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Asymmetric continental deformation during South Atlantic rifting along southern Brazil and Namibia

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Abstract

Plate restoration of South America and Africa to their pre-breakup position faces the problem of gaps and overlaps between the continents, an issue commonly solved with implementing intra-plate deformation zones within South America. One of these zones is often positioned at the latitude of SE/S Brazil. However, geological evidence for the existence of a distinct zone in this region is lacking, which is why it remains controversial and is not included in all modeling studies. In order to solve this problem we present a study of multiple geological aspects of both parts of the margin, SE/S Brazil and its conjugate part NW Namibia at the time of continental breakup. Our study highlights pronounced differences between these regions with respect to Paraná-Etendeka lava distribution, magmatic dyke emplacement, basement reactivation, and fault patterns. In Namibia, faults and dykes reactivated the rift-parallel Neoproterozoic basement structure, whereas such reactivation was scarce in SE/S Brazil. Instead, most dykes, accompanied by small-scale grabens, are oriented margin-perpendicular along the margin from northern Uruguay to São Paulo. We propose that these differences are rooted in large-scale plate movement and suggest a clockwise rotation of southern South America away from a stable northern South America and Africa, in a similar way as proposed by others for a Patagonian continental section just prior to South Atlantic rifting. This rotation would produce margin-parallel extension in SE/S Brazil forming margin-perpendicular pathways for lava extrusion and leading to the asymmetric distribution of the Paraná-Etendeka lavas. NW Namibia instead remained relatively stable and was only influenced by extension due to rifting, hot spot activity, and mantle upwelling. Our study argues for significant margin-parallel extension in SE/S Brazil, however not confined to a single distinct deformation zone, but distributed across ~1000 km along the margin.

Keywords

South Atlantic opening; Gondwana breakup; Paraná-Etendeka Large Igneous Province; intracontinental deformation; South America; Africa

1. Introduction

The separation of Africa and South America occurred during the breakup of Pangea, and more specifically the breakup of Gondwana. Dissection started with the opening of the Central Atlantic, i.e. along NW Africa and North America, in the Lower Jurassic followed by the opening of the Indian Ocean between Africa, Madagascar, India and Antarctica in the Upper Jurassic (Veevers, 2004, and references therein). The South Atlantic opened with rifting to the north of the Falkland Plateau at the beginning of the Cretaceous and seafloor spreading started during the Valanginian or Hauterivian (e.g., Eagles, 2007; Moulin et al., 2010; Rabinowitz and LaBresque, 1979; Torsvik et al., 2009). The Falkland Plateau was sheared off from the southern tip of Africa along a strike-slip fracture zone. Rifting and spreading continuously migrated to the north with South America describing a clockwise rotation away from Africa. At the present latitude of Cameroon, the South Atlantic migrated to the west where it connected with the Central Atlantic. This process left the Benue Trough aulacogen in Central and West Africa (e.g., Burke and Dewey, 1974; Unternehr et al., 1988). Complete separation of South America and Africa is assigned to the Albian (e.g., Eagles, 2007; Moulin et al., 2010; Torsvik et al., 2009; Veevers, 2004). Whether rifting and breakup occurred in response to large-scale plate movements or to regional mantle plume activity is subject to ongoing discussions (e.g., Beniest et al., 2017; Franke, 2013).

Kinematic plate reconstruction models have demonstrated that South America and Africa do not fit perfectly when the continents are restored to their pre-breakup position, a misfit that is generally solved by considering intra-plate deformation within South America. Indeed, intra-continental deformation shortly before or during South Atlantic rifting is by now well-known from the Patagonian region, documented for example in the formation of the Salado, Colorado, and San Jorge basins, all of which run perpendicular to the South American continental margin (Autin et al., 2013,; Fitzgerald et al., 1990; Koopmann et al., 2013; Macdonald et al., 2003). An according N-S rifting phase before the Atlantic opening has been included in some models (Heine et al., 2013). Another margin-perpendicular zone of intra-plate shearing is often positioned at the latitude of SE/S Brazil (e.g., Eagles, 2007; Jacques, 2003; Moulin et al., 2010;

Torsvik et al., 2009; Unternehr et al., 1988) and variously named "Lineament in southern Brazil", "Paraná-Etendeka Fracture Zone", or "Paraná-Chacos Deformation Zone". However, there is a lack of geological evidence for the existence of this zone, and thus not all plate reconstruction models do incorporate this zone (Heine et al., 2013).

Nevertheless, over the last two to three decades numerous studies have been published on geological aspects at the time of continental breakup. A synthesis of these different studies pictures an asymmetric continental syn-rift evolution of SE/S Brazil and its conjugate part across the Atlantic, NW Namibia. Based on a review of previous work we propose a break-up scenario for the South Atlantic.

2. Geological Setting

The basement geology of SE/S Brazil and NW Namibia is controlled by the Rio de la Plata, Congo, and Kalahari cratons which collided during the amalgamation of Gondwana, forming the low-to high-grade metamorphic Dom Feliciano, Kaoko, and Damara mobile belts (e.g., Foster et al., 2009; Goscombe et al., 2005; Oyhantçabal et al., 2011). The Dom Feliciano Belt in SE/S Brazil and the Kaoko belt as its counterpart in NW Namibia (e.g., Konopásek et al., 2016) run sub-parallel to the present-day continental margin, whereas the Damara Belt situated south of the Kaoko Belt is oriented perpendicular to the margin.

Basement rocks are overlain by the intra-continental Karoo/Paraná sedimentary rocks of Carboniferous to Jurassic age (e.g., de Wit et al., 1988; Smith et al., 1993). Their thickness increases from Namibia towards the west into Brazil, where they fill the large Paraná basin, which spans across ~1,400,000 km² (Zalán et al., 1990). The aeolian Botucatu (Brazil) /

Twyfelfontein (Namibia) sandstone of Lower Cretaceous age (Perea et al., 2009; Scherer, 2000) superposes the Karoo/Paraná rocks and inter-fingers with the volcanic rocks of the Paraná-Etendeka Large Igneous Province (Jerram et al., 1999). The latter derived from the Tristan da Cunha hotspot that is now located in the central South Atlantic. The Paraná-Etendeka volcanic rocks erupted within 1 Myr at ~135 Ma (Renne et al., 1992; Baksi, 2017) and have been emplaced shortly before (Stica et al., 2014) or during the onset of South Atlantic rifting at this latitude (e.g., Beglinger et al., 2012, O'Connor and Jokat, 2015; Salomon et al., 2016).

3. Margin Differences

The evolution of the NW Namibian and SE/S Brazilian conjugate South Atlantic rift margins shows remarkable differences in terms of margin morphology, basement inheritance on younger faulting, magmatic dyke and flood basalt emplacement, and stress evolution.

The South Atlantic rift follows the trend of the Neoproterozoic Kaoko and Dom Feliciano Belts (**Figs. 1, 2**; Oyhantçabal et al., 2011). Significant reactivation of Kaoko Belt shear zones occurred during South Atlantic opening, but similar reactivation for Dom Feliciano shear zones is lacking (Salomon et al., 2015a). Instead, the majority of faults in cover rocks in Brazil run oblique to shear zones in the Dom Feliciano Belt, while they are mostly shear zone parallel in the Kaoko Belt (Salomon et al., 2015b). These faults are identified as being predominantly normal faults in Namibia, whereas those in SE/S Brazil are strike-slip faults with average visible lengths of about 5-10 km, trending ENE-WSW.

In addition, several lineaments that represent large fault zones (**Fig. 2**; Milani et al., 1998; Soares et al., 2007; Zalán et al., 1990) run margin-perpendicular in Brazil, in a NW-SE direction through the Paraná basin. These fault zones have previously been assigned to Mesoproterozoic or Archean age (Zalán et al., 1990), but have later been interpreted as having developed in the Mesozoic (Milani et al., 1998). Reactivation of these zones occurred repeatedly throughout their existence, including the phase of Atlantic rifting (Eyles and Eyles, 1993; Karl et al., 2013; Milani et al., 1998; Zalán et al., 1990). In contrast, margin-perpendicular lineaments are missing in the Kaoko Belt in Namibia. A relation of the Rio Grande Fracture Zone north of the Walvis Ridge with the Opuwo Lineament in the Congo Craton (**Fig. 1**) as proposed by Corner (2002), can neither be confirmed in the field nor by geophysical data. South of the Kaoko Belt, margin-perpendicular lineaments do exist in the ~E-W-trending Neoproterozoic Damara Belt (Corner, 2002), but significant reactivation of Damara Belt fabric is proposed for the Campanian/Maastrichtian outside the period of South Atlantic rifting (Raab et al., 2002).

The volcanic rocks of the Paraná-Etendeka Large Igneous Province are present mostly on the South American side and cover an area of about 917,000 km² with a maximum preserved thickness of 1700 m (Peate et al., 1990; Frank et al., 2009), while in Namibia an area of only 78,000 km² is covered with a maximum preserved thickness of around 900 m (Erlank et al., 1984; Milner et al., 1992). These lavas were mostly emplaced via feeder dykes, which in Namibia generally follow the Kaoko (~margin-parallel) and Damara Belt (~margin-perpendicular) structures (**Fig. 1**; Hawkesworth et al., 1992; Trumbull et al., 2004; and own observations). In SE/S Brazil, margin-parallel dykes occur only at the easternmost onshore margin at Florianópolis (Florianópolis dyke swarm: **Fig. 2**; Florisbal et al. 2014) and are otherwise absent in the margin-parallel Dom Feliciano Belt fabric (Zalán et al., 1990). Instead, feeder dykes are oriented mostly NW-SE-directed, as evidenced in the prominent dyke swarms at the Ponta Grossa Arch and eastern Paraguay (Druecker and Gay, 1982; Piccirillo et al., 1990), but also in southernmost Brazil (**Fig. 3**; Hartmann et al., 2016b) and northern Uruguay (Masquelin et al., 2009), where they deviate towards the coast to an E-W orientation (**Fig. 2**). The early Cretaceous Asunción Rift, whose development is related to the breakup of Gondwana (Riccomini et al., 2001), is oriented parallel to the dykes in Paraguay. NW-trending normal faults in southernmost Brazil have also been related to Atlantic opening (Zerfass et al., 2005). Along the shelf offshore, a 50 km-wide margin-perpendicular syn-rift graben, named Mostardas graben, is located southeast of the city of Porto Alegre (**Figs. 2, 4**; Cardozo, 2011; Garcia, 2012).

Deformation bands, i.e. mm-wide zones of shear strain, formed in the Twyfelfontein / Botucatu sandstone formation during the covering of this sandstone with the Paraná-Etendeka lavas (Salomon et al., 2016). These structures are oriented margin-perpendicular in SE/S Brazil (Rodrigues et al., 2015) and margin-parallel in NW Namibia (Salomon et al., 2016).

Offshore, the SE/S Brazil margin morphology encompasses three prominent right-lateral, ~100 km long steps, visible on GEBCO bathymetric data / Google Earth (**Fig. 2**). This contrasts the morphology of the NW Namibian continental margin, which trends smoothly NNW until it reaches the Walvis ridge, formed by the Tristan da Cunha hotspot (**Fig. 1**).

4. Discussion

The most striking difference between NW Namibia and SE/S Brazil is the asymmetric distribution of the Paraná-Etendeka volcanic rocks. The lavas derived from the Tristan da Cunha hotspot, whose plume head is proposed to have been situated underneath southern Brazil, as judged by the large volume of volcanic rocks there (O'Connor and Duncan, 1990; Turner et al., 1994). According to these authors, the plume head migrated towards the east into the rift center at least during or shortly after rifting to form the volcanic chain Walvis Ridge, which commences from NW Namibia. This model, however, contradicts with magnetic susceptibility analyses of the Ponta Grossa and the Florianópolis dyke swarms (Raposo and Ernesto, 1995; Raposo, 1997): magma flow in the inland part of the Ponta Grossa dyke swarm was dominantly horizontal to sub-horizontal, whereas closer to the coast it shifted towards a vertical flow, and the Florianópolis dykes encompassed a sub-vertical to vertical magma flow. If the magma source was the same, this indicates that this source was situated closer to the Florianópolis than to the Ponta Grossa dyke swarm (Raposo, 1997). Seismic and magnetotelluric imaging indicates that the plume head was situated underneath the African plate at the landfall of the Walvis Ridge onto NW Namibia (Heit et al., 2015; Jegen et al., 2016). This has also been favored by Thompson and Gibson (1991) who point out that the dynamic uplift which should occur above a mantle plume (White and McKenzie, 1989) is not evident in the Paraná basin-fill sedimentary record.

With regard to these observations, we favor a scenario where the plume head was situated at or near the rift center on the African side since the beginning of its activity. Such a setting ultimately focusses on the reasons for the Paraná-Etendeka lava concentration on the South American side. It may be that the general flow direction of lavas was directed from Namibia towards Brazil as the basin center is located in southern Brazil, while an elevated inland topography in Namibia (Miller, 2008) could have prevented extended lava flow towards the east. Also, potential differences in the amount of post-rift erosion might have played a role in the asymmetric appearance of the lavas. Both margins had been subject to varying erosion phases (e.g., Cogné et al., 2011; Dressel et al., 2016; Guillocheau et al., 2012; MacGregor, 2012), which may have resulted in an unequal removal of Paraná-Etendeka volcanic rocks. However, erosion should not have affected the deeper parts of the crust, and the occurrence of massive dyke systems on the South American plate, such as the Ponta Grossa and Paraguay dyke swarms, argues for a true asymmetric magma distribution.

For magma sourced from a plume head underneath NW Namibia, dykes protruded more than 1500 km laterally into the South American crust. It is demonstrated that dykes may propagate horizontally far from their source, if a thick rock overburden, e.g. a lava column, induces a vertical compression sufficient to prevent magma from breaching the surface (Pinel and Jaupart, 2004). A well-known example of large-scale horizontal dyke emplacement is the Mackenzie dyke swarm in the Canadian Shield, where dykes can be traced to at least 2100 km away from the related plume head locality (Ernst and Baragar, 1992; Hou et al., 2010).

The orientation of Paraná-Etendeka-related magmatic dykes differs markedly between NW Namibia and SE/S Brazil. In Namibia, magmatic dykes follow the Kaoko and Damara Belt fabric, indicating that this fabric was a zone of weakness which could be used for magma ascent. In order to act as such, the basement fabric must lie in a favorable position relative to the acting stress system, i.e. basement fabric subject to perpendicular compression is less-likely to be used for dyke emplacement. As the Kaoko and Damara belt fabrics are oriented perpendicular to each other, an overall extensional stress regime is therefore required to activate both for dyke intrusion. Regional uplift related to doming could be caused by Atlantic rifting, the presence of the Tristan da Cunha hotspot (Heit et al., 2015; Jegen et al., 2016), and mantle upwelling underneath southern Africa (Burke et al., 2008). An overall extensional setting as indicated by paleostress analysis (Salomon et al., 2015b) pinpoint in this direction as well.

In Brazil, margin-parallel dykes are restricted to the Florianópolis Dyke Swarm, and are otherwise trending NW-SE, which indicates that the margin-parallel Neoproterozoic fabric had only a minor control on the dyke emplacement. Instead, the dykes might follow younger fault zones, as indicated by the accumulated swarm of Ponta Grossa, which parallels a fault zone of potentially early Mesozoic age (Milani et al., 1998). However, the NW-SE dyke orientation occurs continuously from this region to northern Uruguay, over more than 1000 km, making an overall pre-existing fault zone guidance unlikely.

Instead, we stress that both the asymmetric lava distribution and the contrasting dyke orientations are rooted in the large-scale plate kinematics during breakup (**Fig. 5**). Koopmann et al. (2013) and Heine et al. (2013) suggested that southernmost South America ("Patagonian block") rotated clockwise away from southern Africa and South America at around ~150 Ma, and thus prior to the initial South Atlantic rifting (**Fig. 5b**). This subsequently caused the formation of the Colorado and Salado basins in a perpendicular orientation to the South Atlantic rift trend, and whose localities are controlled by the reactivation of a Paleozoic fold-and -thrust belt and a Proterozoic suture, respectively (Autin et al., 2013; Pángaro and Ramos, 2012). This type of rotation might as well explain the observed differences between southern Brazil and Namibia (**Fig. 5c**). Here, extension is confined to specific rifts to a minor degree, such as the Mostardas graben or the Asunción rift, but mostly distributed across > 1000 km along the present-day coastline extending from Uruguay to the north of São Paulo. This wide distribution of deformation could be rooted in a missing major pre-existing deformation zone in this area, such as at the Colorado basin that could potentially accommodate most of the strain via reactivation. Extension in a NE-SW direction, which is also evident from the margin-perpendicular orientation of deformation bands in the Botucatu formation (Rodrigues et al., 2015), produced widespread pathways for dyke intrusion in a NW-SE direction. In this setting, the NE-SW trending Neoproterozoic fabric is in an unfavorable orientation for being reactivated and accordingly, dykes did not intrude into this fabric. Only the Florianópolis dyke swarm is parallel to this fabric, which may be rooted in its proximity to the Atlantic rift center or potentially to the plume head. A later intrusion of this dyke swarm in a different stress field can be excluded, due to its coeval emplacement age with the Paraná-Etendeka lavas (Florisbal et al., 2014; Baksi, 2017). The cause for the deviation of the southernmost dykes from an NW-SE orientation in the inland to an E-W orientation towards the coast remains unclear.

The prominent right-lateral offshore margin steps are interpreted by Stica et al. (2014) as rift transfer zones as they lie in the continuity of oceanic fracture zones and are thought to be associated with rift or intraplate deformation. However, in coast-parallel and –perpendicular seismic cross-sections these morphological margin steps appear as being the result of slumping in a post-breakup phase (Cardozo, 2011; Garcia, 2012).

Paleostress analyses show that SE/S Brazil was mainly subject to strike-slip faulting since breakup (Riccomini, 1995; Strugale et al., 2007). In the top-most preserved Paraná-Etendeka lavas in SE/S Brazil, ENE-oriented strike-slip faults are dominant whereas dyke-parallel normal faults are scarce (Salomon et al., 2015b). This indicates that the NE-SW directed extension due to the proposed clockwise rotation of southern South America away from a stable northern South America and Africa (**Fig. 5c**) has been superposed by other forces shortly during or after breakup, which may include stress components induced by Nazca plate subduction, asthenospheric flow, or flexural margin bending (e.g., Assumpção, 1992; Husson et al., 2012, Salomon et al., 2015b).

5. Conclusions

The complementary South Atlantic passive margins of SE/S Brazil and NW Namibia experienced a distinct asymmetric continental evolution during breakup, with respect to extruding lava volumes, dyke orientations, basement reactivation, and fault patterns. We believe these differences are best explained with large-scale plate movements. Similar to a Patagonian block that rotated clockwise away from a stable Africa and South America and forming distinct South

Atlantic rift-perpendicular basins, we propose a model where southern South America, including Patagonia, rotated away from a stable Africa and northern South America (**Fig. 5**). As no pre-existing major deformation zones, such as the Paleozoic fold-and-thrust belt in the Colorado basin, is located margin-perpendicular in SE/S Brazil, the resulting extension was not confined to a single structure, but distributed across a ~1000 km wide zone along the South Atlantic margin. This resulted in South Atlantic rift-parallel extension forming smaller-scale margin-perpendicular grabens and pathways for magma ascent.

Southern Africa instead remained stable and was subject to overall extension due to rifting, hot spot activity, and mantle upwelling. This allowed the reactivation of rift-parallel Kaoko Belt fabric and the intrusion of dykes into both Kaoko and Damara Belt fabric, despite their perpendicular orientation relative to each other.

As the Tristan da Cunha plume head was likely positioned in the rift center or on the Namibian margin, the enhanced opening of pathways in southern Brazil, Paraguay, and northern Uruguay due to the proposed rotation of southern South America appears responsible for the asymmetric distribution of the Paraná-Etendeka Large Igneous Province.

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References

Assumpção, M., 1992. The regional intraplate stress field in South America. Journal of Geophysical Research - Solid Earth 97: 11889–11903.

Autin, J., Scheck-Wenderoth, M., Loegering, M.J., Anka, Z., Vallejo, E., Rodriguez, J.F., Dominguez, F., Marchal, D., Reichert, C., di Primio, R. and Götze, H.J., 2013. Colorado Basin 3D structure and evolution, Argentine passive margin. Tectonophysics, 604: 264-279.

Baksi, A.K., in press. Paraná flood basalt volcanism primarily limited to ~ 1 Myr beginning at 135 Ma: New 40Ar/39Ar ages for rocks from Rio Grande do Sul, and critical evaluation of published radiometric data. Journal of Volcanology and Geothermal Research.

Beglinger, S.E., Doust, H. and Cloetingh, S., 2012. Relating petroleum system and play development to basin evolution: Brazilian South Atlantic margin. Petroleum Geoscience, 18(3): 315-336.

Beniest, A., Koptev, A. and Burov, E., 2017. Numerical models for continental break-up: Implications for the South Atlantic. Earth and Planetary Science Letters, 461: 176-189.

Burke, K. and Dewey, J.F., 1974. Two plates in Africa during the Cretaceous? Nature, 249: 313-316.

Burke, K., Steinberger, B., Torsvik, T.H. and Smethurst, M.A., 2008. Plume generation zones at the margins of large low shear velocity provinces on the core-mantle boundary. Earth and Planetary Science Letters, 265(1-2): 49-60.

Cardozo, T., 2011. Caracterização do arcabouço estrutural da Bacia de Pelotas e da área emersa adjacente. 110 pp. Dissertação - (mestrado) - Universidade Estadual Paulista, Instituto de

Geociências e Ciências Exatas. Available at http://repositorio.unesp.br/handle/11449/92919 (last accessed 03-01-2017).

Cogné, N., Gallagher, K. and Cobbold, P.R., 2011. Post-rift reactivation of the onshore margin of southeast Brazil: Evidence from apatite (U-Th)/He and fission-track data. Earth and Planetary Science Letters, 309(1-2): 118-130.

Corner, B., 2008. Crustal framework of Namibia derived from an integrated interpretation of geophysical and geological data. The geology of Namibia, 1: 2-1.

de Wit, M.J., Jeffery, M., Bergh, H., Nicolayson, L.O., 1988. Explanation to geological map of sectors of Gondwana. American Association of Petroleum Geologists, Tulsa.

Dressel, I., Cacace, M. and Scheck-Wenderoth, M., 2016. Coupled thermo-mechanical 3D subsidence analysis along the SW African passive continental margin. Arabian Journal of Geosciences, 9(5): 385.

Druecker, M.D. and Gay Jr, S.P., 1987. Mafic dyke swarms associated with Mesozoic rifting in Eastern Paraguay, South America. Mafic dyke swarms. Geological Association of Canada, Special Publication, 34: 187-193.

Eagles, G., 2007. New angles on South Atlantic opening. Geophysical Journal International, 168(1): 353-361.

Erlank, A.J., Marsh, J.S., Duncan, A.R., Miller, R.M., Hawkesworth, C.J., Betton, P.J. and Rex, D.C., 1984. Geochemistry and petrogenesis of the Etendeka volcanic rocks from SWA/Namibia. Spec. Publ. Geol. Soc. S. Afr, 13: 195-245.

Ernst, R.E. and Baragar, W.R.A., 1992. Evidence from magnetic fabric for the flow pattern of magma in the Mackenzie giant radiating dyke swarm. Nature, 356(6369): 511-513.

Eyles, N. and Eyles, C.H., 1993. Glacial geologic confirmation of an intraplate boundary, in the Paraná basin of Brazil. Geology, 21(5): 459-462.

Fitzgerald, M.G., Mitchum Jr, R.M., Uliana, M.A. and Biddle, K.T., 1990. Evolution of the San Jorge Basin, Argentina. AAPG Bulletin, 74(6): 879-920.

Florisbal, L.M., Heaman, L.M., Janasi, V.d.A. and Bitencourt, M.d.F., 2014. Tectonic significance of the Florianópolis Dyke Swarm, Parana-Etendeka Magmatic Province: A reappraisal based on precise U-Pb dating. Journal of Volcanology and Geothermal Research, 289: 140-150.

Foster, D.A., Goscombe, B.D. and Gray, D.R., 2009. Rapid exhumation of deep crust in an obliquely convergent orogen: The Kaoko Belt of the Damara Orogen. Tectonics, 28: TC4002.

Frank, H. T., Gomes, M. E. B., & Formoso, M. L. L., 2009. Review of the areal extent and the volume of the Serra Geral Formation, Paraná Basin, South America. Pesquisas em Geociências, 36: 49-57.

Franke, D., 2013. Rifting, lithosphere breakup and volcanism: Comparison of magma-poor and volcanic rifted margins. Marine and Petroleum Geology, 43: 63-87.

Garcia, W.d.O., 2012. Estudo da influência do lineamento Tibagi e Sinclinal de Torres na estruturação da porção norte da bacia de Pelotas. 71 pp. Trabalho de conclusão de curso (Geologia) - Universidade Estadual Paulista Júlio de Mesquita Filho, Instituto de Geociências e Ciências Exatas. Available at: http://repositorio.unesp.br/handle/11449/119219 (last accessed 03-01-2017).

Goscombe, B., Gray, D., Armstrong, R., Foster, D.A. and Vogl, J., 2005. Event geochronology of the Pan-African Kaoko Belt, Namibia. Precambrian Research, 140(3-4): 103-131.

Guillocheau, F., Rouby, D., Robin, C., Helm, C., Rolland, N., Le Carlier de Veslud, C. and Braun, J., 2012. Quantification and causes of the terrigeneous sediment budget at the scale of a continental margin: a new method applied to the Namibia-South Africa margin. Basin Research, 24(1): 3-30.

Hartmann, L.A., Savian, J.F. and Lopes, W.R., 2016a. Airborne geophysical characterization of geotectonic relationships in the southern Ribeira Belt, Luís Alves Craton, and northern Dom Feliciano Belt, Brazilian Shield. International Geology Review, 58: 471-488.

Hartmann, L.A., Lopes, W.R. and Savian, J.F., 2016b. Integrated evaluation of the geology, aerogammaspectrometry and aeromagnetometry of the Sul-Riograndense Shield, southernmost Brazil. Anais da Academia Brasileira de Ciências, 88: 75-92.

Hawkesworth, C.J., Gallagher, K., Kelley, S., Mantovani, M., Peate, D.W., Regelous, M. and Rogers, N.W., 1992. Paraná magmatism and the opening of the South Atlantic. Geological Society, London, Special Publications, 68(1): 221-240.

Heine, C., Zoethout, J. and Müller, R.D., 2013. Kinematics of the South Atlantic rift. Solid Earth Discussion, 5: 41-115.

Heit, B., Yuan, X., Weber, M., Geissler, W., Jokat, W., Lushetile, B. and Hoffmann, K.-H., 2015. Crustal thickness and Vp/Vs ratio in NW Namibia from receiver functions: Evidence for magmatic underplating due to mantle plume-crust interaction. Geophysical Research Letters, 42(9): 3330-3337.

Hou, G., Kusky, T.M., Wang, C. and Wang, Y., 2010. Mechanics of the giant radiating Mackenzie dyke swarm: A paleostress field modeling. Journal of Geophysical Research-Solid Earth, 115, B02402, doi:10.1029/2007JB005475

Husson, L., Conrad, C.P., Faccenna, C., 2012. Platemotions, Andean orogeny, and volcanism above the South Atlantic convection cell. Earth and Planetary Science Letters 317: 126–135.

Jacques, J., 2003. A tectonostratigraphic synthesis of the Sub-Andean basins: inferences on the position of South American intraplate accommodation zones and their control on South Atlantic opening. Journal of the Geological Society, 160(5): 703-717.

Jegen, M., Avdeeva, A., Berndt, C., Franz, G., Heincke, B., Hölz, S., Neska, A., Marti, A., Planert, L., Chen, J., Kopp, H., Baba, K., Ritter, O., Weckmann, U., Meqbel, N. and Behrmann, J., 2016. 3-D magnetotelluric image of offshore magmatism at the Walvis Ridge and rift basin. Tectonophysics, 683: 98-108.

Jerram, D., Mountney, N., Holzförster, F. and Stollhofen, H., 1999. Internal stratigraphic relationships in the Etendeka Group in the Huab Basin, NW Namibia: understanding the onset of flood volcanism. Journal of Geodynamics, 28(4-5): 393-418.

Karl, M., Glasmacher, U.A., Kollenz, S., Franco-Magalhaes, A.O.B., Stockli, D.F. and Hackspacher, P.C., 2013. Evolution of the South Atlantic passive continental margin in southern Brazil derived from zircon and apatite (U-Th-Sm)/He and fission-track data. Tectonophysics, 604(0): 224-244.

Konopásek, Sláma, J. and Košler, J., 2016. Linking the basement geology along the Africa-South America coasts in the South Atlantic. Precambrian Research, 280: 221-230.

Koopmann, H., Franke, D., Schreckenberger, B., Schulz, H., Hartwig, A., Stollhofen, H. and di Primio, R., 2013. Segmentation and volcano-tectonic characteristics along the SW African continental margin, South Atlantic, as derived from multichannel seismic and potential field data. Marine and Petroleum Geology, 50: 22-39.

Macdonald, D., Gomez-Perez, I., Franzese, J., Spalletti, L., Lawver, L., Gahagan, L., Dalziel, I., Thomas, C., Trewin, N., Hole, M. and Paton, D., 2003. Mesozoic break-up of SW Gondwana: implications for regional hydrocarbon potential of the southern South Atlantic. Marine and Petroleum Geology, 20(3-4): 287-308.

Macgregor, D.S., 2012. Late Cretaceous-Cenozoic sediment and turbidite reservoir supply to South Atlantic margins. Geological Society, London, Special Publications, 369(1): 109-128.

Masquelin, H., Aïfa, T., Muzio, R., Hallot, E., Veroslavsky, G. and Bonnevalle, L., 2009. The Cuaró Mesozoic doleritic dyke swarm, southern Paraná basin, Uruguay: Examples of superimposed magnetic fabrics? Comptes Rendus Geoscience, 341(12): 1003-1015.

Meisling, K.E., Cobbold, P.R. and Mount, V.S., 2001. Segmentation of an obliquely rifted margin, Campos and Santos basins, southeastern Brazil. AAPG Bulletin, 85(11): 1903-1924.

Milani, E.J., Faccini, U.F., Scherer, C.M., Araújo, L.M.D., Cupertino, J.A., 1998. Sequences and stratigraphtc hierarchy of the Paraná basin (Ordovician to Cretaceous), southern Brazil. Boletim IG-USP. Geologia Série Científica, 29, 125-173.

Miller, R.M.G., Becker, T. and Geological, S., 2008. The Geology of Namibia: Upper palaeozoic to cenozoic. Ministry of Mines and Energy, Geological Survey.

Milner, S.C., Duncan, A.R. and Ewart, A., 1992. Quartz latite rheoignimbrite flows of the Etendeka Formation, north-western Namibia. Bulletin of Volcanology, 54(3): 200-219.

Moulin, M., Aslanian, D. and Unternehr, P., 2010. A new starting point for the South and Equatorial Atlantic Ocean. Earth-Science Reviews, 98(1-2): 1-37.

O'Connor, J.M. and Duncan, R.A., 1990. Evolution of the Walvis Ridge-Rio Grande Rise Hot Spot System: Implications for African and South American Plate motions over plumes. Journal of Geophysical Research: Solid Earth, 95(B11): 17475-17502.

O'Connor, J.M. and Jokat, W., 2015. Age distribution of Ocean Drill sites across the Central Walvis Ridge indicates plate boundary control of plume volcanism in the South Atlantic. Earth and Planetary Science Letters, 424: 179-190.

Oyhantçabal, P., Siegesmund, S., Wemmer, K. and Passchier, C.W., 2011. The transpressional connection between Dom Feliciano and Kaoko Belts at 580-550 Ma. International Journal of Earth Sciences, 100(2-3): 379-390.

Pángaro, F. and Ramos, V.A., 2012. Paleozoic crustal blocks of onshore and offshore central Argentina: New pieces of the southwestern Gondwana collage and their role in the accretion of Patagonia and the evolution of Mesozoic south Atlantic sedimentary basins. Marine and Petroleum Geology, 37(1): 162-183.

Peate, D.W., Hawkesworth, C.J., Mantovani, M.S.M. and Shukowsky, W., 1990. Mantle plumes and flood-basalt stratigraphy in the Parana, South-America. Geology, 18(12): 1223-1226.

Perea, D., Soto, M., Veroslavsky, G., Martínez, S. and Ubilla, M., 2009. A Late Jurassic fossil assemblage in Gondwana: Biostratigraphy and correlations of the Tacuarembo Formation, Parana Basin, Uruguay. Journal of South American Earth Sciences, 28(2): 168-179.

Piccirillo, E.M., Bellieni, G., Cavazzini, G., Cominchiaramonti, P., Petrini, R., Melfi, A.J., Pinese, J.P.P., Zantadeschi, P. and Demin, A., 1990. Lower Cretaceous tholeiitic dyke swarms from the Ponta-Grossa arch (southeast Brazil) - Petrology, Sr-Nd isotopes and genetic-relationships with the Parana flood volcanics. Chemical Geology, 89(1-2): 19-48.

Pinel, V. and Jaupart, C., 2004. Magma storage and horizontal dyke injection beneath a volcanic edifice. Earth and Planetary Science Letters, 221(1-4): 245-262.

Raab, M.J., Brown, R.W., Gallagher, K., Carter, A. and Weber, K., 2002. Late Cretaceous reactivation of major crustal shear zones in northern Namibia: constraints from apatite fission track analysis. Tectonophysics, 349(1-4): 75-92.

Rabinowitz, P.D. and LaBrecque, J., 1979. The Mesozoic South Atlantic Ocean and Evolution of Its Continental Margins. Journal of Geophysical Research, 84: 5973-6002.

Raposo, M.I.B., 1997. Magnetic fabric and its significance in the Florianópolis dyke swarm, southern Brazil. Geophysical Journal International, 131(1): 159-170.

Raposo, M.I.B. and Ernesto, M., 1995. Anisotropy of magnetic susceptibility in the Ponta Grossa dyke swarm (Brazil) and its relationship with magma flow direction. Physics of the Earth and Planetary Interiors, 87(3): 183-196.

Renne, P.R., Ernesto, M., Pacca, I.G., Coe, R.S., Glen, J.M., Prévot, M. and Perrin, M., 1992. The age of Paraná flood volcanism, rifting of Gondwanaland, and the Jurassic-Cretaceous boundary. Science, 258(5084): 975-979.

Riccomini, C., 1995. Padrão de fraturamentos do Maciço Alcalino de Cananéia, Estado de São Paulo: relações com a tectônica mesozóico-cenozóica do sudeste do Brasil. Revista Brasileira de Geociências, 25(2): 79-84.

Riccomini, C., Velazquez, V.F. and Gomes, C.D., 2001. Cenozoic lithospheric faulting in the Asuncion Rift, eastern Paraguay. Journal of South American Earth Sciences, 14(6): 625-630.

Rodrigues, M.C.N.d.L., Trzaskos, B. and Lopes, A.P., 2015. Influence of deformation bands on sandstone porosity: A case study using three-dimensional microtomography. Journal of Structural Geology, 72: 96-110.

Salomon, E., Koehn, D. and Passchier, C., 2015a. Brittle reactivation of ductile shear zones in NW Namibia in relation to South Atlantic rifting. Tectonics, 34(1): 70-85.

Salomon, E., Koehn, D., Passchier, C., Hackspacher, P.C. and Glasmacher, U.A., 2015b. Contrasting stress fields on correlating margins of the South Atlantic. Gondwana Research, 28(3): 1152-1167.

Salomon, E., Koehn, D., Passchier, C., Chung, P., Häger, T., Salvona, A. and Davis, J., 2016. Deformation and fluid flow in the Huab Basin and Etendeka Plateau, NW Namibia. Journal of Structural Geology, 88: 46-62.

Scherer, C.M.S., 2000. Eolian dunes of the Botucatu Formation (Cretaceous) in southernmost Brazil: morphology and origin. Sedimentary Geology, 137(1-2): 63-84.

Smith, R.M.H., Eriksson, P.G. and Botha, W.J., 1993. A review of the stratigraphy and sedimentary environment of the Karoo-aged basins of southern Africa. Journal of African Earth Sciences, 16(1-2): 143-169.

Soares, A.P., Soares, P.C., Bettú, D.F. and Holz, M., 2007. Compartimentação estrutural da Bacia do Paraná: a questão dos lineamentos e sua influência na distribuição do Sistema Aquifero Guarani. Geociências, 26(4): 297-311.

Strugale, M., Rostirolla, S.P., Mancini, F., Portela Filho, C.V., Fonseca Ferreira, F.J. and de Freitas, R.C., 2007. Structural framework and Mesozoic-Cenozoic evolution of Ponta Grossa Arch, Paraná Basin, southern Brazil. Journal of South American Earth Sciences, 24(2-4): 203-227.

Stica, J.M., Zalán, P.V. and Ferrari, A.L., 2014. The evolution of rifting on the volcanic margin of the Pelotas Basin and the contextualization of the Paraná-Etendeka LIP in the separation of Gondwana in the South Atlantic. Marine and Petroleum Geology, 50: 1-21.

Thompson, R.N. and Gibson, S.A., 1991. Subcontinental mantle plumes, hotspots and pre-existing thinspots. Journal of the Geological Society, 148(6): 973-977.

Torsvik, T.H., Rousse, S., Labails, C. and Smethurst, M.A., 2009. A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin. Geophysical Journal International, 177(3): 1315-1333.

Travassos, R.P., 2014. Interpretação estrutural regional do escudo sul-rio-grandense - Rio Grande do Sul - Brasil, com base em aeromagnetometria. Universidade de Brasília, Brasília, 64pp. Available at: http://repositorio.unb.br/handle/10482/17864 (last accessed 12-06-2017).

Trumbull, R.B., Vietor, T., Hahne, K., Wackerle, R. and Ledru, P., 2004. Aeromagnetic mapping and reconnaissance geochemistry of the Early Cretaceous Henties Bay-Outjo dike swarm, Etendeka Igneous Province, Namibia. Journal of African Earth Sciences, 40(1-2): 17-29.

Turner, S., Regelous, M., Kelley, S., Hawkesworth, C. and Mantovani, M., 1994. Magmatism and continental break-up in the South Atlantic: high precision 40Ar-39Ar geochronology. Earth and Planetary Science Letters, 121(3-4): 333-348.

Unternehr, P., Curie, D., Olivet, J.L., Goslin, J. and Beuzart, P., 1988. South Atlantic fits and intraplate boundaries in Africa and South America. Tectonophysics, 155: 169-179.

Veevers, J.J., 2004. Gondwanaland from 650-500 Ma assembly through 320 Ma merger in Pangea to 185-100 Ma breakup: supercontinental tectonics via stratigraphy and radiometric dating. Earth-Science Reviews, 68(1-2): 1-132.

Velázquez, V.F., Riccomini, C., Gomes, C.B., Figueredo, L., Figueredo, C., 1998. Relações tectônicas do magmatismo alcalino do Paraguai oriental. Revista do Instituto Geológico São Paulo, 19: 43-49.

White, R. and McKenzie, D., 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. Journal of Geophysical Research: Solid Earth, 94(B6): 7685-7729.

Zalán, P.V., Wolff, S., Astolfi, M.A.M., Vieira, I.S., Concelção, J.C.J., Appi, V.T., Neto, E.V.S., Cerqueira, J.R. and Marques, A., 1990. The Paraná Basin, Brazil. In: M.W. Leighton, D.R. Kolata, D.F. Oltz and J.J. Eidel (Editors), Interior Cratonic Basins, AAPG Memoir, pp. 681-708.

Zerfass, H., Chemale, F. and Lavina, E., 2005. Tectonic Control of the Triassic Santa Maria Supersequence of the Paraná Basin, Southernmost Brazil, and its Correlation to the Waterberg Basin, Namibia. Gondwana Research, 8(2): 163-176.

Figure Captions

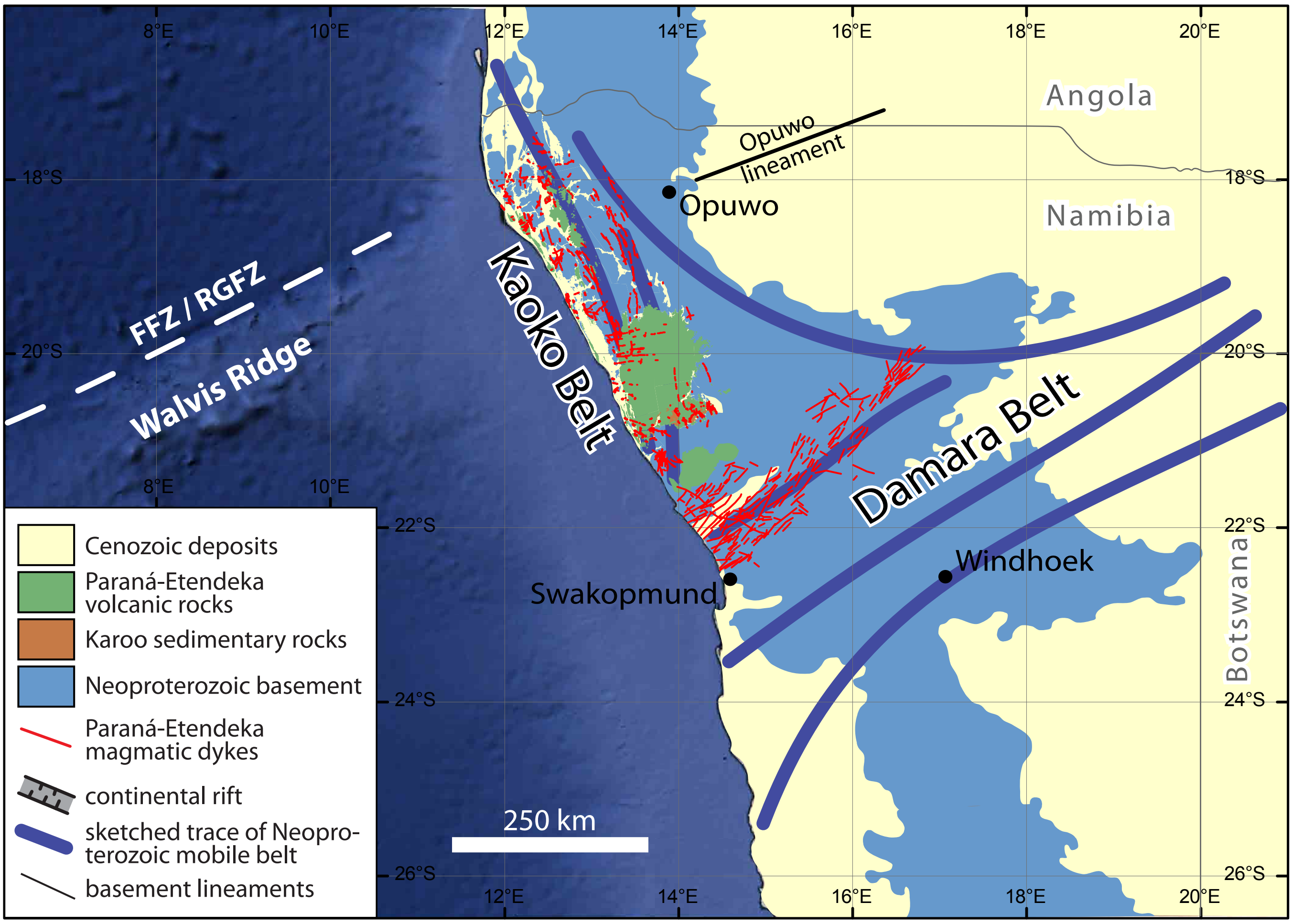
Figure 1: Geologic map of northern Namibia and bathymetric image of the ocean floor. FFZ / RGFZ: Florianópolis Fracture Zone / Rio Grande Fracture Zone. Lithologies after Salomon et al. (2015b) and after Simplified Geological Map of Namibia, 1:2.000.000, Geological Survey of Namibia (1988). Magmatic dykes in Kaoko Belt derived from own mapping and dykes in Damara Belt after Trumbull et al. (2004). Bathymetric image derived from Google Earth.

Figure 2: Geologic map of SE/S Brazil and bathymetric image of the ocean floor. For legend see **figure 1**. Cross-section A-A' is shown in **figure 4**. FFZ / RGFZ: Florianópolis Fracture Zone / Rio Grande Fracture Zone. Lithologies simplified and Ponta Grossa Dyke Swarm after Mapa Geodiversidade do Brasil, 1:2.500.000, Serviço Geológico do Brasil (2006). Florianópolis Dyke Swarm simplified after Hartmann et al. (2016a). Eastern Paraguay Dyke Swarm after Druecker and Gay (1982). Asunción Rift after Velazquez et al. (1998). Basement lineaments after Zalán et al. (1990). Bathymetric image derived from Google Earth.

Figure 3: Analytic signal map showing aeromagnetic anomalies in southernmost Brazil (for location see **figure 2**; modified after Travassos, 2014, and Hartmann et al., 2016b). NW-trending linear structures indicate Paraná-Etendeka related magmatic dykes and NE-trending structures resemble basement structures (Hartmann et al., 2016b).

Figure 4: Coast-parallel seismic cross section located in the Pelotas Basin, offshore SE/S Brazil (modified after Garcia, 2012). The section indicates a 50 km-wide margin-perpendicular syn-Atlantic rift graben ("Mostardas graben"; Garcia, 2012). For location of profile see **figure 2**.

Figure 5: Proposed schematic model of continental break-up. **a)** Setting prior to break-up; **b)** the onset of break-up initiates with the clockwise rotation of Patagonia away from a stable northern South America and Africa, which results in the formation of basins perpendicular to the developing South Atlantic margins (cf. Heine et al., 2013; Koopmann et al., 2013); **c)** in the progress of break-up, southern South America rotates clockwise away from stable northern South America and Africa, which creates an extensional domain in between southern and northern South America. In this domain excessive pathways develop for magma ascending from the Tristan da Cunha hot spot whose plume head is situated in or close to the South Atlantic rift center. In the close vicinity to the plume head, magmatic dykes follow the basement fabric due to domal uplift; **d)** rotation of the South American plate causes complete break-up with Africa.



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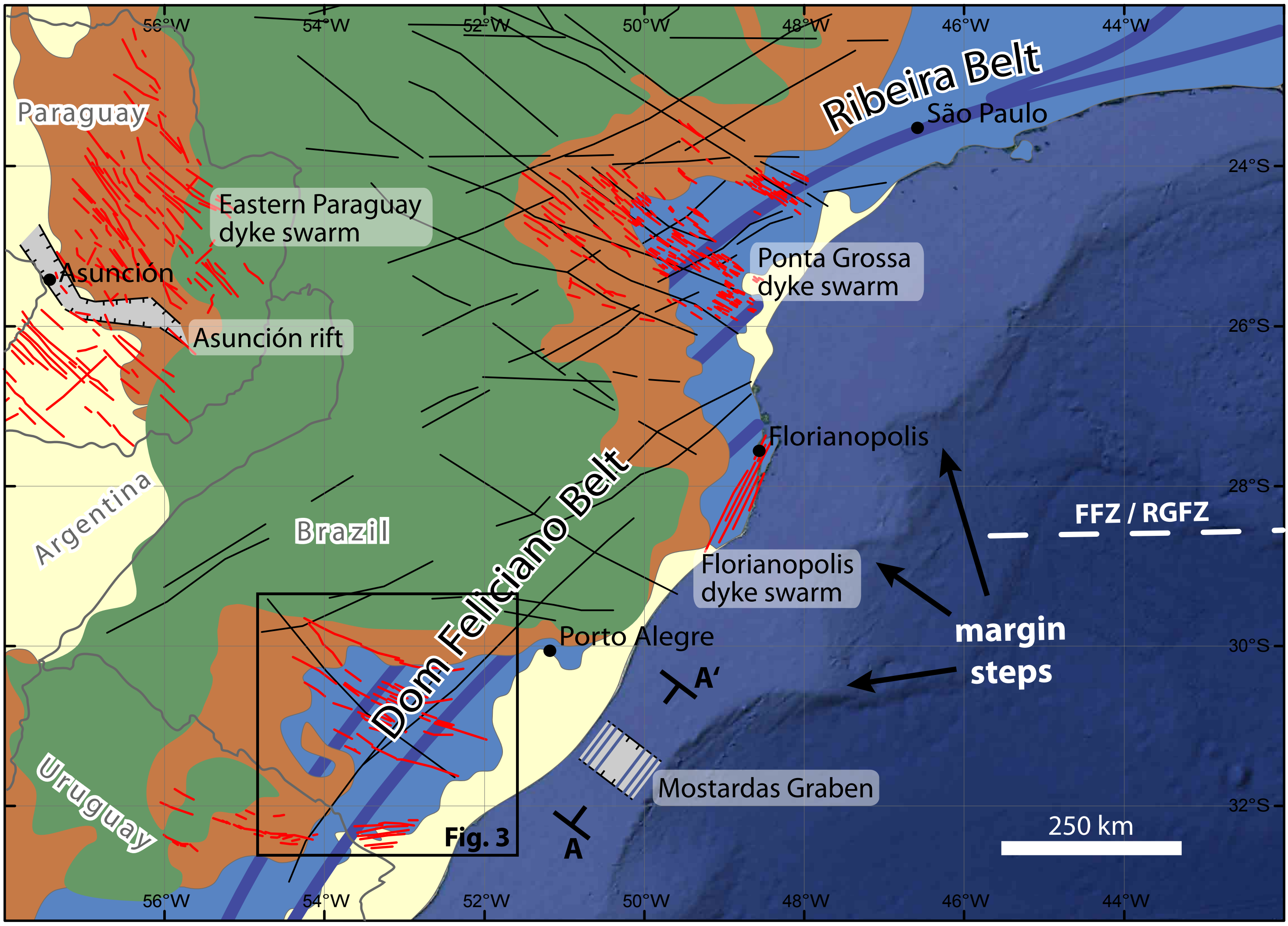

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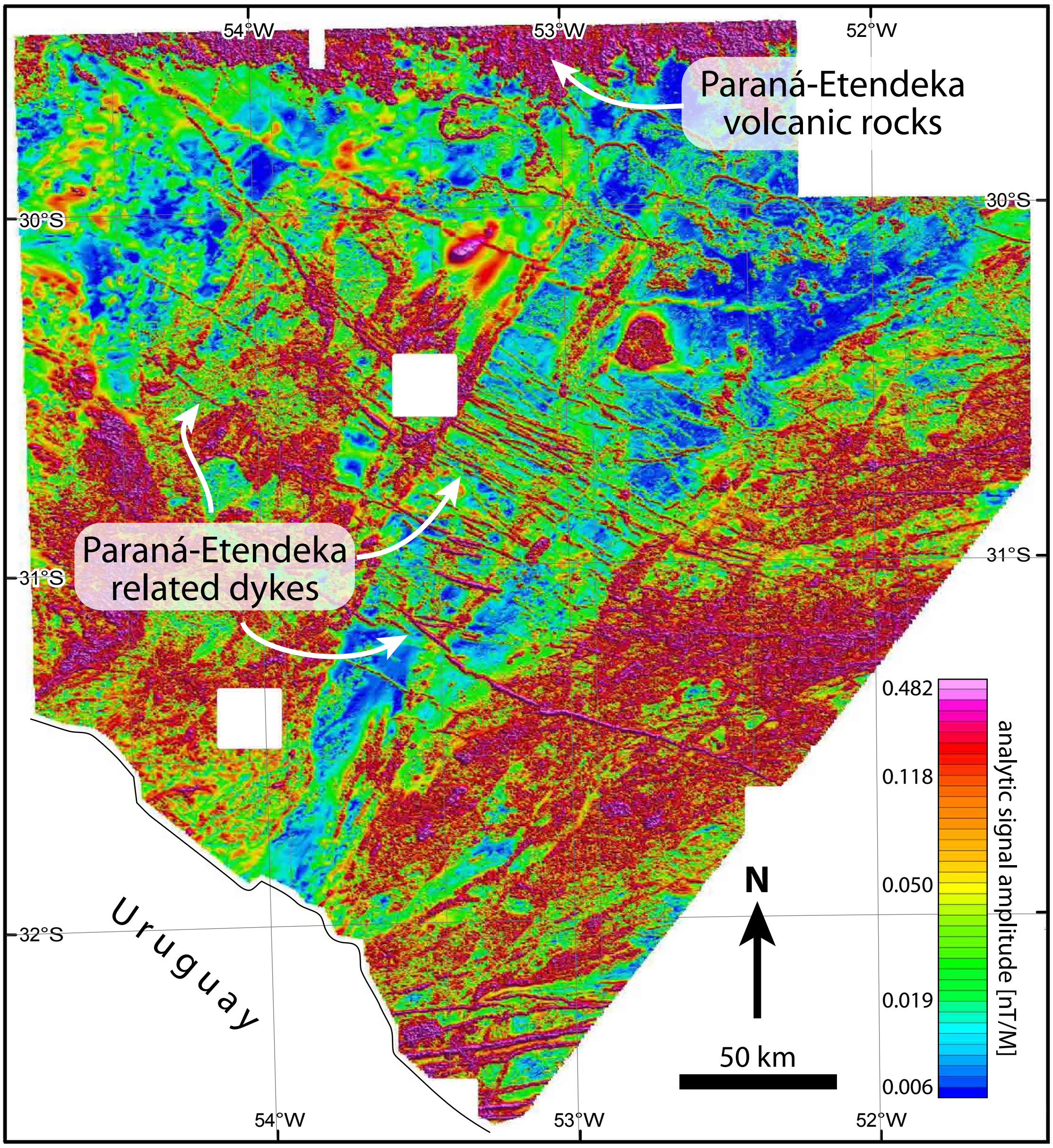

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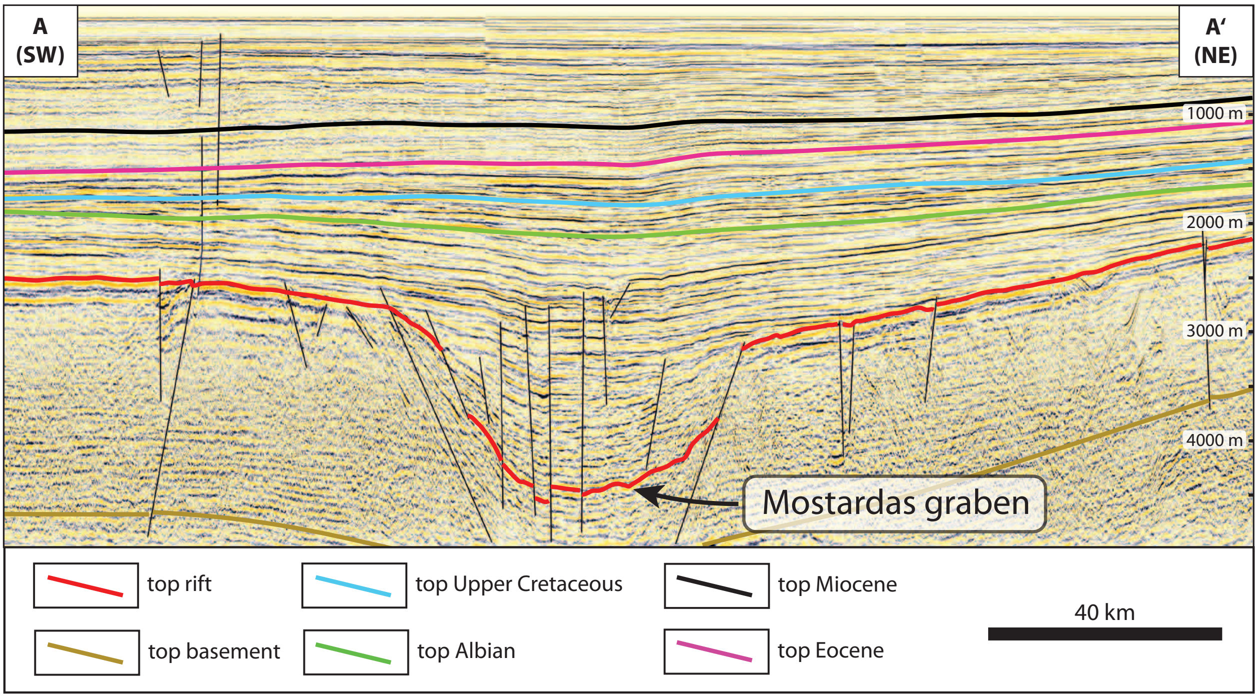

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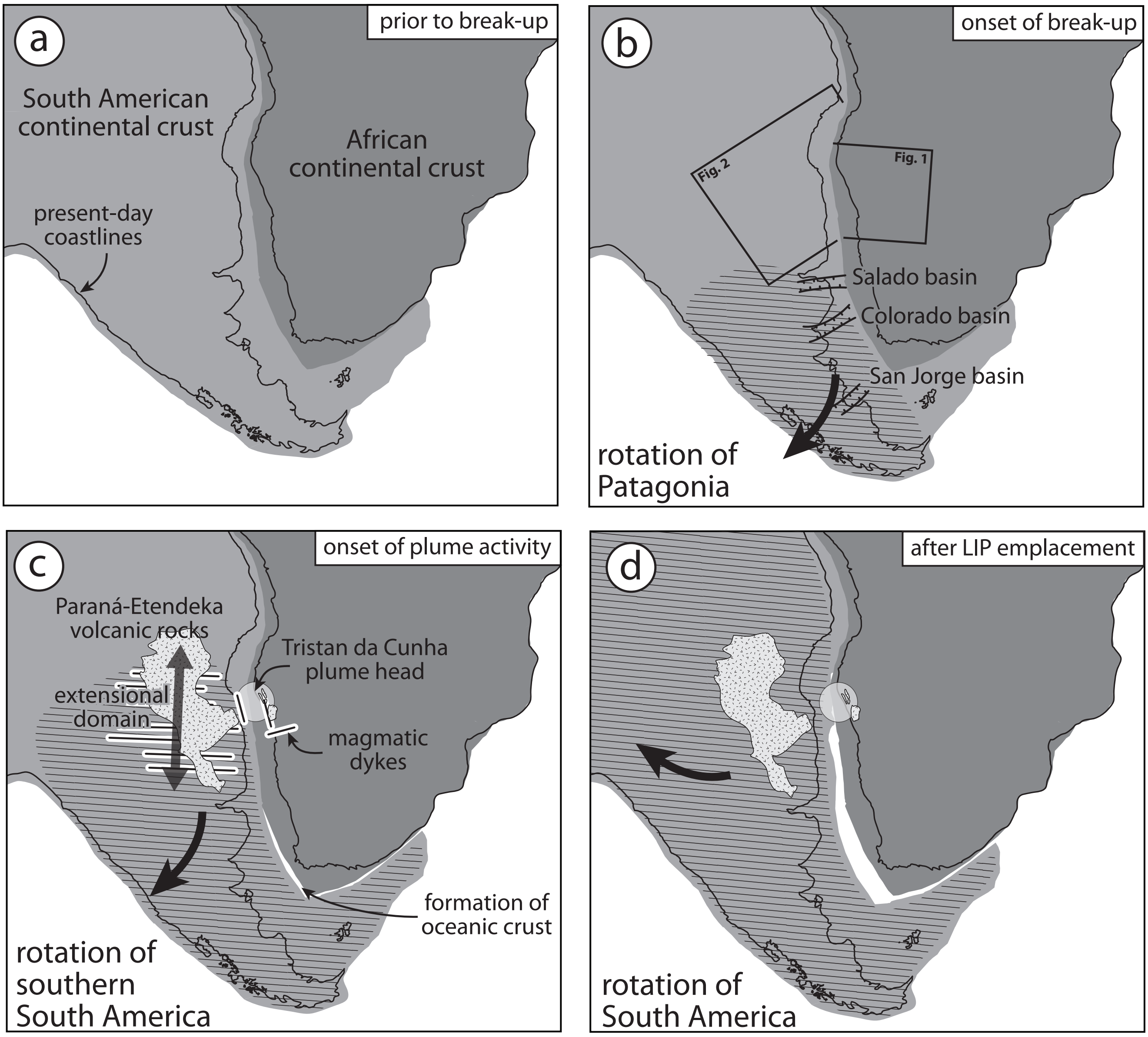

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