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TECTONIC REACTIVATION ALONG THE FLORIANÓPOLIS FRACTURE ZONE, BRAZIL

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ABSTRACT. The Florianópolis Fracture Zone (FFZ), Brazil, delimits the Pelotas and Santos basins and marks a major change in the geology of the continental margins from south to north, along both sides of the South Atlantic Ocean. The continental prolongation of it is represented by Lower and Upper Cretaceous alkaline rocks, Paleocene hydrothermal manifestations and river catchments. Geological review along with total magnetic field reduced to the pole map (EMAG 2) was used to investigate and analyze the Florianópolis Fracture Zone. Our results indicate that the intracontinental NW-SE transfer zones control Upper Cretaceous sedimentation and Lower Cretaceous carbonatitic intrusions. The transition from continental crust to oceanic crust is achieved by the formation of normal faults and horse tail structures near the coastline verging to the FFZ at the already attenuated crust. Alkaline rocks, including carbonatitic ones, arose in the continental crust at the southwest projection of Luis Alves Craton and at the intersection between the transfer zones and the Brusque Metamorphic Complex. The integrated analyses indicated that the location of the FFZ was governed by the geological events in the continental crust. This oceanic/continental trend was later well reactivated after the South Atlantic opening.

Keywords: South Atlantic Ocean; Florianópolis Fracture Zone; Upper Cretaceous alkaline magmatism; structural inheritance; reactivation.

INTRODUCTION

The relationship between fracture zones and continental structures has been the theme of numerous studies (Asmus, 1978; Sykes, 1978; Gamboa and Rabinowitz, 1981; Almeida et al., 1996) and present-day integrated geophysical data supported by geological evidence are bringing new understanding to the relationship. Recent studies (Taylor et al., 2009; Bellahsen et al., 2013; Wolfson-Schwehr and Boettcher, 2019; Şengör et al., 2019) show geometric consistencies between continental margin transfer zones and mid-ocean ridge transform faults suggesting that transform faults originated at structures inherited from the rifting stage (Miller et al., 2002; Bellahsen et al., 2013).

Shear zone in the basement, or contrasting shear strength units, and rifting phase transfer or accommodation zones are the inherited structures candidates to reactivate during the rifting and drifting phase. Examples from the Gulf of Suez (e.g. Jarrige et al., 1990; Moustafa, 1997) and the East African Rift System (e.g. Rosendahl, 1987; Lezzar et al., 2002) show that transfer zones were active during early stages of rifting. It is noteworthy that, in these two examples, the transfer zones are both pre-existing and oblique to the divergence (Taylor et al., 2009; Bellahsen et al., 2013; Şengör et al., 2019).

Transform faults in the Atlantic Ocean have been related to the prolongation of Late Cretaceous Alkaline igneous complex lineaments in the South America and African continents. Those structures lie along small circles centered on the Cretaceous poles of rotation for the South Atlantic and can be correlated with a distinct transform fault (Marsh, 1973).

In the SE Brazilian margin, the Florianópolis Fracture Zone (FFZ) is aligned with the São Paulo Ridge and troughs and the northern Rio Grande Rise E-W edge where differences in relief are around 1500 m (Gamboa and Rabinowitz, 1981). The projection of this oceanic feature to the continent is represented by the Uruguay Lineament related to the catchment of the Uruguay river, aligning Upper Cretaceous to Paleocene alkaline intrusions, and Paraná Basin sedimentary facies width variation (Asmus, 1978; Comin-Chiaramonti et al., 2007). This could mean that the location of the FFZ is influenced by zones of weakness in the continent (Asmus, 1978; Gamboa and Rabinowitz, 1981). Furthermore, indications of the transition from the oceanic to the continental crust are the width variation of the Pelotas Basin Seward Dipping Reflectors (SDR) package and Lower Paleogene alkaline rocks emplaced in the Florianópolis High (Asmus, 1978; Fodor et al., 1983; Stica et al., 2014); such petro-tectonic indications are not discussed to any degree in the literature (Figure 1).

BASEMENT GEOLOGY

The Neo-Proterozoic basement along the continental projection of the FFZ is represented by the northern portion of the Dom Feliciano Belt (Figure 4), which is part of the Mantiqueira Province (Heilbron et al., 2004). The main shear zones are NE-SW striking Itajái-Perimbó and Major Gercino, which divide the terrain into defined domains. The northwestern domain is characterized by a foreland basin which is thrusted over the Luis Alves Craton. The central domain is constituted by metavolcano-sedimentary fold-and-thrust belt of Brusque Metamorphic Complex. The southeastern domain represents an association of voluminous granitic intrusions of the Florianópolis Batholith (Hueck et al., 2018).

The Major Gercino Shear Zone plays an important role in margin reactivation and on the location of the Upper Cretaceous alkaline intrusions of the Lages Province (64 – 77 Ma) (Scheibe, 1986). It marks a rheology contrast between the Brusque and Florianópolis basement units and its strikes NE-SW which are almost 45° with the FFZ E-W main trend. Those characteristics make this domain prone to reactivation because of the contrasting shear strength, which became a stress guide to the deformation. In addition, the 45° relation with the Florianópolis Fracture main direction makes this domain a site susceptible to nucleate shear fractures and faults during oblique applied stress (Misra and Mukherjee, 2015).

MARGINAL BASINS

The Pelotas Basin is compartmentalized by the continuity of the oceanic fracture zones, possibly associated with rift transfer zones (Stica et al., 2014). Magnetic anomalies M4 and M2 indicate that the breakup began at 130 and 127 Ma in the south segment, followed by a second break, as indicated by the M0 magnetic anomalies (~125 Ma) (Stica et al., 2014). The minimum age for the inception of the oceanic crust in the northern segment is inferred to be 113 Ma (Stica et al., 2014).

The Santos Basin central segment opened 18 Ma after the Pelotas Basin SDR deposition begin. It also marks the end of thick evaporite deposition (Upper Aptian-Lower Albian: 113 Ma) (Rabinowitz and LaBrecque 1979; Curie, 1984; Karner and Gamboa, 2007; Torsvik et al., 2009; Moulin et al., 2013). Transfer motion along the FFZ probably accommodated most of this shift in time and position. As a consequence, the continental crust east of the São Paulo Plateau area was highly stretched and intensely injected by magmatic intrusions (Gamboa et al., 2021), reflecting the link between fracture zones and hyperextended basins (Le Pourhiet et al., 2017). At the ASA (Aborted Spreading Axis) (Cande and Rabinowitz, 1978; Meisling et al., 2001; Mohriak, 2001; Gamboa et al., 2021), north flank magmatic activities are registered in the Campanian strata in the form of volcanos (Schattner and de Mahiques, 2020).

Oceanic Crust Indications in the Florianópolis Fracture Zone (FFZ)

The FFZ is a broad tectonized region with a width generally greater than 100 km, which delimits the northern portion of the Rio Grande Rise. Its westward continuity is represented by São Paulo Ridge (Gamboa and Rabinowitz, 1981) (Figure 1). The angle of the fracture zone tracing slightly changes from E-W to the west of the Rio Grande Rise to ENE-WSW towards the continent. The direction of the FFZ in the continental crust changes to NW-SE.

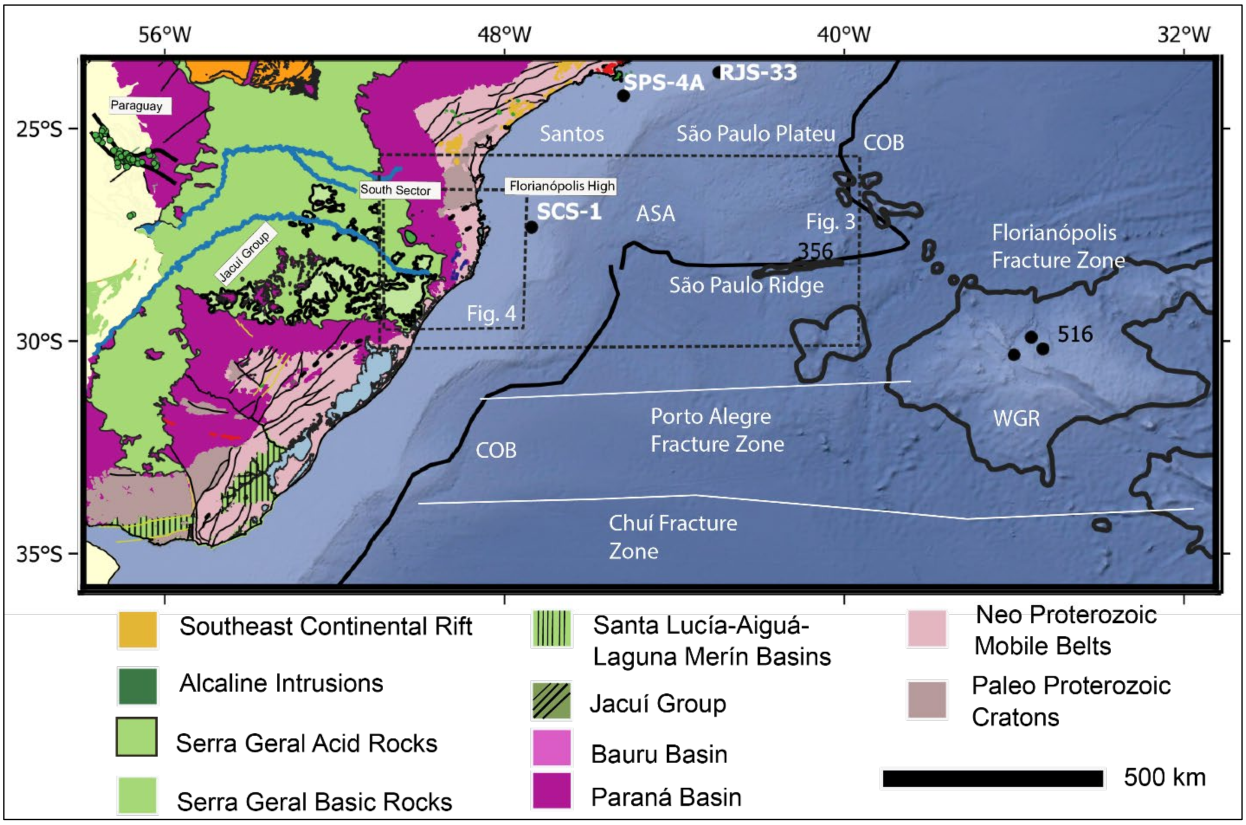

Figure 1: Simplified continental geology, main oceanic structures, and locations of the wells discussed in the text. Compiled from: Riccomini et al. (2002; 2004; 2016); Stica et al. (2014); Cernuschi et al. (2015); Cordani et al. (2016); Gamboa et al. (2021).

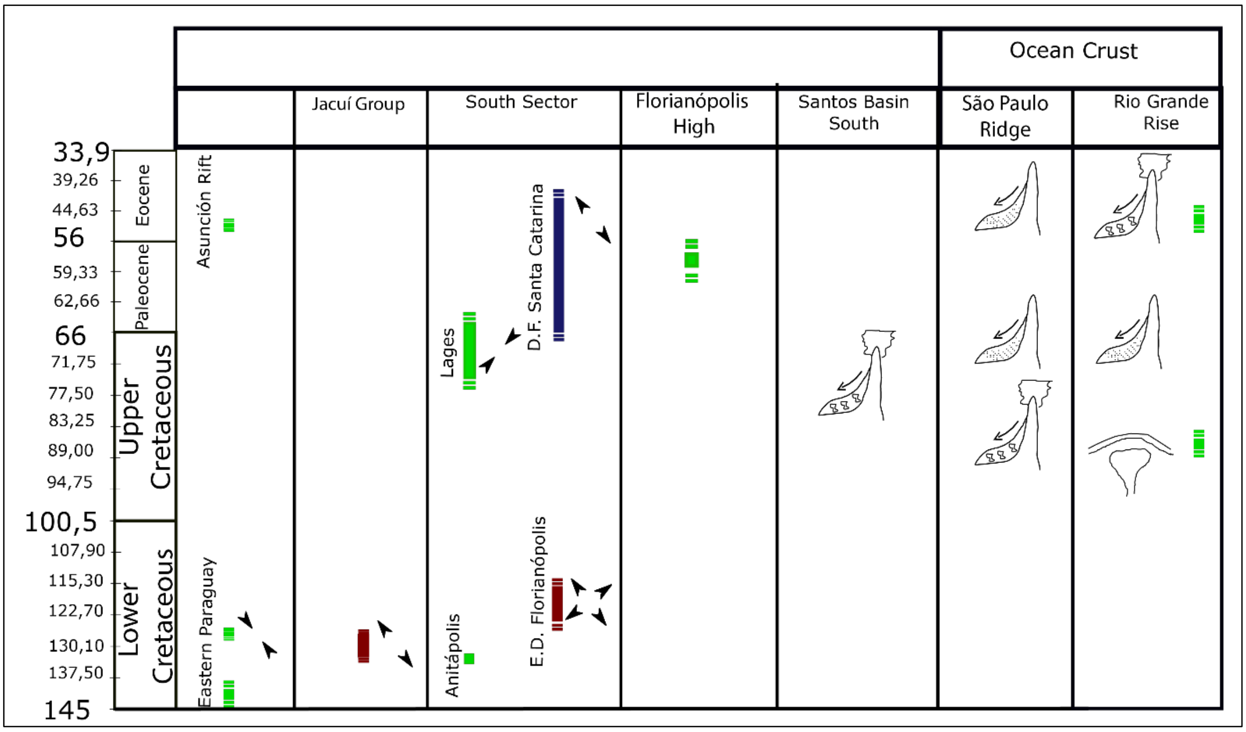

Figure 2: Age of magmatism and paleostress field in the different sectors (Figure 1). Compiled from: Fodor and Thiede (1977); Perch-Nielsen et al. (1977); Fodor et al. (1983); Gamboa and Rabinowitz (1984); Riccomini et al. (2002); Jelinek et al. (2003); Almeida et al. (2013); Florisbal et al. (2014); Riccomini et al. (2016); Schattner and de Mahiques (2020).

The São Paulo Ridge (Figure 1), characterized by a relief of 2000 m at its eastern end, gradually decreases towards the west and is totally buried by sediments at Longitude 45°W. The Deep Sea Drilling Project (DSDP), Site 356, drilled sediment cores and igneous rocks in the São Paulo Ridge (Perch-Nielsen et al., 1977; Fodor et al., 1980) (Figure 1). The analysis of 741 meters of cored sediments recovered from Site 356 indicates that the sediment source is both the Santos Basin and the ridge itself. There are three São Paulo Ridge slump events: in the Eocene, and between the Maastrichtian and Turonian ages (Perch-Nielsen et al., 1977; Fodor et al., 1977; Kumar et al., 1977) (Figure 2). The older slump (Coniacian/Mid Turonian - Unit 6) (Perch-Nielsen et al., 1977) is a conglomerate with basaltic clasts, indicating volcanic activity at the São Paulo Ridge, which were classified as magmatic breccia (Kumar et al., 1977; Kumar and Gamboa, 1979). At the bottom of the overlying unit (Maestrichtian/Santonian – Unit 5) (Perch-Nielsen et al., 1977), it occurs marly calcareous chalks containing small, sub-rounded basalt pebbles, about 3.5 cm long and 2 cm thick, along with pebble-sized fragments of dark mudstone (Perch-Nielsen et al., 1977). The analysis of those igneous clasts recovered from the Site 356 indicates that they were emplaced strictly in a fracture-zone environment, or in a fracture-zone environment that was later subjected to greenschist facies metamorphism (Fodor et al., 1980). The described mineral paragenesis (Fodor et al., 1980) is indicative of fault weakening processes (Wintsch et al., 1995).

The Rio Grande Rise (Figure 1) is a major aseismic rise in the western South Atlantic Ocean. It is divided into West Rio Grande Rise and East Rio Grande Rise (Gamboa and Rabinowitz, 1984). The western portion has an approximate elliptical shape with E-W main axis (Gamboa and Rabinowitz, 1984) bounded northward by the FFZ. The eastern portion has a north-south trend and may represent an abandoned spreading center (Gamboa and Rabinowitz, 1984).

The Rio Grande Rise was drilled during the DSDP Legs 39 and 72. The cores which recovered igneous rocks are the Sites 357 and 516F. The base of Hole 516F includes calcareous and volcanogenic sediments, ferruginous chert, and two or more relatively fresh basalt flow units (Barker et al., 1983). The best estimate of the Ar/Ar age of the basalt at the base of Hole 516F is 86.0 ± 4 Ma, which agrees with estimates from a seafloor spreading model of 84.5 ±0.5 Ma (Mussett and Barker, 1983; Rohde et al., 2013). At Site 357, basaltic pebbles were found embedded in 4 meters of breccia composed mainly by calcareous pelagic matrix at the Middle Eocene section (Fodor and Thiede, 1977). Relations between breccia matrix, mineral paragenesis and chemical analysis of the igneous clasts indicate that those rocks have alkaline affinity and were formed in an ocean island environment triggered by a hot spot or by a fracture zone prior to and during the Eocene time (Fodor and Thiede, 1977).

Analysis of sediments recovered at Sites 357 and 516F along with multichannel seismic allowed Gamboa and Rabinowitz (1984) to propose the following evolutionary model (Figure 2): the Rio Grande Rise presents a first phase of basaltic flow in the Coniacian/Santonian (O´Connor and Duncan, 1990) followed by extensional movements causing rifting during the uplift of the large volcanic bulge (Gamboa and Rabinowitz, 1984; Praxedes et al., 2019). By the Middle Eocene (Fodor and Thiede, 1977; Gamboa and Rabinowitz, 1984), volcanic islands emerged above sea level increasing the deposition of volcanic breccia and ash layers (Gamboa and Rabinowitz, 1984). After volcanism ceased, thermal subsidence took place over the entire rise with intense erosion and sedimentation. Finally, the uppermost sedimentary layers were deposited in pelagic conditions and offset by sub-vertical normal faults (Praxedes et al., 2019).

Continental Crust Magmatism in the Florianópolis Fracture Zone

Thermo-magmatic events in the continental margin in proximity to the FFZ are described and can be subdivided as follows (Scheibe et al., 2005): 1) the early stages of rifting before the Africa-South America separation; 2) the time of sea-floor spreading; 3) a more advanced stage of the continental separation. They can also be subdivided according to their emplacement tectonic control (Figure 2).

The first group is related to the alkaline magmatism in Eastern Paraguay (145-138,9 Ma) followed by flood tholeiitic basalts of the Serra Geral Formation (133-130 Ma). Synchronously, the Anitápolis alkaline-carbonatite complex (132 Ma) and the Florianópolis Dike Swarm (134 Ma) intruded in the Late Proterozoic crystalline basement in Santa Catarina State (Rodrigues, 1985; Scheibe, 1986; Scheibe et al., 2005; Almeida et al 2013; Florisbal et al., 2014).

The second group is related to the Florianópolis Dyke Swarm during the Late Early Cretaceous (134 Ma) and by a second pulse of alkaline magmatism in Eastern Paraguay concentrated in the Asunción Rift (Velázquez et al., 2011). The last group is represented by the Late Cretaceous (76 Ma) alkaline-carbonatite magmatism in Lages Province (Scheibe, 1986; Scheibe et al., 2005; Gomes et al., 2018), by the precipitation of the Santa Catarina Fluorite District (67 to 40 Ma) (Jelinek et al., 2003), and by the alkaline rock recovery by the Petrobras exploration well 1-SCS-1-SC which chronological data indicate 58 Ma for the emplacement of those rocks in the Florianópolis High (Fodor et al., 1983).

The group related to the last phase is represented by the Asunción Rift Alkaline Province. En-echelon NW-SE dykes intruding the Asunción Rift is indicative of the paleostress field related to an E-W dextral couple during the Paleogene (Riccomini et al., 2002).

Intruded in the Luis Alves Craton, it occurs some alkaline rocks in the form of dykes, volcanic flows and plugs (Iglesias et al., 2011). There is no available age data for these occurrences.

Continental Crust Paleotensions Florianópolis Fracture Zone

The Florianópolis Dyke Swarm is characterized by subvertical dykes with generally N208E, N108E and N258W strike, cross-cutting the granitic rocks of the Florianópolis Batholith. Geometric analysis indicates both dextral and sinistral sense of shear during its intrusion (Almeida et al., 2013). According to Almeida et al. (2013), the 119.0 + 0.9 to 139.1 + 3.4 Ma Ar/Ar age (Raposo et al., 1998; Marques et al., 2003; Tomazzoli and Lima, 2006) is related to the extension of the continental crust, indicating a relationship with the stretching and thinning of the continental crust rifting phase (Almeida et al., 2013). Nevertheless, U-Pb data for the swarm indicate a 134 Ma age for this magmatism which is related to the PEMP (Paraná-Etendeka Magmatic Province), in this case associated to a pre-rift scenario (Florisbal et al., 2014), as indicated by the tectonic evolution of the Pelotas Basin.

The Lages Alcaline Province, emplaced between 64 – 77 Ma, generated a dome shape relief with its major axis in the NW-SE direction. The petrogenetic model involves partial mantle fusion, within CO_2 superior mantle contribution previously metasomatized due to basement fault reactivation (Scheibe, 1986). The NW-SE dome main axis indicates that this structure was coeval to a NE-SW SHmax paleostress field, the later cooling switched the main tensor but kept the same SHmax direction. Later phonolite dikes are preferably oriented NE-SW and some NW-SE. NNE-SSW to NE-SW dextral shear faults and the E-W sinistral shear were formed under the same paleostress field direction (Machado et al., 2012).

The Santa Catarina Fluorite District occurs predominantly at the Florianópolis Batholith. Its main occurrences are along NNE-SSW lineaments which, besides fluorite, also contain cataclastic rocks, quartz veins and calcedony. All those elements occur along a stripe 1km wide (Bastos Neto et al., 1991; Jelinek et al., 2003). Local 67 to 40 Ma AFT central ages indicate that this hydrothermal manifestation might have its roots on a regional thermic anomaly related to the FFZ associated magmatism (Jelinek et al., 2003).

The Jacuí Group represents the uppermost stratigraphic unit of the Paraná Basin. It is filled by the fluvial sediments of the Tupancireta Formation which holds volcanoclastic rocks associated to the Serra Geral magmatism. Probably it represents an interior sag basin initiated due to the NW-SE-oriented regional crustal stretching indicated by NE-SW faults and NW-SE clastic dykes (Riccomini et al., 2016).

DATA

A systematic survey of geological data was carried out from publications involving several maps, and the features of interest observed in them were recovered in georeferenced files for their manipulation. Regional geological structures and lineaments were then plotted on the magnetic map of Figure 3 for interpretation.

The image presented (Figure 3A) corresponds to the total magnetic field reduced to the pole (RTP) obtained from the global database EMAG2 (Maus et al. 2009). These authors carried out a meticulous work of compiling and selecting magnetic data from various ship and airborne surveys around the world. Using robust algorithms, these data were leveled and filtered in such a way that the long wavelengths were replaced by extremely reliable satellite measurements.

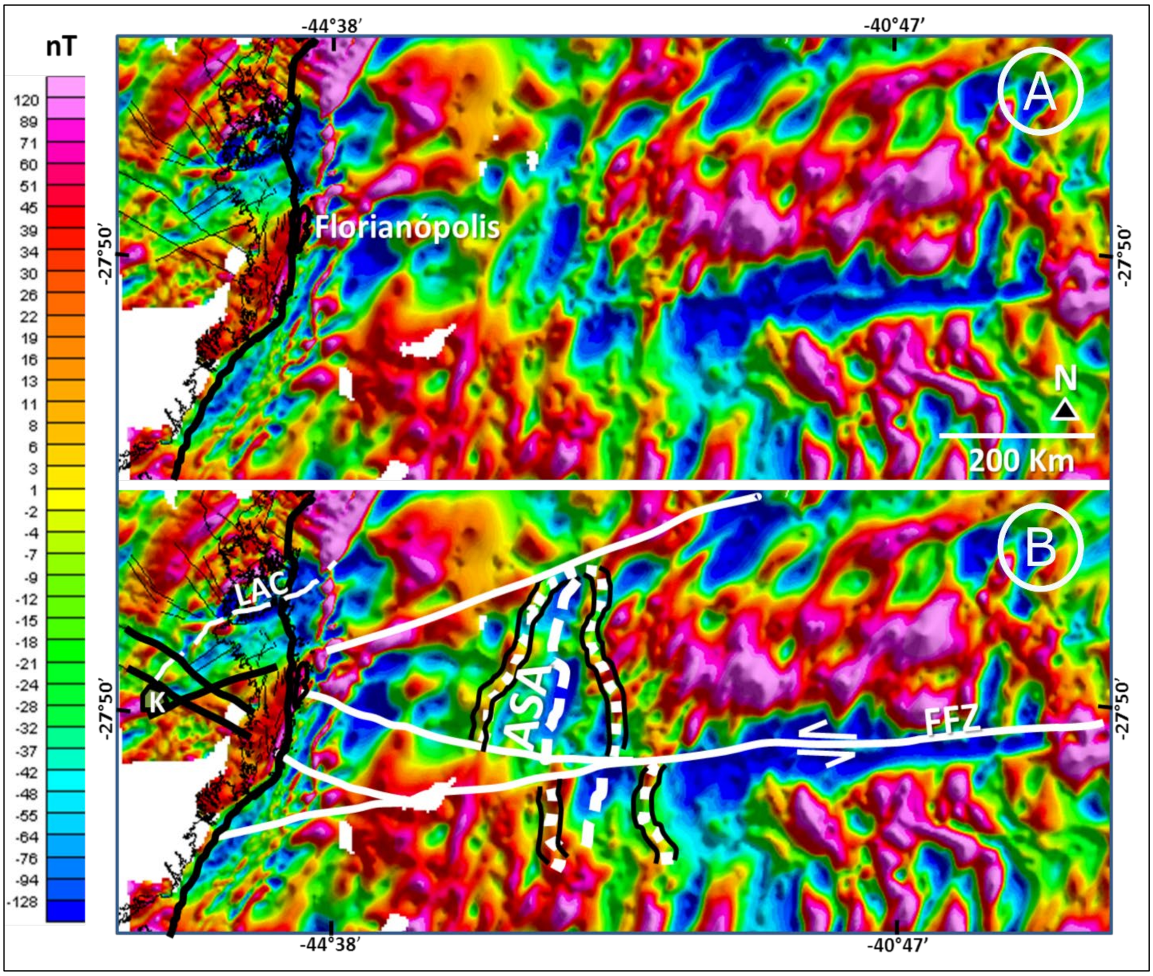

Figure 3: (A) Map of the total magnetic field reduced to the pole. Black feature – geological lineaments and faults (B) – Interpretation highlighting the magnetic lineaments; White features - highlighting the sinistral dislocation of the ASA central axis (doted lines) and its flanks (black lines along with white dots) by the Florianópolis Fracture Zone and its propagation over the continental crust in a horse tail end structural fashion. Circle K – Lages Alkaline District (~70 Ma); ASA – Aborted Spreading Axis; FFZ – Florianópolis Fracture Zone; LAC – Luis Alves Craton.

RESULTS

The main oceanic tectonic features are well delineated by the magnetic anomaly map (Figures 3a, 3b). They are the Aborted Spreading Axis (ASA) (Cande and Rabinowitz, 1978; Meisling et al., 2001; Mohriak, 2001; Gamboa et al., 2021) with a general N-S direction. The strong pink anomalies at east and northwest are volcanic covers already described by Gamboa et al. (2021). The strong blue magnetic anomaly parallel to the Florianópolis Fracture Zone is correlated with the São Paulo Ridge (Gamboa and Rabinowitz, 1981). Figure 3 also shows the adjacent continental platform overlaid by the main Precambrian structures and rocks of the Northern Dom Feliciano Belt as well as reactivation structures and intrusions.

The FFZ ramifies in three different lineaments when it reaches the attenuated crust in a horse splay fashion (Figure 3B). The main lineament direction rotates, mostly probably, in response to the different rheology of the terrain. The new lineaments are named from north to south: Florianópolis Lineament, Lagoa de Imaruí Lineament and Torres Lineament (Figure 4). The Torres Lineament points toward the projection of the NW-SE Torres Sincline.

The FFZ most northern lineament changes its trend to WNW-ESE when crossing the south border of the ASA, dislocating it eastwards indicating a sinistral reactivation.

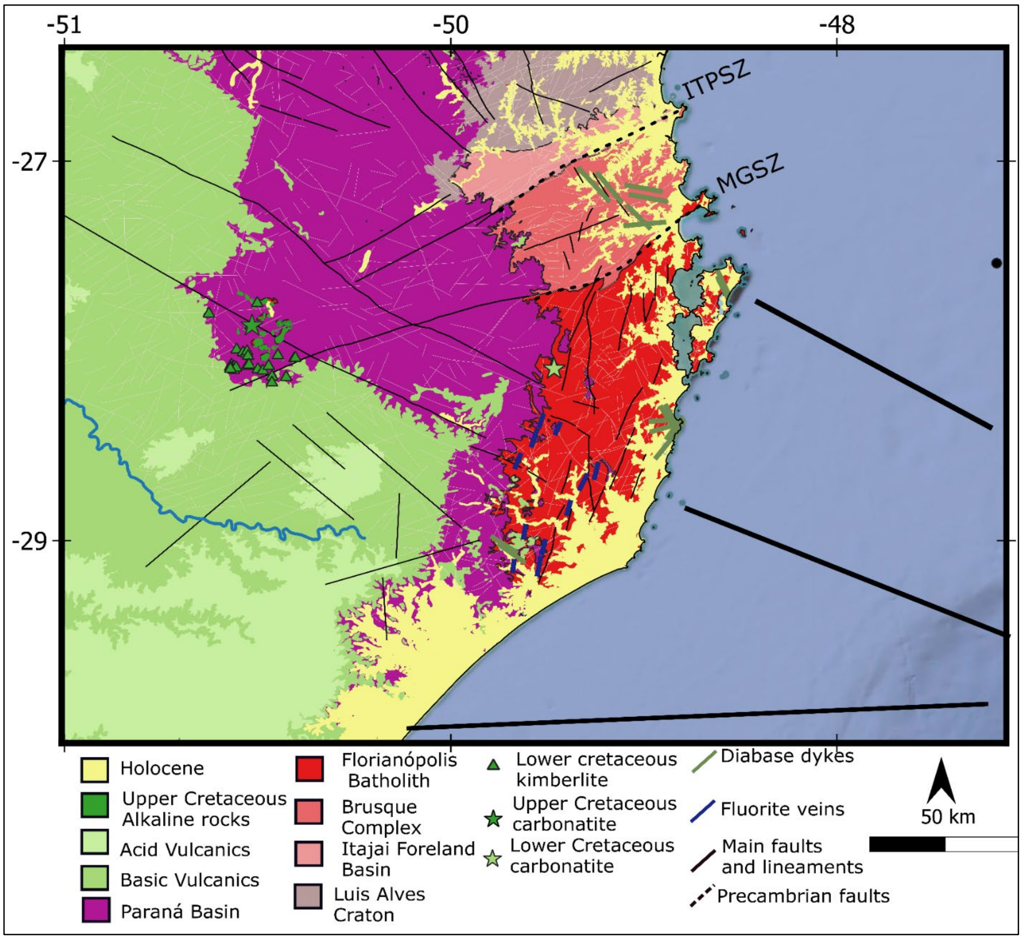

Figure 4: Geological Map of the continental margin adjacent to the Florianópolis Fracture Zone. The ocean lineaments represent the structures mapped with the potential map of Figure 3. Geology compiled from: Rodrigues (1985); Scheibe (1986); Bastos Neto et al (1991); Florisbal et al. (2014); Wildner et al. (2014); Santos et al. (2019).

In the continental crust, the Florianópolis Lineament points toward the carbonatitic occurrence of Anitápolis (132 Ma) and to the NW-SE diabase dykes of the Florianópolis Dyke Swarm. This indicates that it is the first structure formed during the rifting phase. This lineament also has a good correlation with the NW-SE dissected scarps of the Serra Geral Group, indicating a posterior reactivation phase.

The Lagoa do Imaruí Lineament cleary correlates with the Lages Alkaline Dome, indicated by the dome intrusion NW-SE main axis. This lineament exerts a control over the emplacement of NW-SE aligned kimberlites and carbonatites, indicating that this fault might reach the mantle. The NE-SW SHmax tectonic control of the Early Paleocene phonolite dykes related to this intrusion indicates that the landward reactivation of the Lagoa do Imaruí Lineament was concomitant to a plate sinistral rotation.

The magnetic response of the northern Dom Feliciano Mobile Belt clearly correlates with the major tectonic features. The Major Gercino Shear Zone, which characterizes the contact between the Florianópolis Batholith and the Brusque Metamorphic Belt, makes a sharp magnetic contact which reflects the strong shear strength variance between these two units. Its projection to the northeast reaches the north end of the ASA structure.

The Santa Catarina Fluorite District is also compatible with an E-W sinistral couple; however, its 60-40 Ma indicates a diachronic event. This fact means that E-W sinistral couple remained active at least until the Middle Eocene. This thermo-tectonic event is synchronic with the Eocene magmatic activity in the Rio Grande Rise (Fodor and Thiede, 1977) and with the alkaline intrusion in the Florianópolis High (Fodor et al., 1983).

DISCUSSION

The fracture zone reactivation (Pockalny et al., 1997; Maia et al., 2016) implies a plate rotation promoted by rotation pole migration and variations on spreading rate of the ocean floor. These changes modify the fracture zone tracing and create sites of deformation and magmatism.

The FFZ is a reactivation of the former Florianópolis Transform Zone between the Santos and Pelotas Basins during the Late Cretaceous pole migration (Szatmari and Milani, 2016). As the imposed deformation also affects the continental crust, the reactivation process was influenced by the contrasting shear strength between the oceanic and the continental crust (Dauteuil et al., 2002).

The three magnetic anomalies, which present a structural horse tail end geometry, emerged from the FFZ tracing near Longitude 42W (Figure 3B). This position is the inferred position of the Pelotas Basin COB north end. From this point westward, the FFZ progressively thickens until reaching the emerged continental terrain, a correlation made via field geology.

There are two hypotheses for the time of generation of those lineaments; each of them requires a different geotectonic explanation: sin rift tectonics and Late Cretaceous reactivation.

The hypothesis is that lateral rheological variation can promote segmentation along rifted margins. The sinistral finite movement is inferred by the left lateral displacement of the Pelotas Basin aborted spreading axis prolongation and by the NE-SW SHmax dyke intrusion control.

To resolve this differential spreading rate between Pelotas and Santos, the Florianópolis Fracture Zone reactivated and became a site of intense volcanism. The age of volcanism became younger toward the continent.

Figure 5 shows that the magmatism and deformation during the Late Cretaceous are towards the continent. The migration of volcanic activity is related to the variation of pole rotation and spreading rate of the ocean floor during the Late Cretaceous (Pérez-Díaz and Eagles, 2014).

Figure 5B sketches the reactivation of the Florianópolis Fracture Zone at Campanian times. It is characterized by volcano structures emplaced in the Santos Basin Campanian strata, defined as the Santos Cluster (Schattner and de Mahiques, 2020).

The model proposes that magmatic activity migrates towards the continent. In the Turonian times, the magmatic activity occurs in the São Paulo ridge. Plate reorganization during the Late Cretaceous rotates the Florianópolis Fracture Zone.

The magmatism in the prolongation of the FFZ into the continent is controlled by basement inherited structure directions, shear strength variation and far field stress. The Lages Alkaline province is located at the crossing between NW-SE and NE-SW basement directions. Another important factor is the differential shear strength imposed by adjacent basement crustal blocks – the Luis Alves Craton and the Brusque Metamorphic Complex.

The inland magmatism aligned to the regional tracing of the continental portion of the FFZ presents decreasing age towards the continent (Figures 2 and 5) with, however, contrasting paleo tension control. The Asunción Rift alkaline intrusions are controlled by the compressional stress promoted by the far field stress imposed by the subduction of the Nazca Plate under the South America Plate (Riccomini et al., 2002).

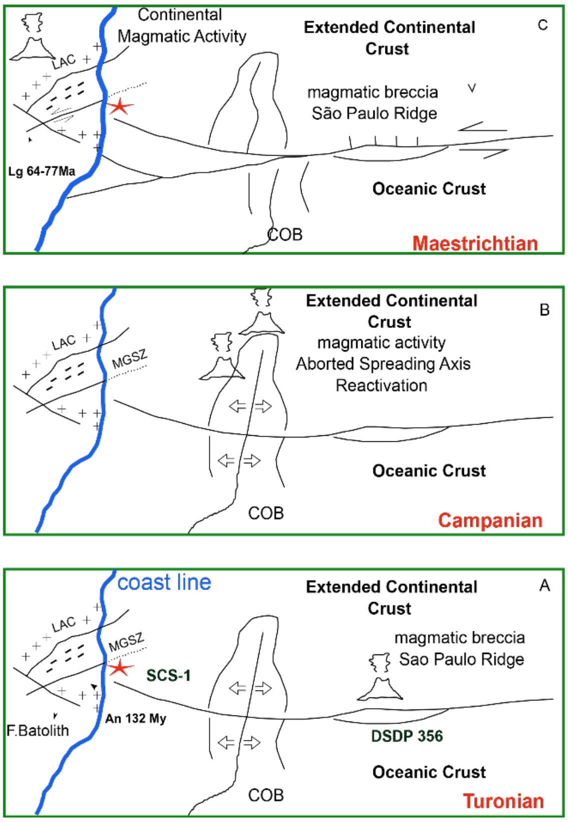

Figure 5: Evolutionary model of the magmatism and reactivation of Florianópolis Fracture Zone during the Late Cretaceous. A) Turonian - in this time the ASA was already formed (Cande and Rabinowitz, 1978; Meisling et al., 2001; Mohriak, 2001; Gamboa et al., 2021) and Anitápolis Alcaline District intruded (An - 132 Ma) (Scheibe, 1986). The reactivation was registered by magmatic breccia recovery by the IODP site 356 in the São Paulo Ridge B) Magmatism activities form volcano structures in the Campanian strata of the Santos Basin south portion (Schattner and de Mahiques, 2020); C) Emplacement of the Lages District (Lg 64 – 77 Ma) controlled by the reactivation and segmentation of the Florianópolis Fracture Zone. The ASA (Gamboa et al., 2021) was also deformed by a sinistral E-W binary.

CONCLUSION

The Florianópolis Fracture Zone (FFZ) bounds the saline hyperextended Santos to the north and the magma rich Pelotas Basins. During the Cretaceous evolution, this fault acted as a transform fault and became a fracture zone after the end of the salt deposition.

Meanwhile in the continental platform, NW-SE basement inherited structures got reactivated as variations in the Paraná Basin sedimentary packages. During these reactivations, the aligned Late Cretaceous alkaline province was intruded (Asunción Rift and Lages).

During the Late Cretaceous, the FFZ already had its principal morphology as the São Paulo Ridge emerged. Pole rotations along with contrasting spreading rates between the Santos and Pelotas Basins reactivated the FFZ. The deformation started at the Rio Grande Rise with the bulging of the ocean floor in the Santonian.

Magmatic and deformation sites move westward in the São Paulo Ridge, where basalt pebbles were found just after the breccia level. In the Campanian, magmatism is registered at the south portion of the Santos Basin (Schattner and de Mahiques, 2020).

The transition from continental crust to oceanic crust is achieved by the formation of a near coastline normal fault parallel to it and horse-tail / splay like structures verging to the FFZ. The shear strength variation and the Late Cretaceous plate reorganization are the competing factor with shear strength controlling the angle variation of the FFZ at the already attenuated crust.

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REFERENCES

Almeida, F. F. M., C. D. R. Carneiro, and A. M. P. Mizusaki, 1996, Correlação do magmatismo das bacias da margem continental brasileira com o das áreas emersas adjacentes: Revista Brasileira de Geociências, **26**, 3, 125–138, doi: 10.25249/0375-7536.19963125138.

Almeida, J., F. Dios, W. U. Mohriak, C. D. M. Valeriano, M. Heilbron, L. G. Eirado, and E. Tomazzoli, 2013, Pre-rift tectonic scenario of the Eo-Cretaceous Gondwana break-up along SE Brazil–SW Africa: insights from tholeiitic mafic dyke swarms, *in* Mohriak, W. U., A. Danforth, P. J. Post, D. E. Brown, G. C. Tari, M. Nemčok, and S. T. Sinha, Conjugate Divergent Margins: Geological Society, London, Special Publications, **369**, 1, 11–40, doi: 10.1144/SP369.24.

Asmus, H. E., 1978, Hipóteses sobre a origem dos sistemas de zonas de fratura oceânicas / alinhamentos continentais que ocorrem nas regiões sudeste e sul do Brasil, *in* Aspectos estruturais da margem continental leste e sudeste do Brasil: Série Projeto REMAC, Petrobras, Cenpes, RJ, Brazil, **4**, 39–73.

Barker, P. F., R. L. Carlson, D. A. Johnson, P. Čepek, W. T. Coulbourn, L. A. Gamboa, N. Hamilton, U. Melo, C. Pujol, A. N. Shor, R. C. Tjalsma, and W. H. Walton, 1983, Site 516: Rio Grande Rise, *in* Barker, P.F., D.A. Johnson, R.L. Carlson, P. Čepek, W.T. Coulbourn, L.P. Gamboa, N. Hamilton, U. Melo, C. Pujol, A.N. Shor, A.E. Suzyumov, L.R.C. Tjalsma, W.H. Walton, and E. Whalen, Initial Reports of the Deep Sea Drilling Project, DSDP, 72: Washington (U.S. Government Printing Office), covering Leg 72 of the cruises of the Drilling Vessel Glomar Challenger, Santos, Brazil to Santos, Brazil, February-April, 1980, 5, 155–338, doi: 10.2973/dsdp.proc.72.105.1983.

Bastos Neto, A., J. Charvet, J. C. Touray, and M.A. Dardenne, 1991, Evolution tectonique du district a fluorine de Santa Catarina (Bresil) en relation avec l'ouverture de l'Atlantique Sud: Bulletin de la Société Géologique de France, 3, 503–513, doi: 10.2113/gssgfbull.162.3.503.

Bellahsen, N., S. Leroy, J. Autin, P. Razin, E. d'Acremont, H. Sloan, R. Pik, A. Ahmed, and K. Khanbari, 2013, Pre-existing oblique transfer zones and transfer / transform relationships in continental margins: New insights from the southeastern Gulf of Aden, Socotra Island, Yemen: Tectonophysics, **607**, 32–50, doi: 10.1016/j.tecto.2013.07.036.

Cande, S. C., and P. D. Rabinowitz, 1978, Mesozoic seafloor spreading bordering conjugate continental margins of Angola and Brazil: Offshore Technology Conference, Houston, Texas, OnePetro, p. 1–8, OTC-3268-MS, doi: 10.4043/3268-MS.

Cernuschi, F., J. H. Dilles, A. J. R. Kent, G. Schroer, A. K. Raab, B. Conti, and R. Muzio, 2015, Geology, geochemistry and geochronology of the Cretaceous Lascano East Intrusive Complex and magmatic evolution of the Laguna Merín Basin, Uruguay: Gondwana Research, **28**, 2, 837–857, doi: 10.1016/j.gr.2014.07.007.

Comin-Chiaramonti, P., A. Marzoli, C. de Barros Gomes, A. Milan, C. Riccomini, V.F. Velázquez, M.M.S. Mantovani, P. Renne, C.C.G. Tassinari, and

P.M. Vasconcelos, 2007, The origin of post-Paleozoic magmatism in eastern Paraguay, *in* Foulger, G. R., and D. M. Jurdy, eds., Plates, Plumes and Planetary Processes, Geological Society of America, GSA Special Paper, **430**, 603–633, doi: 10.1130/2007.2430(29).

Cordani, U.G., V. Ramos, L.M. Fraga, M. Cegarra, I. Delgado, K.G. Souza, F.E.M. Gomes, and C. Schobbenhaus, 2016, Tectonic Map of South America: 2nd ed., 1:5,000,000 Commission for the Geologic Map of the World.

Curie, D., 1984, Ouverture de l'Atlantique sud et discontinuités intra-plaques: une nouvelle analyse: Ph.D. thesis, Université de Bretagne Occidentale, 192 pp.

Dauteuil, O., O. Bourgeois, and T. Mauduit, 2002, Lithosphere strength controls oceanic transform zone structure: insights from analogue models: Geophysical Journal International, **150**, 3, 706–714, doi: 10.1046/j.1365-246X.2002.01736.x.

Florisbal, L. M., L. M. Heaman, V. de Assis Janasi, and M. de Fatima Bitencourt, 2014, Tectonic significance of the Florianópolis dyke Swarm, Paraná–Etendeka Magmatic Province: a reappraisal based on precise U–Pb dating: Journal of Volcanology and Geothermal Research, **289**, 140–150, doi: 10.1016/j.jvolgeores.2014.11.007.

Fodor, R.V., and J. Thiede, 1977, Volcanic Breccia from DSDP Site 357: Implications for the composition and origin of the Rio Grande Rise, *in* Supko, P.R., K. Perch-Nielsen, Y.P. Neprochnov, H.B. Zimmerman, F. McCoy, F. Kumar, J. Thiede, E. Bonatti, R. Fodor, A. Boersma, M.G. Dinkelman, and R.L. Carlson, eds., Initial Reports of the Deep Sea Drilling Project, DSDP, 39: Washington (U.S. Government Printing Office), 21, 537–543, doi: 10.2973/dsdp.proc.39.121.1977.

Fodor, R.V., J.W. Husler, and K. Keil, 1977, Petrology of basalt recovered during DSDP Leg 39B, *in* Supko, P.R., K. Perch-Nielsen, Y.P. Neprochnov, H.B. Zimmerman, F. McCoy, F. Kumar, J. Thiede, E. Bonatti, R. Fodor, A. Boersma, M.G. Dinkelman, and R.L. Carlson, eds., Initial Reports of the Deep Sea Drilling Project, DSDP, 39: Washington (U.S. Government Printing Office), 19, 513–523, doi: 10.2973/dsdp.proc.39.119.1977.

Fodor, R. V., N. Kumar, T. J. Bornhorst, and J. W. Husler, 1980, Petrology of basaltic rocks from the São Paulo ridge, southwestern Atlantic Ocean: Marine Geology, **36**, 1–2, 127–141, doi: 10.1016/0025-3227(80)90044-4.

Fodor, R. V., E. H. McKee, and H. E. Asmus, 1983, K-Ar ages and the opening of the South Atlantic Ocean: basaltic rock from the Brazilian margin: Marine Geology, **54**, 1–2, M1–M8, doi: 10.1016/0025-3227(83)90002-6.

Gamboa, L. A. P., and P. D. Rabinowitz, 1981, The Rio Grande fracture zone in the western South Atlantic and its tectonic implications: Earth and Planetary Science Letters, **52**, 2, 410–418, doi: 10.1016/0012-821X(81)90193-X.

Gamboa, L. A. P., and P. D. Rabinowitz, 1984, The evolution of the Rio Grande Rise in the southwest Atlantic Ocean: Marine Geology, **58**, 1–2, 35–58, doi: 10.1016/0025-3227(84)90115-4.

Gamboa, L. A. P., A. Ferraz, L.H. Drehmer, and L. S. Demercian, 2021, Seismic, magnetic, and gravity evidence of marine incursions in the Santos Basin during the early Aptian, *in* Mello, M.R., Yilmaz, P.O., and B.J. Katz, eds., The supergiant Lower Cretaceous pre-salt petroleum systems of the Santos Basin, Brazil: AAPG Memoir, **124**, p. 257–272, doi: 10.1306/13722322MSB.10.1853.

Gomes, C.B., P. Comin-Chiaramonti, R.G. Azzone, E. Ruberti, and G.E.E. Rojas, 2018, Cretaceous carbonatites of the southeastern Brazilian Platform: A review: Brazilian Journal of Geology, **48**, 2, 317–345, doi: 10.1590/2317-4889201820170123.

Heilbron, M., A. C. Pedrosa-Soares, M. C. Campos Neto, L. C. Silva, R. A. J. Trouw, and V. A. Janasi, 2004, Província Mantiqueira, *in* Mantesso-Neto, V., A. Bartorelli, C.D.R. Carneiro, and B.B. Brito-Neves, eds., Geologia do Continente Sul-Americano: Evolução da obra de Fernando Flávio Marques de Almeida, Beca, São Paulo, chapter XIII, 203–235.

Hueck, M., P. Oyhantçabal, R. P. Philipp, M. A. S. Basei, S. Siegesmund, 2018, The Dom Feliciano belt in southern Brazil and Uruguay, *in* Siegesmund, S., M. A. S. Basei, P. Oyhantçabal, S. Oriolo, eds., Geology of Southwest Gondwana: Regional Geology Reviews, Springer, Heidelberg, p. 267–302, doi: 10.1007/978-3-319-68920-3_11.

Iglesias, C. M. F., H. Zerfass, M. A. S. Silva, C. Klein, 2011. Geologia e recursos minerais da folha Joinville - SG.22-Z-B: Estado de Santa Catarina. Porto Alegre, Brazil: CPRM, 106 p. 1 mapa, color. Escala 1:250.000.

Jarrige, J.-J., P. Ott d'Estevou, P. F. Burollet, C. Montenat, P. Prat, J.-P. Richert, and J.-P. Thiriet, 1990, The multistage tectonic evolution of the Gulf of Suez and northern Red Sea continental rift from field observations: Tectonics, **9**, 3, 441–465, doi: 10.1029/TC009i003p00441.

Jelinek, A. R., A. C. Bastos Neto, and G. Poupeau, 2003, Análise por traços de fissão em apatitas do distrito fluorítico de Santa Catarina: relações entre hidrotermalismo e evolução da margem continental: Revista Brasileira de Geociências, **33**, 3, 289–298, doi: 10.25249/0375-7536.2003333289298.

Karner, G. D., and L. A. P. Gambôa, 2007, Timing and origin of the South Atlantic pre-salt sag basins and their capping evaporites, *in* Schreiber B. C., S. Lugli, and M. Babel, eds., Evaporites Through Space and Time: Geological Society, London, Special Publications, **285**, 1, 15–35, doi: 10.1144/SP285.2.

Kumar, N., L. A. P. Gambôa, B. C. Schreiber, and J. Mascle, 1977, Geologic History and Origin of São Paulo Plateau (Southeastern Brazilian Margin), Comparison with the Angolan Margin, and the early evolution of the Northern South Atlantic, *in* Supko, P.R., K. Perch-Nielsen, Y.P. Neprochnov, H.B. Zimmerman, F. McCoy, F. Kumar, J. Thiede, E. Bonatti, R. Fodor, A. Boersma, M.G. Dinkelman, and R.L. Carlson, eds., Initial Reports of the Deep Sea Drilling Project, DSDP, 39: Washington (U.S. Government Printing Office), 40, 927–945, doi: 10.2973/dsdp.proc.39.140.1977.

Kumar, N., and L. A. P. Gamboa, 1979, Evolution of the São Paulo Plateau (southeastern Brazilian margin) and implications for the early history of the South Atlantic: Geological Society of America Bulletin, **90**, 3, 281–293, doi: 10.1130/0016-7606(1979)90%3C281:EOTSPP%3E2.0.CO;2.

Le Pourhiet, L., D. A. May, L. Huille, L. Watremez, and S. Leroy, 2017, A genetic link between transform and hyper-extended margins: Earth and Planetary Science Letters, **465**, 184–192, doi: 10.1016/j.epsl.2017.02.043.

Lezzar, K. E., J.-J. Tiercelin, C. Le Turdu, A. S. Cohen, D. J. Reynolds, B. Le Gall, and C. A. Scholz, 2002, Control of normal fault interaction on the distribution of major Neogene sedimentary depocenters, Lake Tanganyika, East African rift: AAPG Bulletin, **86**, 6, 1027–1059, doi: 10.1306/61EEDC1A-173E-11D7-8645000102C1865D.

Machado, R., L. F. Roldan, P. D. Jacques, E. Fassbinder, and A. R. Nummer, 2012, Tectônica transcorrente Mesozoica-Cenozoica no Domo de Lages – Santa Catarina: Revista Brasileira de Geociências, **42**, 4, 799–811, doi: 10.5327/Z0375-75362012000400011.

Maia, M., S. Sichel, A. Briais, D. Brunelli, M. Ligi, N. Ferreira, T. Campos, B. Mougel, I. Brehme, C. Hémond, A. Motoki, D. Moura, C. Scalabrin, I. Pessanha, E. Alves, A. Ayres, and P. Oliveira, 2016, Extreme mantle uplift and exhumation along a transpressive transform fault: Nat. Geosci., **9**, 619–623, doi: 10.1038/ngeo2759.

Marques, L. S., M. Babinski, I. R. Ruiz, 2003. Lead isotopes of Early Cretaceous coastal dykes of Paraná Magmatic Province (Florianópolis Swarm): preliminary results: IV Simpósio Sul-americano de Geologia Isotópica. Short Papers, Salvador, BA, Brazil, pp. 605–608.

Marsh, J. S., 1973, Relationships between transform directions and alkaline igneous rock lineaments in Africa and South America: Earth and Planetary Science Letters, **18**, 2, 317–323, doi: 10.1016/0012-821X(73)90070-8.

Maus, S., U. Barckhausen, H. Berkenbosch, N. Bournas, J. Brozena, V. Childers, F. Dostaler, J. D. Fairhead, C. Finn, R.R.B. von Frese, C. Gaina, S. Golynsky, R. Kucks, H. Lühr, P. Milligan, S. Mogren, R. D. Müller, O. Olesen, M. Pilkington, R. Saltus, B. Schreckenberger, E. Thébault, and F. Caratori Tontini, 2009, EMAG2: A 2–arc min resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne, and marine magnetic measurements. Geochemistry Geophysics Geosystems, **10**, 8, Q08005, 1–12, doi: 10.1029/2009GC002471.

Meisling, K. E., P. R. Cobbold, and V. S. Mount, 2001, Segmentation of an obliquely rifted margin, Campos and Santos basins, southeastern Brazil: AAPG Bulletin, **85**, 11, 1903–1924, doi: 10.1306/8626D0A9-173B-11D7-8645000102C1865D.

Miller, J. Mc L., M. S. Norvick, and C. J. L. Wilson, 2002, Basement controls on rifting and the associated formation of ocean transform faults — Cretaceous continental extension of the southern margin of Australia: Tectonophysics, **359**, 1–2, 131–155, doi: 10.1016/S0040-1951(02)00508-5.

Misra, A. A., and S. Mukherjee, 2015, Tectonic inheritance in continental rifts and passive margins: Cham, Springer, 88 p, doi: 10.1007/978-3-319-20576-2.

Mohriak, W. U., 2001, Salt tectonics, volcanic centers, fracture zones and their relationship with the origin and evolution of the South Atlantic Ocean: geophysical evidence in the Brazilian and West African margins: 7th International Congress of the Brazilian Geophysical Society, SBGf, Salvador, BA, Brazil, October 28–31, Expanded Abstract, p. 1594.

Moulin, M., D. Aslanian, M. Rabineau, M. Patriat, and L. Matias, 2013, Kinematic keys of the Santos-Namibe basins, *in* Mohriak, W. U., A. Danforth, P. J. Post, D. E. Brown, G. C. Tari, M. Nemčok, and S. T. Sinha, Conjugate Divergent Margins: Geological Society of London, Special Publications, **369**, 91–107, doi: 10.1144/SP369.

Moustafa, A. R., 1997, Controls on the development and evolution of transfer zones: the influence of basement structure and sedimentary thickness in the Suez rift and Red Sea: Journal of Structural Geology, **19**, 6, 755–768, doi: 10.1016/S0191-8141(97)00007-2.

Mussett, A. E., and P. F. Barker, 1983, $^{40}Ar/^{39}Ar$ Age spectra of basalts, deep sea drilling project Site 516, *in* Barker, P.F., D.A. Johnson, R.L. Carlson, P. Čepek, W.T. Coulbourn, L.P. Gamboa, N. Hamilton, U. Melo, C. Pujol, A.N. Shor, A.E. Suzyumov, L.R.C. Tjalsma, W.H. Walton, and E. Whalen, Initial Reports of the Deep Sea Drilling Project, DSDP, 72: Washington (U.S. Government Printing Office), covering Leg 72 of the cruises of the Drilling Vessel Glomar Challenger, Santos, Brazil to Santos, Brazil, February-April, 1980, 16, 467–470, doi: 10.2973/dsdp.proc.72.116.1983.

O'Connor, J. M., and R. A. Duncan, 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, doi: 10.1029/JB095iB11p17475.

Perch-Nielsen, K., P. R. Supko, A. Boersma, R. L. Carlson, M. G. Dinkelman, R. V. Fodor, N. Kumar, F. McCoy, J. Thiede, H. B. Zimmerman, 1977, Site 356: São Paulo Plateau, *in* Supko, P.R., K. Perch-Nielsen, Y.P. Neprochnov, H.B. Zimmerman, F. McCoy, F. Kumar, J. Thiede, E. Bonatti, R. Fodor, A. Boersma, M.G. Dinkelman, and R.L. Carlson, eds., Initial Reports of the Deep Sea Drilling Project, DSDP, 39: Washington (U.S. Government Printing Office), 5, 141–230, doi: 10.2973/dsdp.proc.39.105.1977.

Pérez-Díaz, L., and G. Eagles, 2014, Constraining South Atlantic growth with seafloor spreading data: Tectonics, **33**, 9, 1848–1873, doi: 10.1002/2014TC003644.

Pockalny, R. A., P. J. Fox, D. J. Fornari, K. C. Macdonald, and M. R. Perfit, 1997, Tectonic reconstruction of the Clipperton and Siqueiros Fracture Zones: Evidence and consequences of plate motion change for the last 3 Myr: Journal of Geophysical Research: Solid Earth, **102**, B2, 3167–3181, doi: 10.1029/96JB03391.

Praxedes, A. G. P., D. L. de Castro, L. C. Torres, L. A. P. Gambôa, and P. C. Hackspacher, 2019, New insights of the tectonic and sedimentary evolution of the Rio Grande Rise, South Atlantic Ocean: Marine and Petroleum Geology, **110**, 335–346, doi: 10.1016/j.marpetgeo.2019.07.035.

Rabinowitz, P. D., and J. LaBrecque, 1979, The Mesozoic South Atlantic Ocean and evolution of its continental margins: J. Geophys. Res., **84**, B11, 5973–6002, doi: 10.1029/JB084iB11p05973.

Raposo, M. I. B., M. Ernesto, and P. R. Renne, 1998, Paleomagnetism and $^{40}Ar/^{39}Ar$ dating of the early Cretaceous Florianópolis dike swarm (Santa Catarina Island), Southern Brazil: Phys. Earth Planet. Inter., **108**, 4, 275–290, doi: 10.1016/S0031-9201(98)00102-2.

Riccomini, C., V. F. Velázquez, C. B. Gomes, A. Milan, and A. E. M. Sallun, 2002, Tectonic evolution of the Asunción Rift, eastern Paraguay: An. Acad. Bras. Ciênc., **74**, 3, 555–555, doi: 10.1590/S0001-37652002000300046.

Riccomini, C., L. G. Sant'Anna, and A. L. Ferrari, 2004, Evolução geológica do rift continental do sudeste do Brasil, *in* Mantesso-Neto V., A. Bartorelli, C. D. R. Carneiro, B. B. de Brito-Neves, orgs., Geologia do continente Sul-Americano: evolução da obra de Fernando Flávio Marques de Almeida: Editora Beca, São Paulo, Brazil, XXIII, p. 383–405.

Riccomini, C., L. G. Sant'Anna, and G. L. Fambrini, 2016, The Early Cretaceous Jacuí Group, a newly discovered volcanoclastic–epiclastic accumulation at the top of the Paraná Basin, southern Brazil: Cretaceous Research, **59**, 111–128, doi: 10.1016/j.cretres.2015.10.020.

Rodrigues, E. P. O., 1985, O complexo alcalino de Anitápolis: um estudo petrológico: Ph.D. thesis, Universidade de São Paulo, SP, Brazil. 174 pp.

Rohde, J. K., P. van den Bogaard, K. Hoernle, F. Hauff, and R. Werner, 2013, Evidence for an age progression along the Tristan-Gough volcanic track from new $^{40}Ar/^{39}Ar$ ages on phenocryst phases: Tectonophysics, **604**, 60–71, doi: 10.1016/j.tecto.2012.08.026.

Rosendahl, B. R., 1987, Architecture of continental rifts with special reference to East Africa: Annual Review of Earth and Planetary Sciences, **15**, 1, 445–503, doi: 10.1146/annurev.ea.15.050187.002305.

Santos, J. M., E. Salamuni, C. L. Silva, E. Sanches, V. B. Gimenez, and E. R. Nascimento, 2019, Morphotectonics in the Central-East region of South Brazil: implications for catchments of the Lava-Tudo and Pelotas Rivers, State of Santa Catarina: Geomorphology, **328**, 138–156, doi: 10.1016/j.geomorph.2018.12.016.

Schattner, U., and M. M. de Mahiques, 2020, Post-rift regional volcanism in southern Santos Basin and the uplift of the adjacent South American coastal range: Journal of South American Earth Sciences, **104**, 102855, doi: 10.1016/j.jsames.2020.102855.

Scheibe, L. F., 1986, Geologia e Petrologia do Distrito Alcalino de Lages, SC: Ph.D. thesis, Instituto de Geociências, Universidade de São Paulo, SP, Brazil, 224 pp.

Scheibe, L.F., S.M.A. Furtado, P. Comin-Chiaramonti, and C.B. Gomes, 2005, Cretaceous alkaline magmatism from Santa Catarina state, southern Brazil, *in* Comin-Chiaramonti, P., and C.B. Gomes, eds., Mesozoic to Cenozoic Alkaline Magmatism in the Brazilian Platform: Edusp/FAPESP, São Paulo, Brazil. 523–572.

Şengör, A.M.C., C. Zabcı, and B.A. Natal'in, 2019, Continental transform faults: Congruence and incongruence with normal plate kinematics, *in* Duarte, J. C., ed., Transform plate boundaries and fracture zones. Elsevier, chapter 9, p. 169–247, doi: 10.1016/B978-0-12-812064-4.00009-8.

Stica, J. M., P. V. Zalán, and A. L. Ferrari, 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, doi: 10.1016/j.marpetgeo.2013.10.015.

Sykes, L. R., 1978, Intraplate seismicity, reactivation of preexisting zones of weakness, alkaline magmatism, and other tectonism postdating continental fragmentation: Reviews of Geophysics, **16**, 4, 621–688, doi: 10.1029/RG016i004p00621.

Szatmari, P., and E. J. Milani, 2016, Tectonic control of the oil-rich large igneous-carbonate-salt province of the South Atlantic rift: Marine and Petroleum Geology, **77**, 567–596, doi: 10.1016/j.marpetgeo.2016.06.004.

Taylor, B., A. Goodliffe, and F. Martinez, 2009, Initiation of transform faults at rifted continental margins: Comptes Rendus Geoscience, **341**, 5, 428–438, doi: 10.1016/j.crte.2008.08.010.

Tomazzoli, E.R., and E.F. Lima, 2006, Magmatismo ácido na Ilha do Arvoredo - SC: Rev. Bras. Geoc., **36**, 1, 57–80, doi: 10.25249/0375-7536.20063616180.

Torsvik, T. H., S. Rousse, C. Labails, and M. A. Smethurst, 2009, A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin: Geophys. J. Int., **177**, 3, 1315–1333, doi: 10.1111/j.1365-246X.2009.04137.x.

Velázquez, V. F., C. Riccomini, C. de B. Gomes, and J. Kirk, 2011, The Cretaceous alkaline dyke swarm in the central segment of the Asunción Rift, eastern Paraguay: its regional distribution, mechanism of emplacement, and tectonic significance: Journal of Geological Research, Article ID 946701. 18 p., doi: 10.1155/2011/946701.

Wildner, W., E. Camozzato, J. A. Toniolo, R. B. Binotto, C. M. F. Iglesias, and J. H. Laux, 2014, Mapa geológico do estado de Santa Catarina. Porto Alegre: CPRM, Escala 1:500.000. Programa Geologia do Brasil. Subprograma de Cartografia Geológica Regional, Brazil.

Wintsch, R. P., R. Christoffersen, and A. K. Kronenberg, 1995, Fluid-rock reaction weakening of fault zones: Journal of Geophysical Research: Solid Earth, **100**, B7, 13021–13032, doi: 10.1029/94JB02622.

Wolfson-Schwehr, M., and M. S. Boettcher, 2019, Global characteristics of oceanic transform fault structure and seismicity, *in* Duarte, J. C., ed., Transform plate boundaries and fracture zones: Elsevier, chapter 2, p. 21–59, doi: 10.1016/B978-0-12-812064-4.00002-5.

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