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Contrasting stress fields on correlating margins of the South Atlantic

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ABSTRACT

The "passiveness" of passive continental margins across the globe is currently under debate since several studies have shown that these margins may experience a variety of stress states and undergo significant vertical movement post-breakup. Of special interest is the South Atlantic, because the bounding continents have very different recent geological histories, with Africa experiencing continental rifting whereas South America is influenced by subduction on the Pacific side. It is not clear to what extent the Atlantic continental margins are subject to the same stresses and vertical motions as the main continents. To address this problem, we performed a paleostress analysis of two originally adjacent areas, i.e. NW Namibia and SE/S Brazil. Both areas are covered by the ~133-Ma-old Paraná-Etendeka extrusives that were emplaced shortly before or during the onset of the Atlantic rifting. Thus, the volcanics serve as a time marker for syn- or post-rift deformation. Collected fault slip data in the volcanics reveal remarkable differences between the two correlating areas. NW Namibia was dominated by extension in ENE-WSW and SW-NE directions, and by minor strike-slip movement with NW-SE directed compression. SE/S Brazil was mostly affected by strike-slip faulting, with compression oriented E-W and SW-NE. Similar fault systems appear widespread across SE Brazil and may be the combined result of flexural margin bending and the Nazca plate subduction. The results of NW Namibia differ from known compressional stress tensors in western South Africa, post-dating 90 Ma. The south-western African continental margin may thus have experienced a spatially variable stress history. Our results show that the tectonic evolution of the continental margins of the South Atlantic is not passive and that both margins vary significantly in structural style and stress fields, indicating that variable plate boundary forces play a major role in margin evolution.

1. Introduction

Rifting of continents and the following continental break-up leads to the development of relatively stable continental margins (McKenzie, 1978). They are generally characterized by listric normal faults, rotated blocks and down-lapping sedimentary sequences. Typical examples can be found along the eastern and western rims of the Atlantic Ocean. In terms of relative vertical motion, the initial rift is characterized by a subsiding graben and adjacent high rift flanks. During break-up, volcanic activity may lead to widespread rock and surface uplift of the whole rift and this is followed by subsidence due to cooling and thermal contraction of the underlying lower lithosphere and asthenosphere. The original rift flanks adjacent to the continental margins are thought to remain at high elevation even though they are subject to considerable erosion. However, this relatively simple history has been challenged by studies that indicate that passive continental margins may be subject to multiple rock and surface uplift and subsidence phases and are thus not completely passive. Examples of margins with such complex uplift histories include the margins of northwest Britain (Stoker et al., 2010) and western Greenland (Bonow et al., 2006). The evolution of the South Atlantic passive continental margins is also currently debated (Karl et al., 2013). These margins have been affected by rifting, hotspot activity and potentially by far field stresses and regional flexural bending. There are significantly different views on how similar or different the continental margins east and west of the South Atlantic behave. Some authors (Cobbold et al., 2001) argue that far field stresses from the Andean orogeny subjected the passive continental margin of Brazil to margin-perpendicular compression throughout the Cenozoic. Others argued that the Brazilian and Namibian margins have been influenced by flexural bending due to sediment loading offshore (e.g., Lima et al., 1997; Dauteuil et al., 2013; Reis et al., 2013). On the eastern margin of the Atlantic upwelling of the African superplume, a large thermal anomaly in the lower mantle beneath southern Africa (e.g., Ritsema et al., 2011) is thought to be responsible for the high average topography of southern and eastern Africa (e.g., Lithgow-Bertelloni and Silver,

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1998; Al-Hajri et al., 2009; Moucha and Forte, 2011). Japsen et al. (2012a) favor a model where both continental margins undergo the same multiple uplift events driven by transfer of far field stresses from one continent to another.

An understanding of the behavior of continental margins following continental breakup is vital to our understanding of plate tectonics and the effects of far field stresses across continents. Therefore, we choose to perform a paleostress analysis of NW Namibia and SE/S Brazil, two areas that were connected prior to the opening of the South Atlantic (Figs. 1, 2a). The areas are ideally suited for such a study since they are covered by volcanic rocks of the Paraná-Etendeka Large Igneous Province (Milner et al., 1995), which were emplaced just before or during the onset of the South Atlantic opening (Renne et al., 1992; Torsvik et al., 2009). Furthermore, the study areas are situated at similar distances (200–250 km) from the continent-ocean boundary (as defined by Torsvik et al., 2009). The paleostress analysis was conducted using measurements on fault planes and striations on faults within the basalts of the Paraná-Etendeka sequence in order to estimate stress fields during or post breakup and thus attain an understanding of the onshore tectonic evolution of both margins.

2. Geologic setting

The continental margins of NW Namibia and SE/S Brazil are characterized by low-to-high grade metamorphic basement rocks of Neoproterozoic age (560–530 Ma) forming the Kaoko Belt on the Namibian side and the Dom Feliciano Belt on the Brazilian side, both of which developed during the amalgamation of Gondwana (e.g., Goscombe et al., 2005; Foster et al., 2009; Oyhantçabal et al., 2011; Fig. 1). The present-day continental margins run parallel or sub-parallel to prominent shear zones and the main trends of foliation and lineation in both belts. Where the shear zones are partly covered by overlying rocks, they are thought to maintain their general trend in a NE direction in the Dom Feliciano Belt, based on interpolation (e.g., Chemale et al., 2012) and a N-NNW direction in the Kaoko Belt, based on aeromagnetic data (Corner, 2008).

The basement rocks are overlain by sedimentary rocks of the Karoo (southern Africa) and the Paraná basins (South America). They belong to a set of intracontinental basins which span South America, Africa, Antarctica and Australia (de Wit et al., 1988; Smith et al., 1993). The basin sediments were deposited from the Carboniferous to the Jurassic. The deposits are widely exposed in SE/S Brazil, whereas in NW Namibia they are mainly restricted to the Huab area (Miller, 2008, and references therein; Fig. 2).

The aeolian sandstone of the Botucatu (Brazil) and Twyfelfontein Formations (Namibia) overlies the Karoo/Paraná sedimentary rocks (Fig. 2). The age of these formations is Upper Jurassic to Lower Cretaceous (e.g., Scherer, 2000; Dentzien-Dias et al., 2007; Perea et al., 2009). The Botucatu/Twyfelfontein Formation reaches a thickness of up to 150 m (Mountney and Howell, 2000) and inter-fingers with the volcanics of the Paraná-Etendeka Large Igneous Province (Jerram et al., 1999), which covers large parts of South America and southern Africa. In Brazil, these extrusives are referred to as the Serra Geral Formation, while in Namibia they are attributed to the Etendeka Group. Today the Serra Geral Formation covers an area of about 1.2×10^6 km^2 (Melfi et al., 1988) with a maximum observed thickness of about 1700 m (Peate et al., 1990), whereas the Etendeka Group covers about 78.000 km^2 in Namibia with a maximum thickness of around 900 m (Erlank et al., 1984; Milner et al., 1992; Gallagher and Hawkesworth, 1994). The Paraná-Etendeka Large Igneous Province consists of up to 120 lava flows (Hartmann et al., 2012) which vary significantly in chemical composition ranging from basaltic lavas to massive quartz latites (Milner and Ewart, 1989; Milner et al., 1992). A stratigraphic correlation of lavas across the Atlantic was established by Milner et al. (1995). The age of the Large Igneous Province is 133 ± 1 Ma (Renne et al., 1992) and the eruption period lasted approximately 2.4 million years (Milner et al., 1995). In the northern part of the Brazilian study area, an alkaline intrusion (Lages Volcanic Field) is dated to 76 Ma (Gibson et al., 1999). About 400 km north of our

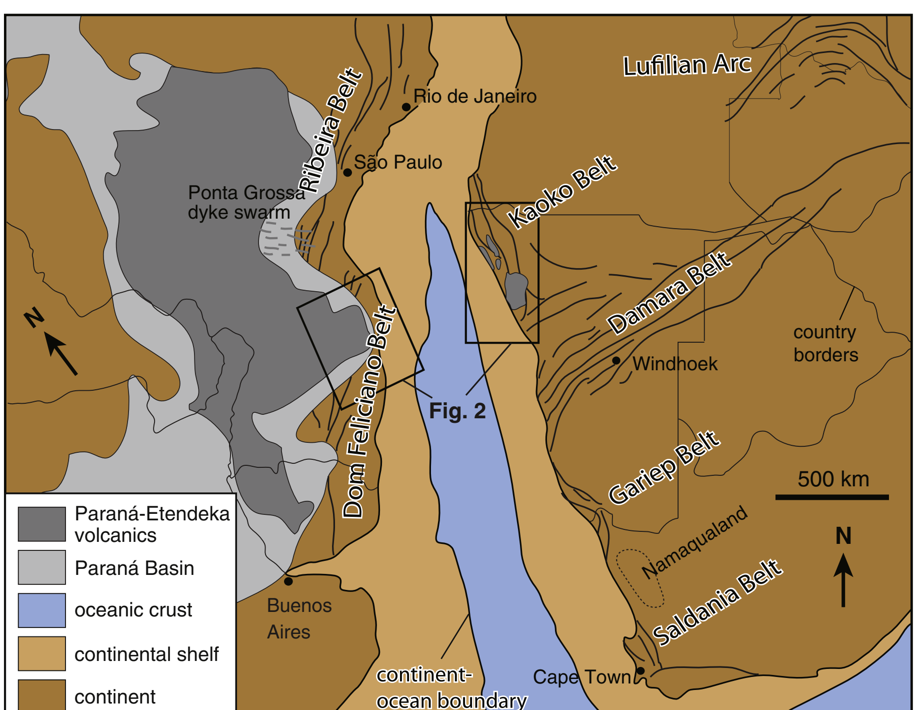

Fig. 1. Simplified paleo-geological map of southern Africa and southern Brazil at 121 Ma (sketched after Heine et al., 2013) with major Neoproterozoic structural elements (thick black lines on continents; adopted from de Wit et al., 2008) and sketched present extent of the Paraná Basin and Paraná-Etendeka Large Igneous Province (after Waichel et al., 2012).

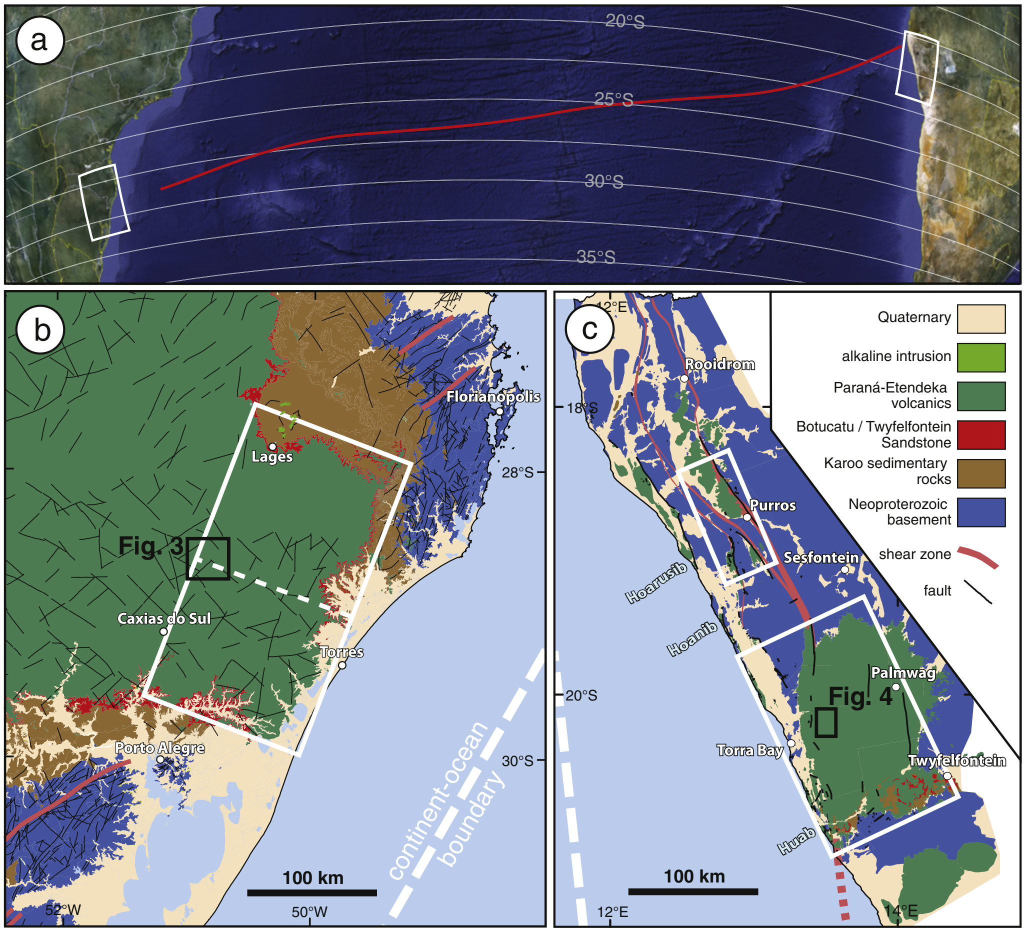

Fig. 2. a) Location of the two study areas along the South Atlantic, with a transform fault exemplarily marked in red used to correlate the position of the margins (satellite image: GoogleEarth). b) Geological map of study area in Brazil. Lithology simplified after and faults adopted from Mapa Geodiversidade do Brasil, 1:2.500.00, Serviço Geológico do Brasil (2006). Location of shear zones after Passarelli et al. (2011). c) Geological map of study area in Namibia. Location of shear zones after Foster et al. (2009) and own observations. Continent-ocean boundary after Torsvik et al. (2009). All visited outcrops lie within the white rectangles. The dashed line in b) indicates the boundary between the northern and southern study area in Brazil (see text for further explanation).

Brazilian study area lies the NW-trending Ponta Grossa dyke swarm (Fig. 1) that can be traced for at least 300 km into the continental interior from the margin (Strugale et al., 2007). The swarm comprises hundreds of dykes and is related to a late phase of the Paraná-Etendeka volcanic extrusion (e.g., Piccirillo et al., 1990; Renne et al., 1996; Deckart et al., 1998).

The volcanics of the Paraná-Etendeka Large Igneous Province were emplaced shortly before or during the onset of the South Atlantic rifting. At this latitude, the oldest magnetic polarity chron in the oceanic crust is identified as M4 (M5n) (Rabinowitz and LaBrecque, 1979; Moulin et al., 2010). For this chron, geomagnetic polarity timescales set an age in the range of 126–130 Ma (126 Ma in Channell et al., 1995; 130 Ma in Gradstein et al., 2004; Tominaga and Sager, 2010; 127 Ma in Malinverno et al., 2012).

Offshore seismic profiles reveal extensive listric normal faulting along both continental margins (Gladczenko et al., 1997; Blaich et al., 2011). Offshore, syn-rift emplacement of basalts is interpreted for both sides of the Atlantic (Bauer et al., 2000; Blaich et al., 2011) and is related to the Paraná-Etendeka extrusives (Beglinger et al., 2012). Other offshore data, however, indicate pre-rift extrusion of the Paraná-Etendeka volcanics (Stica et al., 2014). An Albian rift is situated approximately coast-parallel offshore NW Namibia (Holtar and Forsberg, 2000). In onshore NW Namibia, syn-volcanic normal faulting of the Etendeka Group is reported by Milner and Duncan (1987) and Stollhofen (1999). North of the Brazilian study area between the cities of São Paulo and Rio de Janeiro, the continent was furthermore affected by Cenozoic development of the Continental Rift of Southeastern Brazil. This rift developed during the Paleogene and has continuously been active throughout the Cenozoic including some phases of inversion (e.g., Riccomini, 1989; Ferrari, 2001).

Morphologically both margins differ significantly. Along the Namibian coast the margin is smooth with a trend of ~165° (SSE), while along SE/S Brazil it trends approximately 210° (SW) (Torsvik et al., 2009) but has E-W trending right-lateral steps that are visible on bathymetric maps (i.e. GEBCO data on Google Earth, Fig. 2a). These steps are in the prolongation of oceanic fracture zones and regarded as old rift-transfer zones (Stica et al., 2014). Between Florianopolis and Rio de Janeiro, the Brazilian margin is segmented by WNW trending transfer zones (Meisling et al., 2001), which have been reactivated left-laterally in the Neogene (Cobbold et al., 2001; Karl et al., 2013).

3. Methodology

Our study is concentrated on the Paraná-Etendeka extrusives and the interfingering Twyfelfontein/Botucatu Sandstone, as these rocks were emplaced during or shortly before the onset of the South Atlantic rifting. All deformation recorded in these lithologies is either related to rifting or post-dates it. Both study areas (Fig. 2) were analyzed using existing geological maps, satellite imagery provided by Google Earth, and 30 m-ASTER digital elevation models in order to map lineaments and identify potential faults (Figs. 3, 4). For measuring lineaments, no minimum length was applied and curving lineaments were separated into segments.

Field investigations were carried out to collect fault slip data and to analyze fault relationships. Outcrops were selected by the means of availability, i.e. mostly road cuts and open pits in Brazil, and mostly along incised river valley and mountain shoulders in Namibia. Mechanically formed striations and fiber growth were used as slip indicators (Fig. 5). Cross-cutting relationships were recorded, i.e. faults being cut off by other faults or fiber packages on slickenside surfaces. These criteria help to place stress systems into a relative chronological order. Overprinting between fiber packages however was not used for establishing a chronological order since it is hard to determine their relative age (Sperner and Zweigel, 2010). As fiber growth found on fault planes consisted of quartz and calcite only, we did not use mineral growth as an indicator for subsets or relative timing of subsets. Fiber growth is dependent on fluid flow, which could have (re-)occurred at any time, and mineralogy is dependent on the spatial distribution of quartzitic and/or calcitic rocks hosting the fluid system.

All measurements were corrected for the magnetic declination. In the field, we grouped the collected fault slip data into three categories regarding their quality (1 = excellent, 2 = good, 3 = poor), i.e. how well we could see the slip indicators and direction of movement. For the paleostress analysis, we later neglected quality 3 measurements and data with a misfit of more than 10° between the fault plane and respective slickenside orientation. It is to be noted, that the interpretation of our data does not change significantly if it is restricted to only quality 1 measurements.

The fault slip data were then used to perform a stress inversion for which the following assumptions are necessary:

- Measurements on small outcrop scale faults are representative of regional stresses and local block rotation has not distorted the stress fields significantly.
- The material is homogeneous at large scale so that the fault slip inversion gives the infinitesimal strain tensor, which can be directly linked to the stress tensor.
- The data allow the separation of multiple stress events.

It must be kept in mind, that the linkage of the infinitesimal strain tensor to the stress tensor in particular may be a source of error if the rock is not isotropic. The directions of stress and strain might differ due to reactivation of inherited structures in the rock. Another problem concerns deformation of foliated rocks, in which the stress may only be large enough to produce visible deformation in areas with a favorable foliation orientation.

The data were processed following the "stress inversion via simulation" method developed by Sippel et al. (2009), which combines the PBT-Method (Turner, 1953; Sperner et al., 1993) with the Multiple Inverse Method of Yamaji (2000). The PBT-method calculates the orientation of the principal strain axes for each measured fault. The basis of this calculation is the Mohr–Coulomb fracture criterion, where a fracture plane is created at a certain angle between the normal and shear stress axis (typically 30° between σ_1 and the fracture plane; e.g., Handin, 1966; Byerlee, 1968; Twiss and Moores, 2007), depending on the cohesion and friction of the specific rock. In return, it is thus possible to calculate the orientation of the principal strain axes for a given fault movement on a newly formed plane. The data that are acquired give the three principal strain directions for each single fault measurement.

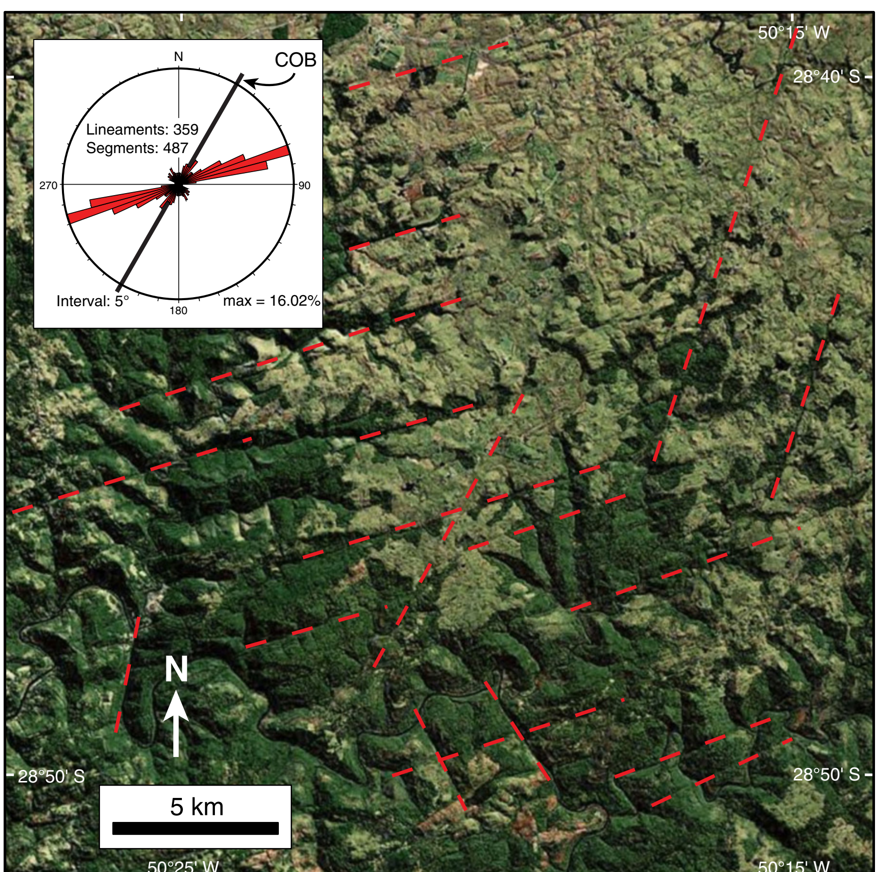

Fig. 3. Satellite image of a part of the study area in Brazil showing distinctive lineaments (satellite image: BingMaps). Rose diagram representing lineaments mapped in Paraná-Etendeka basalts in the SE/S Brazilian study area on satellite imagery. Note that lineament segments are plotted. Lineaments are divided into segments if they are curving.

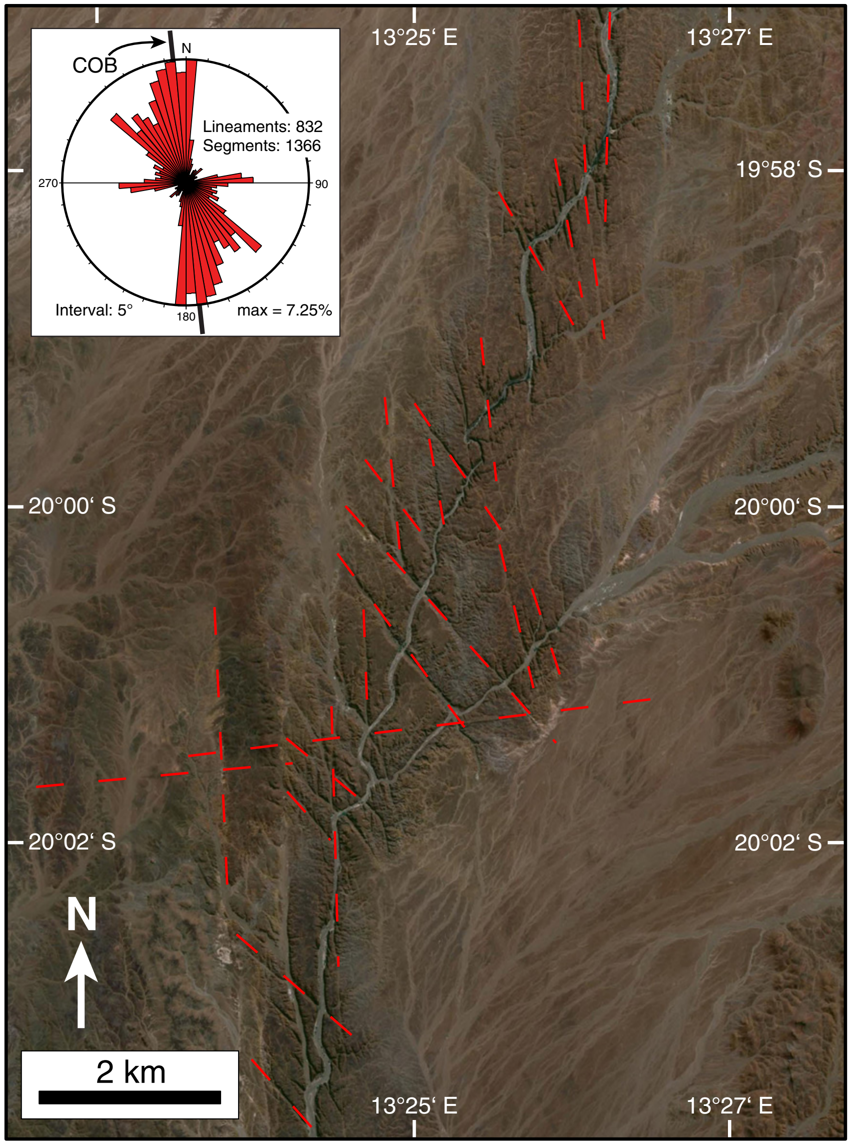

Fig. 4. Satellite image of a part of the study area in Namibia showing distinctive lineaments (satellite image: GoogleEarth, DigitalGlobe). Rose diagram representing lineaments mapped in Paraná-Etendeka basalts in the NW Namibian study area on satellite imagery. Note that lineament segments are plotted. Lineaments are divided into segments if they are curving.

In order to attain significant larger scale stress tensors from these single fault plots we are looking for faults with similar strain patterns and thus for clusters of principal strain axes. This is usually first done on a single outcrop basis and then extended to outcrop clusters and larger areas. In a data set that contains several stress histories, one has to identify single stress events with consistent orientations that are significant. For this, at least four independent fault solutions are needed (Angelier and Goguel, 1979; Sippel, 2009). Once stress fields are found these can be compared across several outcrops to identify large scale stress fields. All the data from one identified stress field are then included into one data set and the Multiple Inverse Method is used to determine if the inversion is accurate.

The Multiple Inverse Method (Yamaji, 2000) calculates the reduced stress tensor, i.e. the stress ratio of the principal stress axes, of all possible subsets of implemented faults with a minimum subset-size of 4 faults. This approach follows the Direct Inverse Method (Angelier, 1984) which determines the stress ratio by calculating the minimum misfit angle between the movement directions of a selected fault set. The basis for this approach is the Wallace–Bott theory, which states that slip along a plane occurs parallel to the direction of maximum resolved shear stress (Wallace, 1951; Bott, 1959).

The PBT-Method is conducted with the commercial software TectonicsFP (Reiter and Acs, 1996–2010), which further allows easy manual separation of fault clusters, and the Multiple Inverse Method with the open-source MIM Software Package of Yamaji and Sato (2005) where the separated fault clusters are implemented. A detailed description of the working process is given by Sippel et al. (2009).

In contrast to earlier methods (Sippel et al., 2009), we decided to merge the measurements of the single outcrops into one data set and use contour plots of the calculated principal stress axes to identify stress fields (Figs. 6b, 7). Merging the data has the advantages of minimizing the disturbance by local block rotation or tilting; reducing the risk of interpreting stresses induced by local fault or fracture interactions; and of reducing the influence of outcrop orientation. It further has the advantage of including single measurements in the larger scale stress analysis that might be regarded as insignificant in a single outcrop or sub-region analysis. Effects of lithology or basement structure variations on the spatial strain distribution are regarded as minimal, since no significant changes occur throughout the study areas. With this approach, local variations of stress fields are not easily detected, but contour plots of the whole data set allow us to identify stress fields that have affected the whole study area. A PBT-analysis of local subsets is presented as

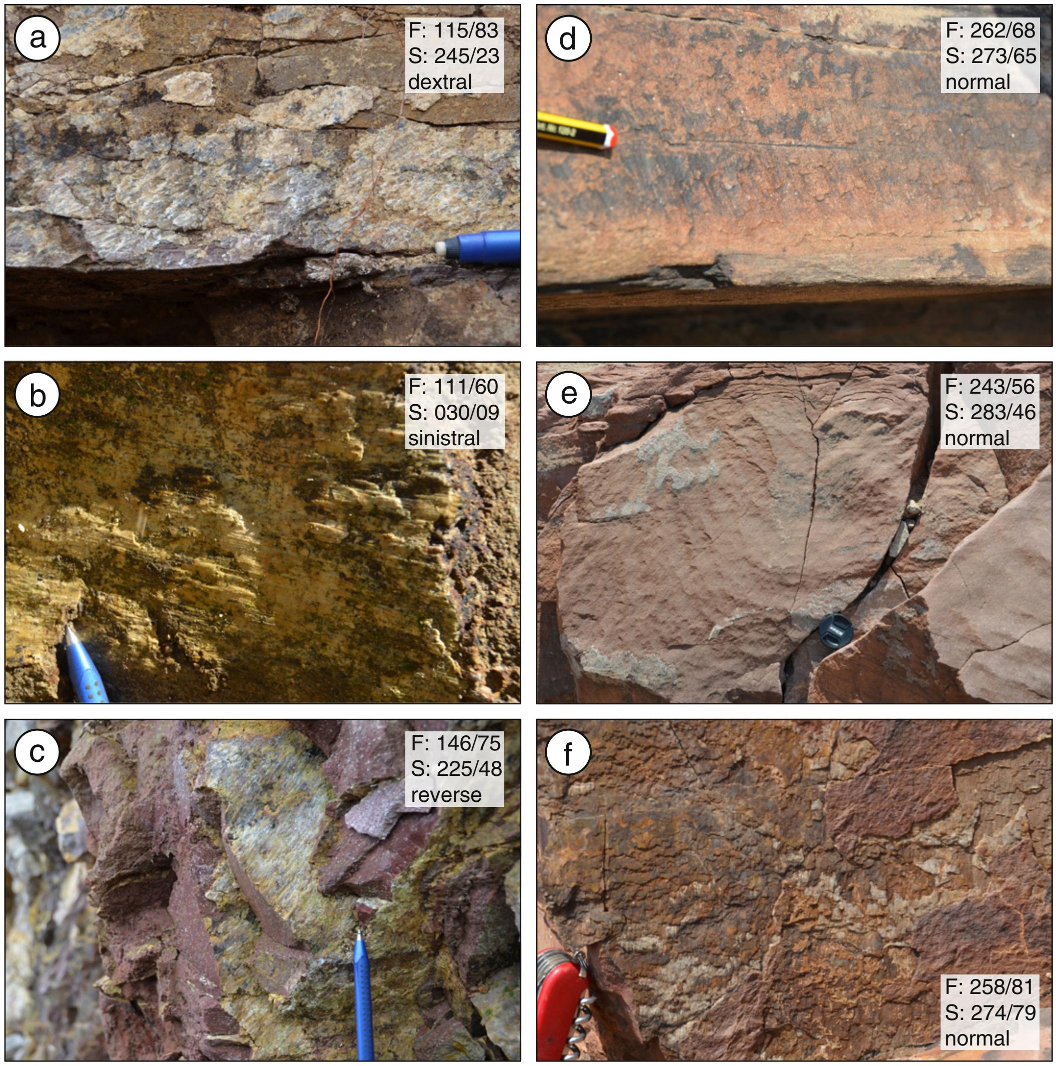

Fig. 5. Examples of fault slickensides found in the field with fault plane orientation (F), slickenside orientation (S) and shear sense. (a–c: Brazil; d–f: Namibia).

supplementary material (Figs. S1, S2). We decided only to select and analyze the most prominent stress concentration maxima seen in the contour plots.

4. Results

4.1. Lineaments

We mapped 359 lineaments in the Serra Geral volcanics in SE/S Brazil using satellite imagery provided by Google Earth and 30 m-ASTER digital elevation models. An example of the lineaments is given in Fig. 3 and a rose diagram is used to show the overall trend of all measured lineaments (location of Fig. 3 shown in Fig. 2). In Brazil, a closely spaced set of lineaments striking ENE dominates the pattern completely. Two less pronounced sets exist with strikes around NE and NW. When the trend of the lineaments is compared to the geological map in Fig. 2, one can observe that a) most of the lineaments do not trend parallel to the margin and b) the main lineament trend is not parallel to basement shear zones (shown in light red in Fig. 2). Margin parallel lineaments may be expected if margin parallel faults or joints were formed. This does not seem to be the case in Brazil, or if such faults and joints exist they are only minor. The oblique trend of the lineaments with respect to basement shear zones may indicate that reactivation of these zones does not play a major role in the development of younger faults in the basalts. A small number of the lineaments have a trend that is parallel or subparallel to shear zones in the basement and might thus be indicative for reactivation of basement structures.

In Namibia, we mapped 832 lineaments in the Etendeka volcanics. A typical example of lineaments on the Etendeka plateau is presented in Fig. 4 and the trend of all lineaments is shown in a rose diagram in the upper left hand corner in Fig. 4. The majority of the lineaments strike N-S to NNW-SSE or NW-SE. A less pronounced set of lineaments strikes E-W. The satellite image presented in Fig. 4 shows three main trends, N-S strike, NW-SE strike and E-W strike. The position of Fig. 4 is indicated in the geological map in Fig. 2 where it becomes clear that a) the NW-SE trend of lineaments is parallel to the margin and b) the N-S trend is parallel to basement shear zones. In Namibia one can thus expect that margin parallel normal faults dominate the lineament pattern in combination with reactivation of shear zones in the basement. Only a minor E-W trend of lineaments is not compatible with this interpretation.

In summary, mapping of lineaments in SE/S Brazil and NW Namibia produces very different patterns for both continental margins indicating that they have different fault or fracture patterns and thus experienced different stress histories.

4.2. Fault slip analysis

We performed a fault slip analysis in order to unravel the stress fields of the two opposite continental margins. In Brazil, we collected

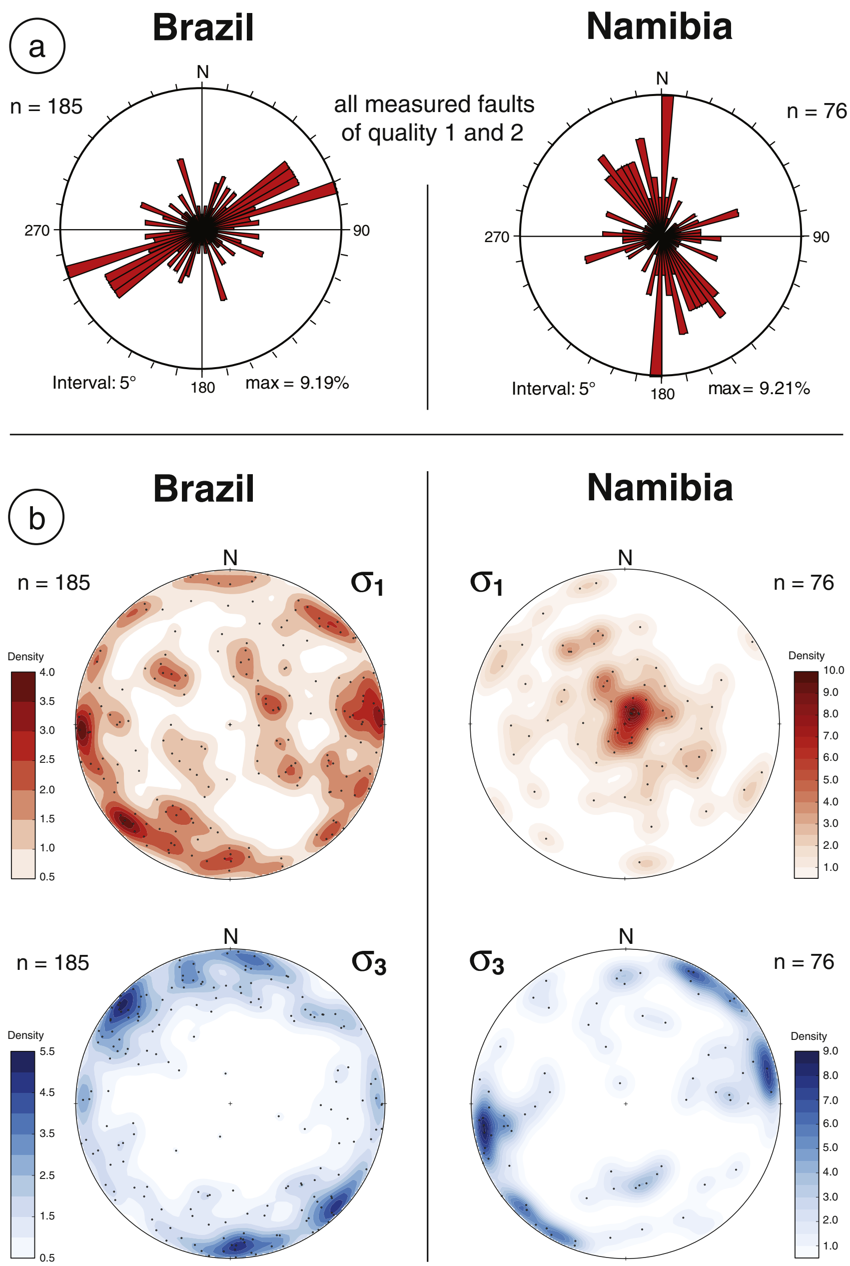

Fig. 6. a) Rose diagram illustrating the strikes of the measured faults. b) Contour plots of the principal stress axes σ_1 and σ_3 of the measured faults in the Paraná-Etendeka basalts and the Botucatu/Twyfelfontein sandstone. The stress axes are calculated for each fault with $\theta = 30°$, i.e. the angle between the maximum principal stress and the shear plane. (Rose diagrams are generated with TectonicsFP software of Reiter and Acs, 1996–2010, and contour plots with OpenStereo of Grohmann and Campanha, 2010.).

field data in 35 outcrops of the Serra Geral volcanics and the Botucatu Sandstone and obtained 185 measurements of quality 1 and 2 ("excellent" and "good") (see supplementary material for fault slip data and outcrop coordinates). Examples are shown in Fig. 5a–c. Only a few outcrops exhibited no faults or only bad quality data. Measurements in outcrops near mapped lineaments do not consistently show an orientation parallel to the respective lineament. Overall, however, the faults have approximately the same strike orientation as the mapped lineaments (e.g. orientation maxima lie within 5°) indicating that the latter might be produced by the faults (Figs. 3, 6a). The faults were then analyzed with the PBT-method that gives the orientation of the principal stresses for each single fault measurement. The combined results of all the orientations of the stress axis are shown as contour plots on the left hand side of Fig. 6b. Red contours are for the main compressive stress axes, σ_1, and blue contours for the smallest principal stress axes, σ_3. According to the Anderson principle, a vertical σ_1 and horizontal σ_3 indicate an extensional regime with normal faults, a horizontal σ_1 and a vertical σ_3 characterize a compressional regime with reverse faults, and a horizontal σ_1 and σ_3 are indicative of a compressional regime with strike-slip faults. Fig. 6b clearly shows, with the data from Brazil, that σ_3 is on the outside of the stereonet and thus horizontal with maxima indicating NW-SE and N-S trends. σ_1 shows a more complex distribution with several maxima on the outside of the stereonet indicating a horizontal σ_1 mainly in an E-W and a SW-NE direction and minor maxima with variable moderate dip orientations. Overall, the pattern is clearly dominated by strike-slip with two major trends, one with an E-W directed compression and the second with a SW-NE directed compression. In addition, a minor strike-slip regime with a N-S compression component may be present alongside minor extensional regimes with variable extension directions (Fig. 6b). The setting becomes clearer when we divide the study area into northern and southern parts (Fig. 7, dashed line in Fig. 2b). In the southern half, two strike-slip

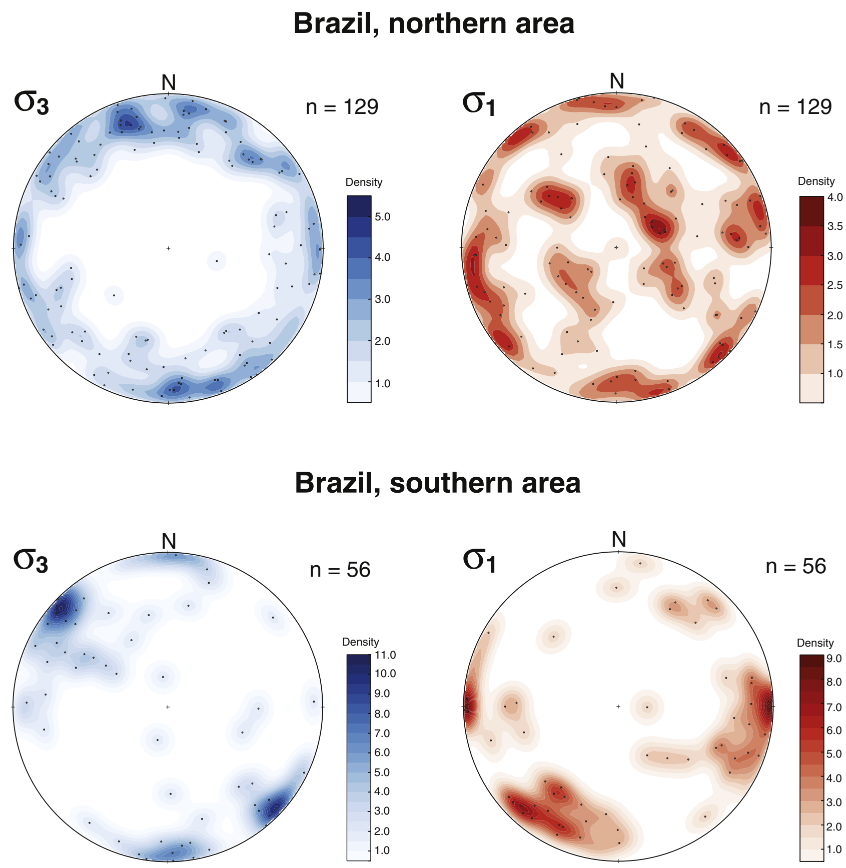

Fig. 7. Contour plots of σ_1 and σ_3 stress axes of measured faults in SE/S Brazilian study area, divided into a northern and southern area. Whereas the northern area shows large scatter in the orientation of the stress axes with various maxima, the data in the southern area indicate two distinctive maxima that are also present in the northern area. (Contour plots generated with the software OpenStereo of Grohmann and Campanha, 2010.).

systems dominate with σ_1 oriented SW and W. As these two systems also appear in the northern area, the focus of this study lies on them. The SW compressional strike-slip regime has a sinistral transpressional character ($\Phi = 0.20$) with the south-eastern side moving upward along the ENE trending faults (Fig. 8). The strike-slip system with compression to the W affects the same fault system, yet in a dextral pure strike-slip regime ($\Phi = 0.50$). No cross-cutting relationships were found to relatively date the stress regimes of these two strike-slip systems. In conclusion, we see that the Brazilian margin is strike-slip dominated with faults that are not parallel to the margin and that the faults are unrelated to major reactivation of basement structures, since shear zone-parallel faults are rare. The northern part of our study area, towards the Ponta Grossa dyke swarm, shows more complex stress patterns indicating several possible extensional and strike-slip directions. The data are not good enough to separate these possible regimes with confidence. The fault dip data that do not fit into the calculated stress tensors are shown in Supplementary Fig. S3.

In Namibia, we collected 76 fault slip measurements in 26 outcrops in the Etendeka volcanics and the Twyfelfontein Sandstone that could be used for further processing. Examples are shown in Fig. 5d–f. A number of outcrops exhibited no faults or only bad quality. The local lithologies and large-scale geology are very similar to those in Brazil, but there is a relative scarcity of faults cropping out in Namibia, perhaps due to the different weathering and erosional history, or a less active tectonic history. As in Brazil, the strikes of the faults resemble the orientations of the lineaments (Figs. 4, 6a). The fault slip data set produces a steeply plunging σ_1 maximum and a sub-horizontal σ_3 (right hand side of Fig. 6b). The stress regime in Namibia seems to be mainly extensional with two main orientations of extension, in ENE-WSW and in SSW-NNE direction.

28 measurements, i.e. 37% of the total considered data, indicate an extensional regime with σ_3 oriented ENE (Fig. 8). Most of the faults strike ~NNW, yet seven strike E to NE. Four of these are measured along basalt dykes, i.e. structures along which fault movement at a low shear-to-normal stress ratio is likely. A best-fit stress ratio is achieved with $\Phi = 0.05$, showing radial extension (Fig. 8). A second extensional stress field is indicated by 8 measurements with faults striking ~NW, σ_3 oriented NNE and a stress ratio of $\Phi = 0.20$. 10 fault slip measurements represent a strike-slip regime with compression to the NW and a stress ratio of $\Phi = 0.60$, indicating a transtensional stress regime. Similar to Brazil, a relative timing of these three stress regimes cannot be obtained with our data set as no cross-cutting relationships were found. The fault dip data that do not fit into the calculated stress tensors are shown in Supplementary Fig. S3.

5. Discussion

5.1. Differences between the two correlating continental margins

The orientations of lineaments mapped on satellite imagery (Figs. 3, 4) differ markedly between the two correlating margins. In NW Namibia, the majority of lineaments trend parallel to the continent-ocean boundary, whereas in SE/S Brazil the dominant lineament orientation is rotated clockwise by ~40° from the continent-ocean boundary and only a minor set strikes parallel to the margin. In both study areas all lineament maxima are very similar to the orientation maxima of faults that were measured in the field (Figs. 3, 4, 6a). We can draw two conclusions from this similarity, a) the lineaments may be related to faults and b) the small-scale outcrop measurements are representative of large-scale trends.

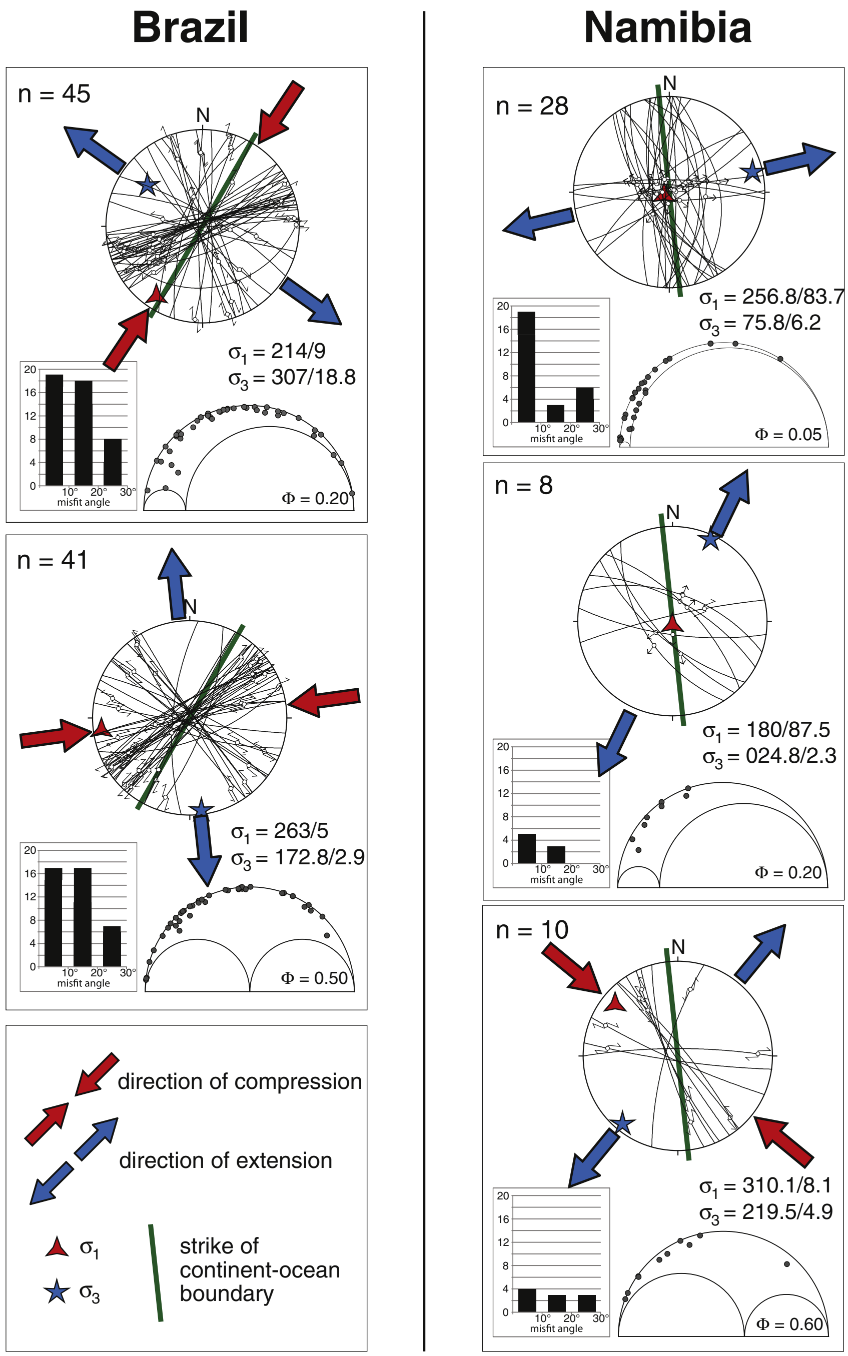

Fig. 8. Paleostress regimes determined for the Brazilian and Namibian study areas. Lower-hemisphere stereonets show orientation and slip direction of faults representing the respective stress regimes. The histogram shows distribution of misfit angles of the implemented fault dip data with regard to the orientation of the stress axes. Faults with a misfit angle of ≤30° are regarded as having a high slip potential (Nemcok and Lisle, 1995; Sippel et al., 2009). Triaxial Mohr diagram plots the normal-to-shear stresses on the faults in the given stress field. Φ indicates the stress ratio of the principal stress axes (e.g. Φ is 0 if $\sigma_1 > \sigma_2 = \sigma_3$ or 1 if $\sigma_1 = \sigma_2 > \sigma_3$).

The fault slip data also show major differences between Namibia and Brazil (Fig. 8). NW Namibia is largely dominated by extension, while in SE/S Brazil strike-slip dominates the kinematic regime. In Namibia, the largest data set forms an extensional stress regime with σ_3 oriented ENE, which is perpendicular to the continental margin and could therefore be the result of Atlantic rifting and later margin extension. A Mohr-ratio of $\Phi = 0.05$ indicates a component of radial extension, which could be related to domal uplift above the Tristan da Cunha plume that was still present in this area during rifting (Turner et al., 1994). A second minor stress field in Namibia exhibits NE-SW extension, while a third minor stress field shows strike-slip with the compressional axis oriented NW-SE. It is not clear how important the last two stress regimes are on a larger continental scale. The three stress fields account for 61% of the data implying that the study area has experienced additional stresses. However as no clear stress pattern can be calculated from the remaining data, their origin is not interpreted here.

In SE/S Brazil, the stress pattern appears very different as two strike-slip systems dominate the study area, with their compressional axes oriented E-W and NE-SW (Fig. 8). Extensional faults related to the Atlantic rifting either do not exist onshore or are overprinted. Margin-parallel faults are scarce in our study area, indicating that rift-related faulting played a minor role onshore, reducing the likelihood of an overprinted extensional stress regime. Nonetheless, such a stress regime must have affected the margin, as documented by rift-related extensional faulting offshore (Blaich et al., 2011), so it seems likely the rift-related faulting was restricted to a narrow strip between the continent-ocean boundary and the present-day coastline. The prominent NW trending Ponta Grossa dyke swarm (Fig. 1), which was emplaced in the late phase of the Paraná volcanic extrusion and thus at times of rifting, indicates NE-directed extension, i.e. parallel to the margin. If this is also true for our study area ~400 km south of the Ponta Grossa dyke swarm, this could explain the scarcity of margin parallel faults.

In addition to the two dominant strike-slip regimes, the number of paleostress tensors that can be extracted from the fault slip data of the northern and southern Brazilian study areas varies. While in the south, 63% of the data can be attributed to either the strike-slip stress regimes with compressional axis oriented E-W or NE-SW, in the north only 39% of the data fit into these two regimes. Due to the large scatter of the remaining 61% of data in the north, any separation of this data would have to be seen as highly speculative. However it is clear that the northern study area has experienced a far more complex stress evolution than the southern one. The scatter seems unlikely to be related to inheritance of Precambrian basement structures, as Neoproterozoic shear zones in the basement seem to strike NE throughout the study area (Passarelli et al., 2011), a direction appearing only subdued in the younger fault pattern.

What other reasons may produce the complicated stress patterns in the northern part of our Brazilian study area? Reconstruction of the breakup history of South America and Africa is confronted by several misfits of the conjugated continental margins, which are resolved by implementing major fault systems across the continents which accommodate the deformation necessary to reconstruct the ocean margins (e.g., Nürnberg and Müller, 1991; König and Jokat, 2006; Eagles, 2007; Torsvik et al., 2009; Moulin et al., 2010). One of these fault systems is placed as a major transform fault on the Brazilian side extending from the Florianopolis Fracture Zone in the South Atlantic through the whole continent to the Pacific margin (compare for example Fig. 24 of Moulin et al., 2010, and Fig. 5 of Torsvik et al., 2009). If this fault or larger scale deformation zone exists, it runs straight through the northern part of our study area. A structure of such extent would be prone to frequent reactivation (Franco-Magalhaes et al., 2010; Karl et al., 2013) and could explain the complex fault slip data obtained in this area. Indeed, our data might serve as an indicator for the existence of a major fault system. However, aside from the Florianopolis Fracture Zone, a more evident factor is the appearance of the upper Cretaceous Lages Intrusion close to the northern edge of the study area (Fig. 2). It is shown that magmatic intrusions and later inflation of magmatic bodies disturb the regional stress field and induce local stress fields. Examples are found at Mount St. Helens (Lehto et al., 2010), at La Réunion (Chaput et al., 2014), or in the northern Canadian Shield (Hou et al., 2010). Anderson (1937) and Gudmundsson (2006) modeled how the principal stress axes are oriented around an intrusive body. In addition, analogue modeling has shown that magma chambers disturb the pattern of regional deformation (Montanari et al., 2010). One effect of an intrusion is rotation of the principal stress axes away from vertical and horizontal plunges to intermediate plunge angles. The emplacement of the Lages Intrusion should also have affected the local stress system and could therefore have contributed to the scattering of fault-slip data in the northern part of the Brazilian study area: it may for example have produced the ~30°–70° dip angles of σ_1 (upper right rose diagram in Fig. 7).

The minor inversion of the NE-trending basement structure in SE/S Brazil contrasts with much stronger basement inversion further north between São Paulo and Rio de Janeiro (Fig. 1), where shear zones of the Ribeira Belt trend ENE-WSW, in an approximately 20° clockwise deviation from directions in SE/S Brazil. In the Ribeira Belt, Cenozoic reactivation of old shear zones is well documented (Cogné et al., 2011, 2013), which implies that a change of ~20° in strike is sufficient for such structures to be reactivated. In further contrast to SE/S Brazil, evidence for shear zone reactivation is clearly seen in NW Namibia. This is suggested by Marsh et al. (2001) and Stanistreet and Charlesworth (2001) and is hinted at by the increased concentration of faults directly along shear zones (Fig. 2c) and the overall parallelism of mapped shear zones to the measured faults in the field (Fig. 6a).

5.2. Comparison with other Brazilian stress data

Several paleostress studies have been conducted in the greater area of SE/S Brazil (e.g., Riccomini, 1995; Fernandes and Amaral, 2002; Strugale et al., 2007; Machado et al., 2012; Fig. 9). All of these studies, which are also mainly based on analyzing fault slip data, conclude on the presence of strike-slip systems dating from Cretaceous to present times. Some of these regimes have approximately the same orientation as our two main strike-slip regimes and these are summarized in a chronographic chart in Fig. 9. Based on these studies, the NE-SW compressional strike-slip regime falls into a time frame ranging from the Upper Cretaceous to at least the Paleocene and possibly to the Oligocene. Although more speculative, the E-W compressional strike-slip regime might have affected the passive margin during the Neogene to present.

In general, strike-slip faulting is prominent along the Brazilian passive margin. In the near-coastal region of NE Brazil, present strike-slip faulting with an E-W compressional axis is well known, as indicated by seismic data and borehole breakouts (e.g., Lima et al., 1997; Bezerra et al., 2011; Reis et al., 2013). As the compressional axis trends approximately parallel to the coast and the extensional axis perpendicular to it this pattern is explained as an effect of flexural bending of the continent-ocean transition, where cooling of the oceanic crust and sediment loading leads to subsidence offshore and uplift onshore (e.g., Assumpção, 1998; Ferreira et al., 1998). Assumpção et al. (2011) suggested the same mechanism to also affect the SE Brazilian margin based on a study of earthquakes offshore there. Indeed, the strike-slip system with NW-SE extension observed in SE Brazil (Fig. 8) is associated with a lowest principal stress that is oriented approximately coast-perpendicular and could thus derive from flexural bending. However, an additional compressive force has to be active to produce strike-slip faulting. Further, flexural bending cannot explain the second strike-slip system with compression perpendicular to the margin.

Further effects that are discussed to influence the passive margin are ridge push related to the South Atlantic mid-ocean ridge and basal drag of mantle flowing underneath the tectonic plates. To what degree these forces influence intraplate stresses is debated (e.g., Richardson, 1992; Coblentz and Richardson, 1996; Steinberger et al., 2001; Hirsch et al., 2010; Husson et al., 2012; Green et al., 2013). Whereas ridge push is directed away from the mid-Atlantic ridge, the direction of basal drag is controlled by mantle flow patterns that do not necessarily align with spreading axes (Savage, 1999). For the South Atlantic, it is argued that asthenospheric flow is directed from underneath southern Africa towards South America as response to the upwelling of the African superplume (Behn et al., 2004; Forte et al., 2010; Husson et al., 2012; Colli et al., 2013). Along the Brazilian margin, recent stress systems have been attributed to partly derive from these forces. The orientation of strike-slip systems along the NE Brazilian margin has been suggested as the combined result of flexural bending and ridge push or basal drag (Assumpção, 1992). Further, Assumpção (1998) relates earthquake offshore SE Brazil with reverse focal mechanism to the same combined effect, although Assumpção et al. (2011) makes primarily flexural stresses along the shelf responsible for the seismicity. Similarly, Japsen et al. (2012b) argue for ridge push having only a subdued effect on a Campanian uplift phase of the NE Brazilian margin as it coincides with a decline of the Atlantic spreading rate, which would rather result in a decrease of ridge push. With respect to our study area, it is not clear to which degree ridge push and basal drag shall result in NE-SW directed horizontal compression, i.e. margin-parallel compression, or contribute to a change to E-W directed horizontal compression. Still, even though regional variations of orientation occur along the Brazilian margin, the combined

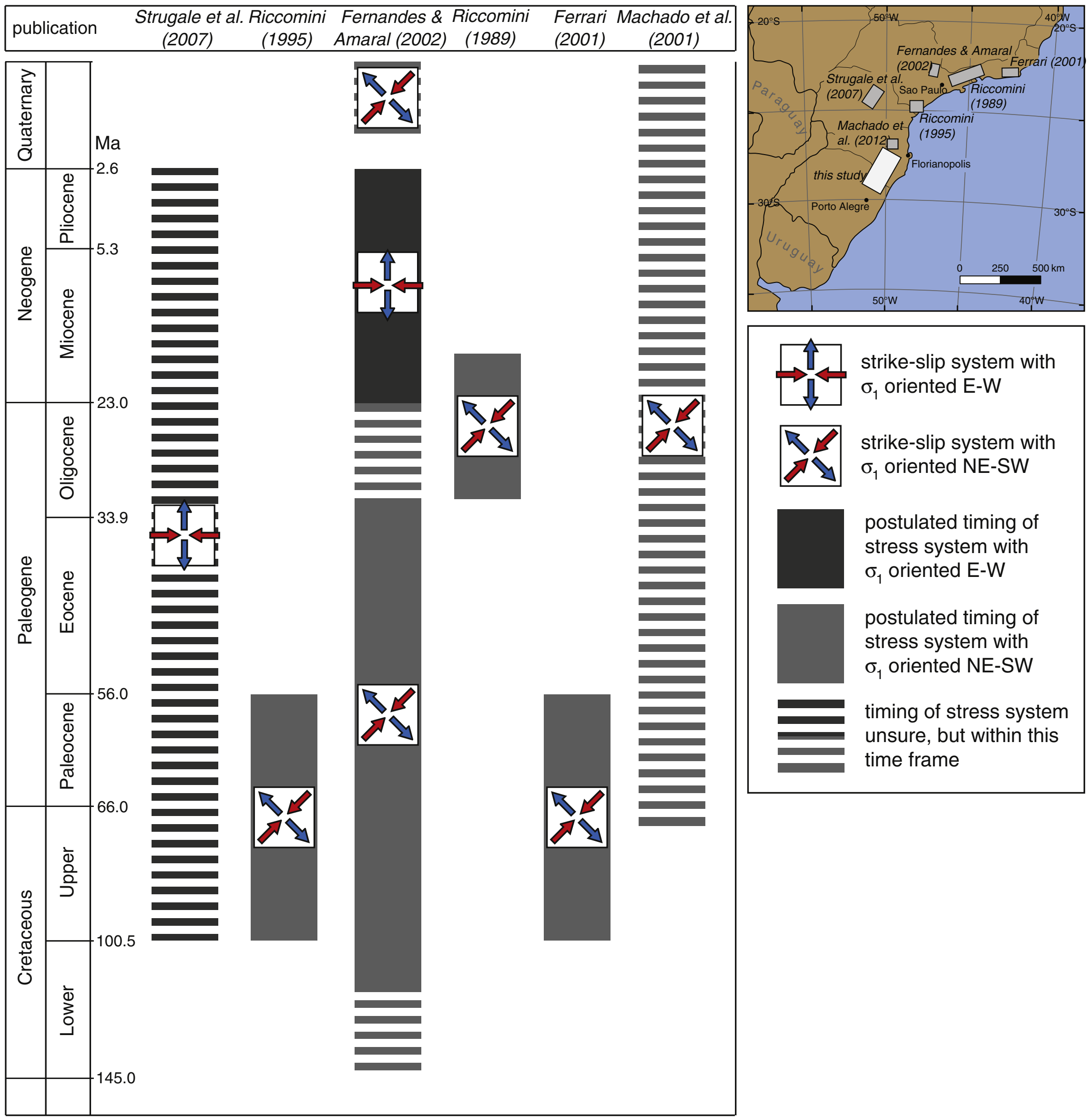

Fig. 9. Compilation of published paleostress systems in SE Brazil similar to the stress fields determined in this study. Study areas of respective publications are displayed as gray squares in map inset.

forces of ridge push and basal drag on the eastern side of the continent, and the subduction on its western side may result in the observed overall strike-slip fault regime as suggested and modeled by others (e.g., Coblentz and Richardson, 1996; Cobbold et al., 2007; Husson et al., 2012).

An aspect that could explain the observed change of strike-slip systems in SE Brazil through time is the changing subduction direction of the Nazca plate underneath South America: Cobbold et al. (2001, 2007) relate the NE-SW and E-W compression in SE Brazil to the subduction direction, which was NE directed between 47 and 28 Ma and ENE directed from 25 Ma to present (Somoza and Ghidella, 2012), slightly overlapping with the respective compressive stress axis of the strike-slip regimes in SE/S Brazil (Fig. 9). However, major uplift of the Andes started approximately at the beginning of the Miocene (Maloney et al., 2013, and references therein), which indicates that the NE directed subduction has not resulted in significant compression of the continent. This Miocene uplift however coincides well with the E-W directed strike-slip system observed by Fernandes and Amaral (2002; Fig. 9) and Neogene E-W compression suggested by Cogné et al. (2013) for the Taubaté basin between São Paulo and Rio de Janeiro.

The recent M_W 8.8 Maule earthquake in Chile in 2010 resulted in coseismic displacement across the continent with movements of up to 6 mm at the east-Brazilian coast (Vigny et al., 2012), indicating that stress can be transferred across a whole continent. In addition, S/SE Brazil is at about the same latitude as the flat-slab subduction section of the Nazca Plate underneath South America (27°00′S–33°30′S; e.g., Ramos et al., 2002), which is generally made responsible for the uplift of the Sierras Pampeanas in central Argentina, ~600–800 km east of the trench (e.g., Jordan et al., 1983). The flat-slab subduction started around 18–12 Ma which coincides with the uplift of the Sierra Pampeanas starting at around 8 Ma (Ramos et al., 2002). This implies that the eastwards directed flat-slab subduction transmitted stresses further into the continent than normal-angle subduction did before and thus was more likely to influence the SE/S Brazilian margin. These observations, i.e. the displacement during the Maule earthquake and deformation propagation since the flat-slab subduction, lead us to conclude that the observed E-W compressional strike slip system in the SE/S derives from the subduction zone.

In summary, the observed strike-slip system with NE-SW directed compression and NW-SE directed extension, i.e. margin perpendicular, could be the combined result of flexural bending, which causes margin-perpendicular extension, and subduction of the Nazca plate, ridge push and basal drag, which lead to a general compressive setting. The effect of flexural bending is later superposed by E-W compression deriving from the accelerated Andean uplift in the Neogene.

5.3. Comparison with other South African stress data

There are significant differences between our paleostress data and paleostress regimes published for SW South Africa (Viola et al., 2012). In Namaqualand (Fig. 1), Viola et al. (2012) identified two compressional events younger than 90 Ma (their D7 and D9) indicated by a significant number of fault slip data, whereas the extensional stress field related to the opening of the South Atlantic appears subdued with only a small number of fault slip data. Yet again, rift-related extension is observed in the Saldania Belt near Cape Town by Will and Frimmel (2013) (Fig. 1). One can explain the scarcity of extensional faults related to the South Atlantic opening in Viola et al.'s (2012) data by the great distance (~350 km) of their study area from the continental margin. In contrast, our study area is about 200 km from the continent-ocean boundary and the study area of Will and Frimmel (2013) is even closer to it. Extensional faulting in Africa is known to be restricted to rift zones that may be between 100 km and 300 km wide (Morley, 1999).

Our second extensional stress field with a NE-SW directed extension direction might correspond to that responsible for D8 of Viola et al. (2012) as both the extension directions and stress ratios ($\Phi = 0.20$ of our stress field and 0.25 of D8) are similar. D8 is related to a NE-SW extensional phase that is postulated to have affected the whole African continent in the Campanian-Maastrichtian (Guiraud and Bosworth, 1997). The basis for this postulation is a number of ~N-NW trending rifts of that age in northern and northern-central Africa and along the southern African margin during this time (Fig. 29 in Guiraud and Bosworth, 1997). However, the assigned rift event in the Orange Basin offshore western South Africa is now considered to be a gravitational margin failure induced by punctuated margin uplift and thermal subsidence (de Vera et al., 2010). We are therefore cautious of linking the NE-SW extensional stress system to an African wide Campanian-Maastrichtian extension phase.

As flexural bending of the lithosphere due to sediment loading offshore is considered a mechanism affecting the Brazilian margin, the same mechanism should be considered for the African margin. The Walvis and Orange basins, offshore and to the SW of the Namibian study area and western South Africa, accumulated significant amounts of sediments (Miller, 2008, and references therein) and flexural bending along the onshore margin of NW Namibia and elsewhere along the African margin due to sediment load may be significant (Dauteuil et al., 2013). Flexural bending would result in margin perpendicular extension related to our NE-SW extensional stress field, and equally contribute to the most pronounced E-W extensional stress tensor, which we primarily assign to the South Atlantic rifting. To what extent our data reflects the Albian rift offshore NW Namibia, described as a local tectonic event by Holtar and Forsberg (2000), is unclear.

The compressional events in the data of Viola et al. (2012; their D7 and D9) are not easy to correlate with our stress data. Our strike-slip system may represent the present-day stress field, as the compressional axis has a similar orientation as the present-day maximum horizontal compression in southwest Africa (Viola et al., 2005; Heidbach et al., 2008), but might also correlate to the D7 event of Viola et al. (2012). Viola et al. (2012) link both their D7 and D9 to compression that is evident in northern and central Africa during the Late Santonian and Late Maastrichtian, respectively (Guiraud and Bosworth, 1997; Bosworth et al., 1999). The Late Santonian compression is related to "the first general compressional episode registered by the African–Arabian plate during the Alpine Cycle" (Guiraud et al., 2005) and also the Late Maastrichtian event is related to counterclockwise rotational northward drift of Africa–Arabia into Eurasia (Guiraud and Bosworth, 1997). If we assume that Viola et al. are correct in concluding that far-field stresses are responsible for compression in Namaqualand, the question arises why this compression is not expressed in NW Namibia. Our data show only a minor set of reverse faults and in addition, both events are not observed in the ~E-W striking Lufilian Arc in southern Congo (Fig. 1; Kipata et al., 2013). The effects of possible far-field compression should be similar or even better developed in north-western Namibia or southern Congo, because both areas lie closer to the source of transmitted stress, i.e. northern Africa. We therefore suggest the option that regional compressional stress fields existed, which are responsible for the observed compression in southern Africa, for Late Cretaceous rock and surface uplift in the Damara Belt in central Namibia (Raab et al., 2002) and for post-Eocene rock and surface uplift in South Africa (Japsen et al., 2012a).

Regarding local variations of the stress fields, we need to consider the geometry of the Neoproterozoic basement structure and its influence on younger structures. The Kaoko Belt, which underlies the Etendeka basalts, is dominated by an approximately N-S trending foliation (e.g., Passchier et al., 2002; Goscombe and Gray, 2008) whereas in the Damara Belt, south of the study area, foliation and lineaments trend about ENE-WSW (e.g., Kisters et al., 2004; Corner, 2008). As foliation surfaces are prone to reactivation as faults, N-S directed compression would more likely produce thrust faults in the Damara Belt than in the Kaoko Belt. Reverse faulting along ENE trending faults is indeed observed in Late Tertiary calcretes near the town of Omaruru in the Damara belt (Klein, 1980). Strong basement control on rift-related extension is also argued by Will and Frimmel (2013) who analyzed dykes and faults along the southern African margin from Cape Town to Angola. This implies that southern Africa reacts highly heterogeneously to the application of far-field stresses, as also proposed by others (e.g., Janssen et al., 1995; Ziegler et al., 1995). A detailed paleostress study in the Damara Belt might help to resolve this matter, because in this case paleostress tensors in the Damara Belt should be very different than in the nearby Kaoko Belt.

Upwelling of the African superplume, which is thought to have led to the high topography of southern Africa and associated widespread rock and surface uplift (e.g., Nyblade and Robinson, 1994; Gurnis et al., 2000; Flament et al., 2014), should result in overall extensional stress regimes in southern Africa as it stretches the crust, a mechanism generally outlined by Hafner (1951). The African superplume is inferred to have remained unchanged in size and position for the last 300 Ma (Burke et al., 2008) with the African continent riding over it after the breakup of Gondwana (Braun et al., 2014). Another model to explain the high topography is introduced by Moore et al. (2009) who link circumferential drainage divides in southern Africa to reorganizations of oceanic spreading axes which induced compressive stresses to the continent. However, neither model fits the paleostress data well. Compression derived from oceanic spreading ridges, i.e. ridge push, should result in margin-perpendicular compressive stress, which is not observed by Viola et al. (2012) and Will and Frimmel (2013) or our study. On the other hand, an influence of the African superplume is hard to combine with the compressive stress regimes outlined by Viola et al. (2012). This indicates that these effects may play at most a supporting role in the stress history of southern Africa.

In summary, varying paleostress data in southern Africa may be the result of regional stress variations or a heterogeneous deformation that is controlled by the basement structure. Ridge push from the Atlantic spreading axis seems not to exert a strong control on the margin as no margin-perpendicular compression is observed. The overall extensional regime in NW Namibia may derive from flexural bending due to sediment loading offshore and the continuous uplift of the African superplume.

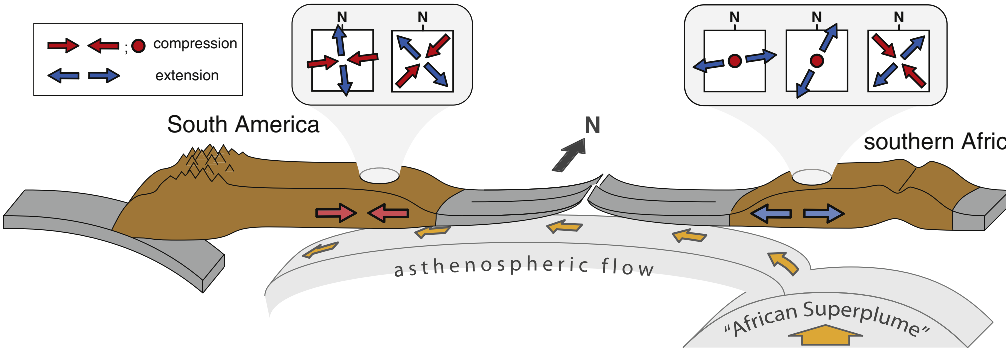

Fig. 10. Schematic cross-section through South America, the South Atlantic and southern Africa with a summarized sketch of the principal obtained paleostress regimes in SE/S Brazil and NW Namibia. While the southern African continental margin appears to have been mainly subject to extension, the South American passive margin has experienced mostly compressive stresses in strike-slip regimes. The differences might be due to the boundary conditions, i.e. mantle dynamics (freehand sketch following geophysical models; see text for references) and the subduction zone along the west of South America.

6. Conclusions

Paleostress analysis on two originally adjacent areas of the South Atlantic, SE/S Brazil and NW Namibia shows that lineament trends, fault patterns, stress regimes and basement reactivation have been significantly different on both sides of the South Atlantic since its opening. NW Namibia has experienced mostly extension related to the Atlantic rifting and flexural bending of the margin, whereas SE/S Brazil has experienced compressional stresses resulting in two major strike-slip regimes with compression parallel and at a high angle to the margin (Fig. 10). In Brazil, our results are in good agreement with other paleostress studies, which depict similar strike-slip systems, indicating that a large part of the passive margin was subject to strike-slip faulting. The strike-slip regime with compression parallel to the continental margin might be the combined result of flexural bending of the margin and stress transmitted from NE directed subduction of the Nazca plate in the Paleogene. This stress system is later overprinted by the E-W compressional strike-slip regime resulting from the Andean uplift and the flat-slab subduction in the Neogene. For both study areas, we regard an influence of ridge push from the Atlantic mid-ocean ridge as subdued, because no margin-perpendicular compression is observed in the study areas.

Paleostress studies are scarce along the southern African passive margin, but it appears that stress regimes are more variable. The available data may indicate that margin parallel extension is restricted to a zone less than 350 km wide along the ocean continent boundary. Reactivation of basement shear zones is common in NW Namibia with shear zones striking sub-parallel to the orientation of normal faults. In SE/S Brazil, reactivation is either absent or plays a minor role since most shear zones are not oriented in a favorable position for reactivation during strike-slip, in contrast to significant reactivation of shear zones during the formation of the Cenozoic continental rift system further north between São Paulo and Rio de Janeiro.

The overall difference between a normal faulting-dominated margin in Namibia and a strike-slip faulting-dominated margin in Brazil could be rooted in the different boundary conditions that the continents experience. Africa is influenced by continental rifting and the African superswell with a significant vertical uplift and local scale extension at the margin, whereas South America may be entirely under compression due to the subduction on the continent's western side and a westward asthenospheric flow beneath the South Atlantic.

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Appendix A. Supplementary data

The measured minor faults near a very prominent N–S trending normal fault with large-scale down-faulting to the west, in the center of our NW Namibian study area, supports our approach of merging the data. Despite the clear extension direction of the fault, fault slip data obtained near this fault indicate a broadly N–S extension (encircled white in Supplementary Fig. S2). This shows that it is not self-evident that the data of local subsets resolves even prominent faulting events nearby. However, the overall image of the merged data resolves the E–W extension (Fig. 6b). Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gr.2014.09.006.

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