we have subdivided the Cretaceous African plate, hence we do not think that it is necessary to present more data from these publications on which we have based our decision to subdivide Africa into more plates.

17. *"'Mercator projections are pretty obscure and without specifying the projection parameters used (pole, spheroid, datum), border on the useless. Why were these projections used?"'*

Simply because this projection maximises the space for the corresponding regions of interest for the sake of improving readability of the maps. Other projections, like Mercator, would decrease the "signal to noise" ratio in those images, including areas which are not of interest to the study region. We have added the projection parameters in the figure description and now provide the maps as separate PDFs in the online archive.

18. *"Paragraph starting on p52:26 – The original interpre- tations of strike slip in the Doba-Dosea-Salamat basins have been questioned, see http://www.searchanddiscovery.com/documents/abstracts/*

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2004hedberg_baku/extended/reynolds/reynolds.htm. I think this interpretation of less strike slip actually fits better with the interpretations in this paper (see Fig. 5) but do raise other issues as discussed below."

While the abstract of that contribution is certainly promising, we have no detailed information about this publication. We agree that based on the statements made in this abstract, the interpretations do indeed agree with our proposed model.

19. *"The Borogop fault is not shown on Fig. 4, the Africa base map, but does appear in the reconstructions starting with fig.12. The Central African Shear Zone is not shown on any map yet is apparently an important province boundary"*

We have included these fault zones in the appropriate figures.

20. *"P53:16 – With published estimates of extension ranging from 15 to 56 km in the Muglad basin, a summary of reasoning for the choice of 35 km is needed, otherwise it just seems like an arbitrary choice."*

35 km represented a single value. We are now giving a range of values corresponding for the smallest and largest amount of extension as predicted by our plate model. These values range between 30 and 60 km and match published estimates of 30 and 56 km for the basins at different locations. Further, we have now included a section on how we have arrived at our estimates.

21. *"P53:19 to 21 – Reeves et al. (1987) did not observe 'subsurface reverse faulting of Early Cretaceous age'. They observed isolated outcrops of Jurassic or possibly Triassic rocks co-located with a linear positive gravity anomaly."*

Reviewer 1 is correct. We have altered the stage pole for the NEA-SAf plate pair – see response below.

22. *"At the far west end of the NEA-SAF boundary in the Bongor Basin at 11N, 15E extension calculated from the pole in Table 1 is 57 km. This would seem too much extension as the basin itself is only about 80 km wide (Fig. 5).[...] At the far east end of the NEA-SAF boundary in the Lamu Basin at 1S, 42E (east of the Anza compression mentioned above and off Fig. 5) implied compression is 44 km. This too would seem to be far too much deformation, especially compression in an area where only extension is reported in the literature. Clearly this choice of rotation pole needs some more justification."*

We thank Reviewer 1 for pointing this out. We have subsequently adjusted the stage rotation pole for our plate pair NEA-SAf to be located south of the Lamu Embayment in the Somali Basin, implying extension for the Anza Trough region in line with the Muglad and Melut basins (see revised manuscript).

However, to clarify some of the extension amounts: The extension in the western CARS is distributed between the northern boundary of Southern Africa in the Doba Basin and the Bongor basin, an area approximately 300 km wide at present day. The actual implemented extension in the Bongor basin alone (between our Bongor Block and NE Africa) amounts to about 25 km over 40 Myrs which we believe to be a reasonable estimate. In our new model we have implemented about 65 km of extension between the northern margin of SAf and the SW margin of NE Africa, distributed over a present-day length of 300 km and two main depositional axes (Bongor and Doba Basins).

The amount of compression in the Anza Basin was approximately 15 km and not 44km. In our revised model this is now changed to approximately 7 km extension in the central Anza Trough.

23. *"Discussion on extension in the Termit region. The chosen extension amount of 70 km in the Termit Graben would seem to be too much. The basin itself is only about 200 km wide (Genik Fig. 6), implying 54%*

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extension. [...] Make sure that the section was correctly converted to depth for the extension calculation. Show the calculation in a style similar to Fig. 3 in any case."

We are aware of the scale in Genik's figure. However, we have removed this paragraph as there is too limited information on crustal structure given. Instead we have added a new section on using sediment thickness data to infer total extension.

24. *"P56:18 in, not until"*

The sentence in question is "The present-day South American continent is composed of a set of Archean and Proterozoic cores which were assembled until the early Paleozoic, ...", which we think is correct as the bulk of the South American continent was assembled *until* the Paleozoic and not *in* the Paleozoic.

25. *"There is a disconnect between Figs. 1 and 7. There are several basins shown on Fig.1 but not on Fig.7,"*

Fig. 1 shows *rift structures* as defined by rift-bounding normal faults, whereas Figs 4 and 7 show *sedimentary basin outlines*. Please compare the captions for Figs. 1, 4 and 7. We have changed the phrase "rift basins" to "rift structures" to better clarify this distinction.

26. *"Leb changes symbol to Lev and MaN changes to NF. This region is pretty complicated but having different interpretations of basin geometry and names in the same paper doesn't help."*

This goes back to the rift structures vs. sedimentary basin definition. We have replaced "Leb" (Leboulaye Rift) with "Lev" (General Levalle).

27. *"For instance, in the Colorado Basin (p61:9) a value of 80 km is used, nearly double the value of 45 km given by Pangaro and Ramos (2012)*

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referenced in the previous sentence. Why? More justification for values chosen is needed."

We apologise again here, as this value was a typo resulting from an earlier iteration on the plate kinematic model. The actual extension we model in the Colorado Basin between 150 and 120 Ma is between 50 km in the eastern part and about 20 km in the western most part. This is perfectly conforming to the reported value of 45 km of Pángaro and Ramos (2012). We have changed the text accordingly.

28. *"There are some points that should be explained, such as the geometry of the salt basins when salt was deposited."*

Our main purpose of this paper is to present a coherent kinematic framework for the South Atlantic rift. While we agree that an attempt at reconstructing the salt basin geometry would be useful, we have little to no data beyond the salt basin outline which could be added to provide better constraints on the geometry and timing of the salt basin.

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