The late rifting phase and continental break-up of the southern South Atlantic: the mode and timing of volcanic rifting and formation of earliest oceanic crust

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Abstract: Multichannel seismic and potential field data shed light on the final rifting stage in the southern South Atlantic. This was associated with major episodes of magmatism during the Early Cretaceous continental break-up. An asymmetrical simple shear-dominated variable strain rifting model is proposed with the margin asymmetry visible in shelf width, amplitude of magnetic anomalies, orientation of break-up-related sedimentary basins and basement slope angle. Along-margin rotation in spreading- and later rifting-direction from north–south to west–east are of great importance for the asymmetries. Such rotational opening may also explain why the southernmost segments of the South Atlantic are magma starved, with a sharp transition to a volcanic-rifted margin type northwards. Interpretation of pre-M5 (*c.* 130 Ma) magnetic seafloor spreading lineations constrains the timing of excess break-up-related volcanism and transition to 'normal' seafloor spreading. Termination of magnetic anomalies within seaward-dipping reflector sequences points towards a deposition of the volcanics from south to north prior to and during the early rift and opening stages. Identification of previously unknown pre-M5 magnetic lineations offshore Argentina completes the lineation pattern in the southern South Atlantic. The oldest magnetic anomaly related to oceanic spreading is M9 (*c.* 135 Ma). Older anomalies, previously identified as M11 (*c.* 137 Ma) offshore Cape Town, are related to structural or magnetization variations within seaward-dipping reflector sequences.

The South Atlantic continental margins (Fig. 1) formed after the break-up of Gondwana, with Antarctica separating from Africa and South America at around 155 Ma and opening the Weddell Sea prior to the onset of South Atlantic rifting (Jokat *et al.* 2003). The South Atlantic opened in the Early Cretaceous with suggested opening ages between 126 Ma and 137 Ma (Rabinowitz & LaBrecque 1979; Unternehr *et al.* 1988; Nürnberg & Müller 1991; Gladczenko *et al.* 1997; Jokat *et al.* 2003), and it is commonly proposed that this process progressed from south to north (Rabinowitz & LaBrecque 1979; Austin & Uchupi 1982; Uchupi 1989; Jackson *et al.* 2000). Prior to and during the early phase of the formation of the ocean basin, voluminous volcanism affected both Mesozoic intracratonic basins onshore (Paraná-Etendeka large igneous province (LIP)) and the rifted crust offshore (O'Connor & Duncan 1990; Hinz *et al.* 1999; Jerram *et al.* 1999; Bauer *et al.* 2000; Trumbull *et al.* 2007; Franke *et al.* 2010; Moulin *et al.* 2010).

The first of the approaches to determine the age of the oldest parts of the South Atlantic using magnetic anomalies was done by Talwani & Eldholm (1973), Larson & Ladd (1973) and Rabinowitz (1976). They identified magnetic lineations offshore South Africa that constrain the age of this margin but failed to reach a similar result for the Argentine margin. In an extensive study of the African and South American margins south of Rio Grande Rise/Walvis Ridge, Rabinowitz & LaBrecque (1979) made the first detailed reconstruction of the Mesozoic South Atlantic. The subsequent Cenozoic evolution of the ocean was described by Cande *et al.* (1988). A reinterpretation of the whole opening history of the South Atlantic, including new rotation poles, was done by Nürnberg & Müller (1991) using the older anomaly identifications by Rabinowitz & LaBrecque (1979) in the area of interest of this study.

Rabinowitz & LaBrecque (1979) identified lineations back to M11 off Cape Town, but they were able to recognize only M3 or M4 off Argentina. Larson & Ladd (1973) and, more completely, Rabinowitz & LaBrecque (1979) also identified a lineated magnetic anomaly (G-anomaly) in the vicinity of the shelf edge along most parts of the margins. Due to its unusual properties, this anomaly was not considered a simple seafloor-spreading

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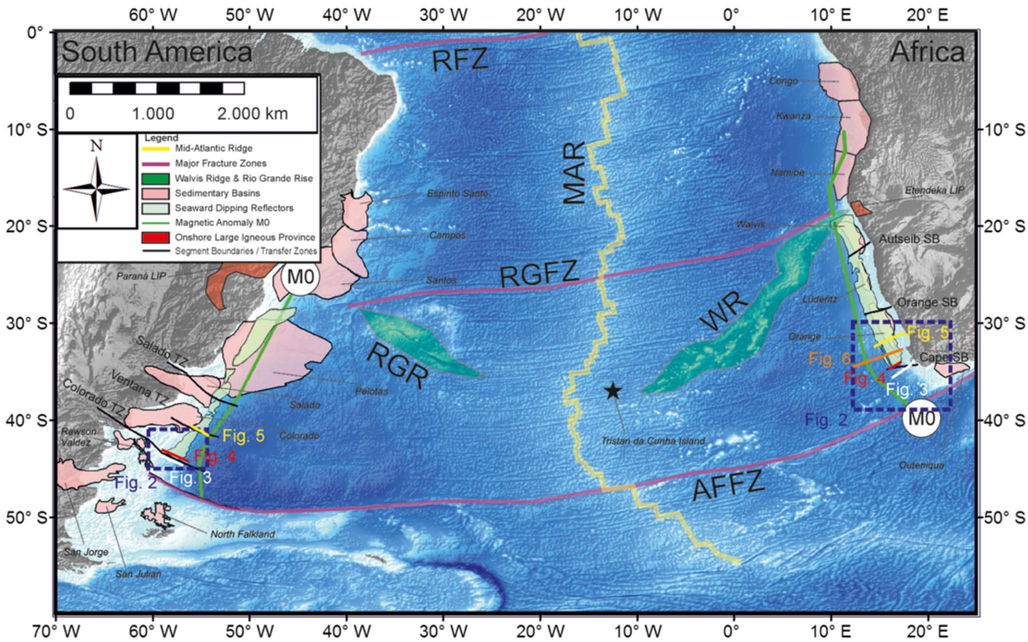

Fig. 1. Regional map of the South Atlantic showing the topography and bathymetry, as well as important regional features. These features include sedimentary basins of the southernmost South Atlantic (Africa south to north – Outeniqua Basin, Orange Basin, Lüderitz Basin, Walvis Basin, Namibe Basin, Kwanza Basin, Congo Basin; South America south to north – North Falkland Basin, San Julian Basin, San Jorge Basin, Rawson & Valdez Basins, Colorado Basin, Salado Basin, Pelotas Basin, Campos Basin, Santos Basin, Espirito Santo Basin), the distribution of seaward-dipping reflector sequences (SDRS) along the passive continental margins and the boundaries separating structurally distinct margin segments on either margin. The segment boundaries separating the magma-starved segments from the volcanic-margin segments have been named the Colorado Transfer Zone (Colorado TZ) (Franke *et al.* 2007) and Cape Segment Boundary (Cape SB), respectively (Koopmann *et al.* 2013). Note the almost margin-perpendicular basin axes of the Argentinean South American basins in contrast to the margin-parallel basins on the southern African west coast. For orientation, the two onshore large igneous provinces (LIPs) of the region, Paraná-LIP (South America) and Etendeka-LIP (South Africa), are included on the map, together with the major fractures zones of the region, the Agulhas Falkland Fracture Zone (AFFZ), the Rio Grande Fracture Zone (RGFZ) and the Romanche Fracture Zone (RFZ). Magnetic Anomaly M0 is shown as the oldest continuous seafloor spreading anomaly in the South Atlantic. The rectangles mark the extent of the magnetic anomaly maps shown in Figure 2. Also shown are the locations of the profiles presented in Figures 3–6. Note the difference in distance from the southernmost SDRS to the AFFZ. MAR, Mid Atlantic Ridge; RGR, Rio Grande Rise; WR, Walvis Ridge.

anomaly but was interpreted as an edge anomaly at the boundary between oceanic and continental crust (Rabinowitz 1976; Rabinowitz & LaBrecque 1979). A recent study by Moulin *et al.* (2010) also proposes the presence of M7 magnetic anomalies in the southern part of the South Atlantic but implies that most of the movement of the Austral and Nubian African blocks for the first opening stage occurred between chrons M4 and M2.

Reflection seismic investigations revealed that the volcanic margin type is widespread in the South Atlantic (Hinz 1981; Austin & Uchupi 1982; Gerrard & Smith 1982; Gladczenko *et al.* 1997, 1998; Hinz *et al.* 1999; Bauer *et al.* 2000; Talwani & Abreu 2000; Franke *et al.* 2010; Franke 2013). The most distinct indicator for the volcanic character of the margin is the occurrence of a seaward-dipping reflector sequence (SDRS), which is commonly thought to represent voluminous emplacement of volcanics (e.g. Mutter *et al.* 1982; Mutter 1985). Hinz *et al.* (1999) proposed that the magnetized volcanics of the SDRS are the source of the large positive magnetic anomaly on the Argentine margin. Bauer *et al.* (2000) and Corner *et al.* (2002) came to a similar conclusion at the Namibian margin. Following the approach suggested by Franke *et al.* (2007) and based on the mapping of SDRSs, Koopmann *et al.* (2013) updated the finding of break-up relevant margin segmentation for the African margin. Reflection seismic studies on both conjugated margins (Franke *et al.* 2010; Koopmann *et al.* 2013) showed a sudden onset of volcanism as revealed by the presence of SDRSs. Previous studies of the conjugated margins of the South Atlantic concentrated on one margin (Gladczenko *et al.* 1998; Franke *et al.* 2007), considered the South Atlantic at a larger scale (Moulin *et al.* 2010; Blaich *et al.* 2011) or started their investigation after break-up (e.g. Cande *et al.* 1988). The dataset acquired by Bundesanstalt für Geowissenschaften und Rohstoffe (BGR; Federal Institute for Geosciences and Natural Resources) and used for this study enables consideration of the pre-break-up phases and the earliest phases of seafloor-spreading in the southernmost South Atlantic.

Present interpretations of the magnetic anomaly lineation pattern display asymmetries between the conjugated margin segments in the African and Argentine basins. Detailed investigations of the symmetry of rifted margins after the work of Rabinowitz & LaBrecque (1979) are not available or rather cover more northerly South Atlantic margin segments (e.g. Brazil–Namibia (Talwani & Abreu 2000) or Brazil–Gabon/Angola (Mohriak *et al.* 2002)) in a broader overview.

Here we present a combination of a structural investigation of rift-related margin structures, based on conjugated multichannel seismic (MCS) data with a study of the magnetic anomalies of the earliest oceanic crust, based on partly unpublished potential field data (Fig. 2). Results of this integrated analysis of magnetic and seismic data from the conjugated margins of South America and southern Africa are used to discuss several hypotheses on the South Atlantic margins regarding volcanic structures and the break-up process.

Dataset

South African margin

Between 1991 and 2003, four scientific cruises were accomplished by the BGR along the continental margin of western Africa and a total of 12 200 km of MCS data were acquired (BGR91: 4200 km of MCS data; SO85: 1900 km; BGR95: 2800 km; BGR03: 3300 km). Magnetic and gravimetric data were recorded simultaneously along MCS lines. BGR seismic data were acquired using different setups of a multichannel streamer system, commonly with a shot point interval of 50 m and a sampling rate of 4 ms. Seismic data from cruise BGR03 were reprocessed for this study by applying prestack deconvolution, frequency filtering, multiple attenuation by radon filtering and surface-related multiple elimination, post-stack deconvolution and post-stack Kirchhoff time migration.

The open file dataset GEODAS published by the National Geophysical Data Center in Boulder/Colorado on CD-ROM contains a large set of magnetic line data from cruises since the early 1960s. There are hardly any specific surveys on the continental margin of South Africa. Instead, a lot of transit lines to and from Cape Town were surveyed with magnetics. These data had already been used by Rabinowitz & LaBrecque (1979) to identify magnetic lineations and the G-anomaly. Here, we have used the data to compile a magnetic map (Fig. 2c, d) for the Cape Basin off southern Africa. All data were selected according to their age and quality. Some of the oldest data were not used because of potential navigational problems. Lines that contained erroneous data were also discarded. All remaining total intensity data were newly processed using the appropriate International Geomagnetic Reference Field (IGRF). Gridding and contouring were performed using GMT routines (http://gmt.soest.hawaii.edu/). Illumination is set from an approximate location at the mid-oceanic ridge (from the east for the Argentine map, from the west for the African map). There are still some remnants of mis-levelled lines in the database, but we believe that the map gives a valuable overview about the general features of the anomalous magnetic field in the area.

South American margin

Between 1987 and 2004, four marine geophysical cruises were accomplished by the BGR along the continental margin of South America and a total of about 24 000 km of MCS data were acquired (BGR87: 3700 km, SO85: 4300 km, BGR98: 12 000 km, BGR04: 3800 km). BGR surveys used different setups of a multichannel streamer system with varying acquisition and processing parameters (Hinz *et al.* 1999; Franke *et al.* 2007). Accompanying the acquisition of reflection seismic data, magnetic and gravimetric data were acquired on most lines using varying instrumental setups. These cruises provided the MCS dataset used for previous BGR investigations of different aspects of the margin (Franke *et al.* 2006, 2007, 2010; Schnabel *et al.* 2008; Grassmann *et al.* 2011; Becker *et al.* 2012; Franke 2013).The magnetic map in Figure 2a, b is based largely on the 1998 (BGR98 cruise) dataset. All total intensity data were corrected using the appropriate IGRF reference fields. Gridding and display parameters (colour scale and illumination) are the same as in Figure 2c, d for the African data.

Interpretation

Magma-poor v. volcanic-rifted margin type on MCS data

For interpretation, conjugated profiles on the South Atlantic margins were investigated.

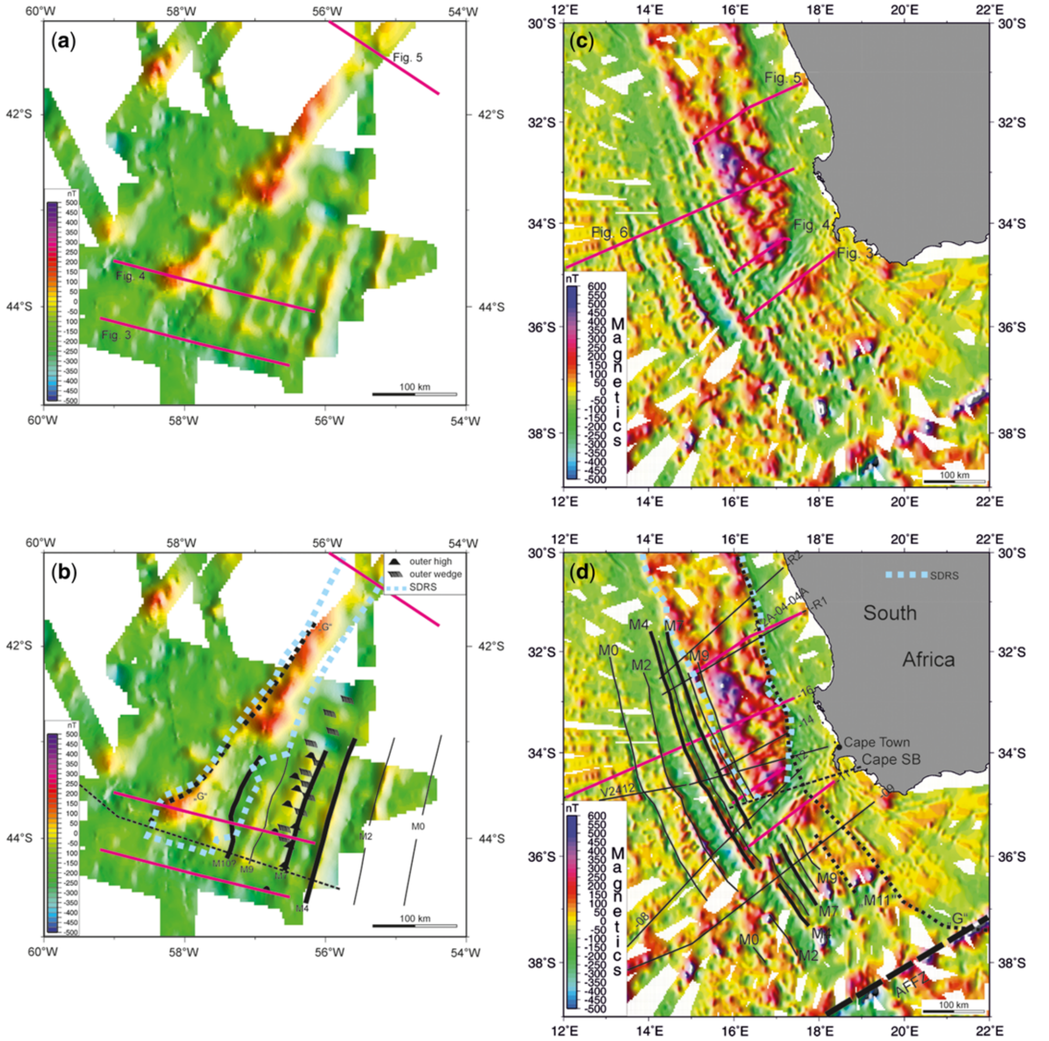

Fig. 2. Gridded magnetic anomaly maps of offshore (**a**, **b**) South America and (**c**, **d**) South Africa. Note the different scales. Marked in pink are the profiles from surveys BGR98 (South America) and BGR03 (Africa) shown in Figure 3 (BGR98-11 and BGR03-11), Figure 4 (BGR98-20 and BGR03-12), Figure 5 (BGR98-39 and BGR03 02A-04-04A) and Figure 6 (BGR03-16A). On the magnetic anomaly maps, important features and structures are visible. The mapped area of a seaward-dipping reflector sequence occurrence fits the margin-parallel positive magnetic anomaly, especially on the African margin. On the South American margin, the data now allow the interpretation of seafloor spreading anomalies as old as M9r in this structurally important region of the South Atlantic. Note how the oldest anomalies close in from south to north to merge into the large margin-parallel positive anomaly. Note further the much higher amplitudes of the magnetic signal on the African side and the different distance between magnetic anomalies M0r and M9r on either margin (*c.* 175 km on the South American compared to *c.* 150 km on the African margin). For reference, the 'G-anomaly' (a bold dotted line marked 'G') and 'M11' offshore South Africa are shown (from Rabinowitz & LaBrecque 1979).

Stratigraphically, four main reflectors shown in Franke *et al.* (2010) and Becker *et al.* (2012) for the Argentine margin and Brown *et al.* (1995) and Hartwig *et al.* (2012) for the African margin were mapped and uniformly named in the figures shown here. From oldest to youngest, these reflectors are: the base of post-rift-sediments reflectors (mostly representing the break-up unconformity over continental crust); a distinct unconformity within Aptian to Albian sediments; the Cenomanian–Turonian unconformity; the Maastrichtian–Palaeocene unconformity.

On the southernmost conjugated profiles (BGR98-11 and BGR03-11) shown here (Fig. 3), approximately 40 km south of the Colorado Transfer Zone (TZ) (Franke *et al.* 2007), respectively the Cape Segment Boundary (SB) from Koopmann *et al.* (2013), the margins are remarkably different from typical volcanic rifted margins. On the African side, the continental slope appears remarkably steep, with a basement slope angle of over 5°, while the American side shows a relatively high basement slope angle of 2.5°. Still, neither section really matches descriptions of 'typical' magma-poor margins such as the Iberian Margin (Whitmarsh *et al.* 2001; Lavier & Manatschal 2006; Péron-Pinvidic & Manatschal 2009; Reston 2009). Listric faults related to rift basins are mostly missing, and extremely thinned crust alongside sections of exhumed mantle is completely absent. On ship-track magnetic data for the African profile, seafloor spreading anomalies can be correlated to as old as M9, whereas the American side, due in part to much lower amplitudes, does not allow a satisfying correlation to seafloor spreading anomalies older than M4 (Becker *et al.* 2012). The gravity data (Fig. 3a) likely reflect sedimentary structures (contourites, mass wasting events; Gruetzner *et al.* 2011). The base-of-sediments reflector (post-rift) is located about 2 s two-way travel time (TWT) deeper on the Argentine profile than on the conjugate African section.

Eighty kilometres north of the southernmost MCS lines shown in Figure 3 and just north of the Colorado TZ and the Cape SB, the conjugated profiles (BGR98-20 & BGR03-12) (Fig. 4) show what the southern profiles were distinctively missing; sets of arcuate SDRSs that are almost uniformly interpreted as volcanic or volcano-sedimentary in origin based on geophysical data and drilling results (Hinz 1981; Eldholm *et al.* 1995; Planke *et al.* 2000). The SDRSs and related volcanics (outer wedges, upper crustal reflectors (UCR)) extend over a width of up to 200 km on the African profile (the maximum described for this 'First-order Segment II', Koopmann *et al.* 2013) and 180 km on the South American profile, and they extend up to 3.5 s TWT, equivalent to 9 km thickness assuming a 5.5 km s^{-1} interval velocity for the SDRS. In the SDRS on these conjugated profiles prominent, reflectors separate larger, acoustically blanker sequences, likely indicating episodicity within emplacement and/or intermediate erosion of the volcanic material SDRS (Hinz *et al.* 1999). In the magnetic data, a large positive anomaly (LP) can be seen 'covering' with a good fit the extension of the SDR wedges 1–3 (seaward of the 'G-anomaly' of Rabinowitz & LaBrecque (1979)). Less prominent outer wedges (SDR wedge 4) are seen further offshore, approximately correlating to magnetic chrons M7 to M5. These outer wedges are separated from the main SDRS by an area where no distinct reflectors can be identified below the base-of-sediment reflector. Exclusively on the Africa profile, the SDRSs are highly fractured, with fractures reaching up to the Aptian–Albian unconformity reflector. The post-rift sedimentary column on the African margin is thinner, and the base-of-sediments (post-rift) reflector on the American side is again located about 2 s TWT deeper than the reflector on the conjugated African margin.

The third MCS transect shown here (BGR98-39 and BGR03-02A-04-04A), 300 km further north along the margins (Fig. 5), reveals the variability in volcano-tectonic characteristics already described for the individual margins (Clemson *et al.* 1997; Gladczenko *et al.* 1998; Franke *et al.* 2007; Becker *et al.* 2012; Koopmann *et al.* 2013). The basement slope angle side is now shallower than 1° on either margin, suggesting more pronounced crustal thinning due to an orthogonal plate separation direction with respect to the rift-axis, instead of the possibly oblique-dominated plate movements in the beginning of the South Atlantic on the magma-poor margin sections further south. Further, the profiles appear more symmetrical than those shown in Figures 3 and 4. The arcuate SDRSs are now less sharply separated by prominent reflectors and appear to be generally more homogeneous and more sequential than further south. SDRS width on the African side is 150 km (and still close to the of 200 km seen on Figure 4, the maximum described for 'First-order Segment II', Koopmann *et al.* 2013) on the African side and slightly less on the American side, forming a 280 km-wide emplacement area. The margin-parallel positive magnetic anomaly again correlates nicely with the area of SDRS occurrence. The South American margin base-of-sediment reflector is about 2 s TWT lower than its African counterpart.

Conjugated magnetic features

The magnetic maps in Figure 2 show two conjugated segments of the Argentine and South African margins as indicated in Figure 1. Both maps have the same scale, amplitude range and equivalent illumination directions. These maps reveal large differences between the conjugate margins. See the Discussion for a broader view on the implications of the magnetic anomaly pattern.

Southern African margin. The previously interpreted seafloor-spreading lineations M0–M9 on the African side (Rabinowitz & LaBrecque 1979) are well developed south of 33°S. It is an intriguing feature of these lineations that they have rather high amplitudes in the south at 35–36°S but that the

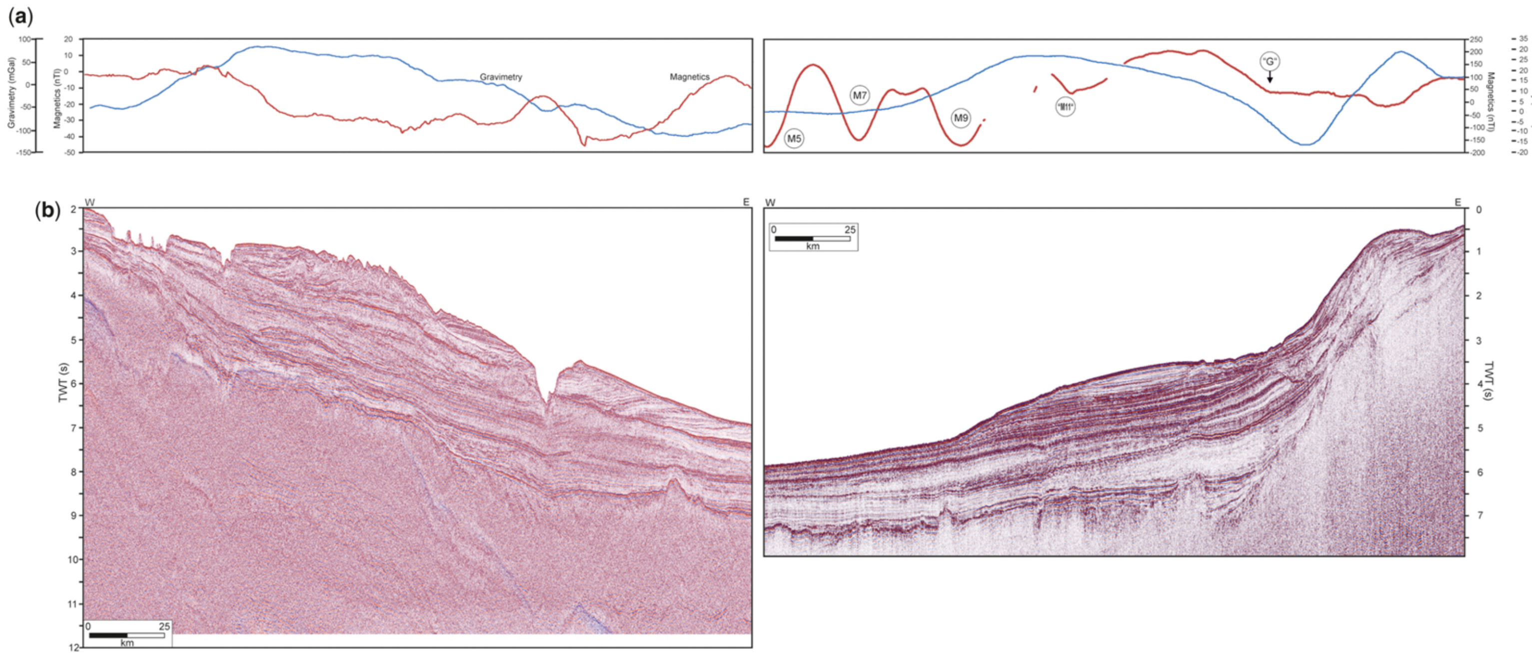

Fig. 3. Approximately conjugated sections of BGR marine geophysical data profiles BGR98-11 (left, South America) and BGR03-11 (right, South Africa) (see Figs 1 & 2 for location): (**a**) ship-track potential field data; (**b**) uninterpreted multichannel seismic (MCS) profile.

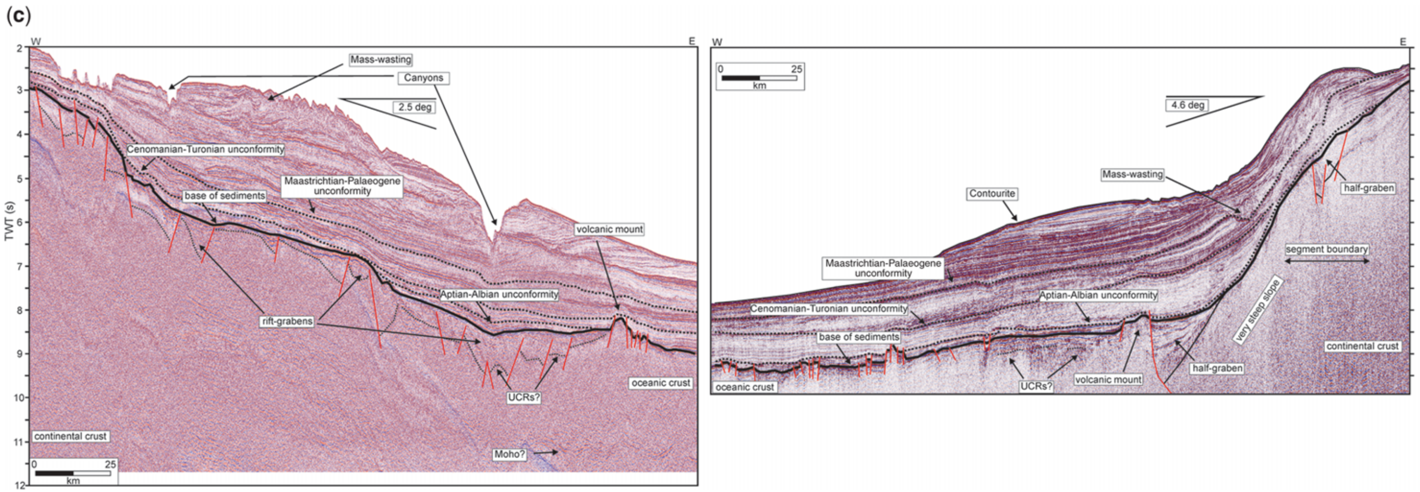

Fig. 3. (*Continued*) (**c**) interpreted MCS profile. The African profile features a comparably steep continental basement slope, a few rift graben and a volcanic mount. Seafloor spreading anomalies can be correlated to as old as M9r on the African side. The base of sediments reflector is meant to represent the onset of post-rift sedimentation, but due to a lack of well control and margin-parallel seismic data, it could not be called the break-up unconformity. Above continental crust, the base of sediments reflector may represent the break-up unconformity. This reflector appears a lot smoother landward of the seafloor spreading anomalies than it does further seaward. No clear correlation to seafloor spreading anomalies can be made from the data on the American profile. A set of flat-lying upper crustal reflectors (UCRs) appears on the South American profile. On either margin, a gravity high seems to correspond to sediment build-up on the slope. On the South American side, the whole margin appears about 2 s (TWT) lower, with more sediments on the comparably shallow-dipping basement. The large positive magnetic anomaly is marked 'LP', and the linear 'G-anomaly' (from Rabinowitz & LaBrecque 1979) is indicated at the landward end of that zone.

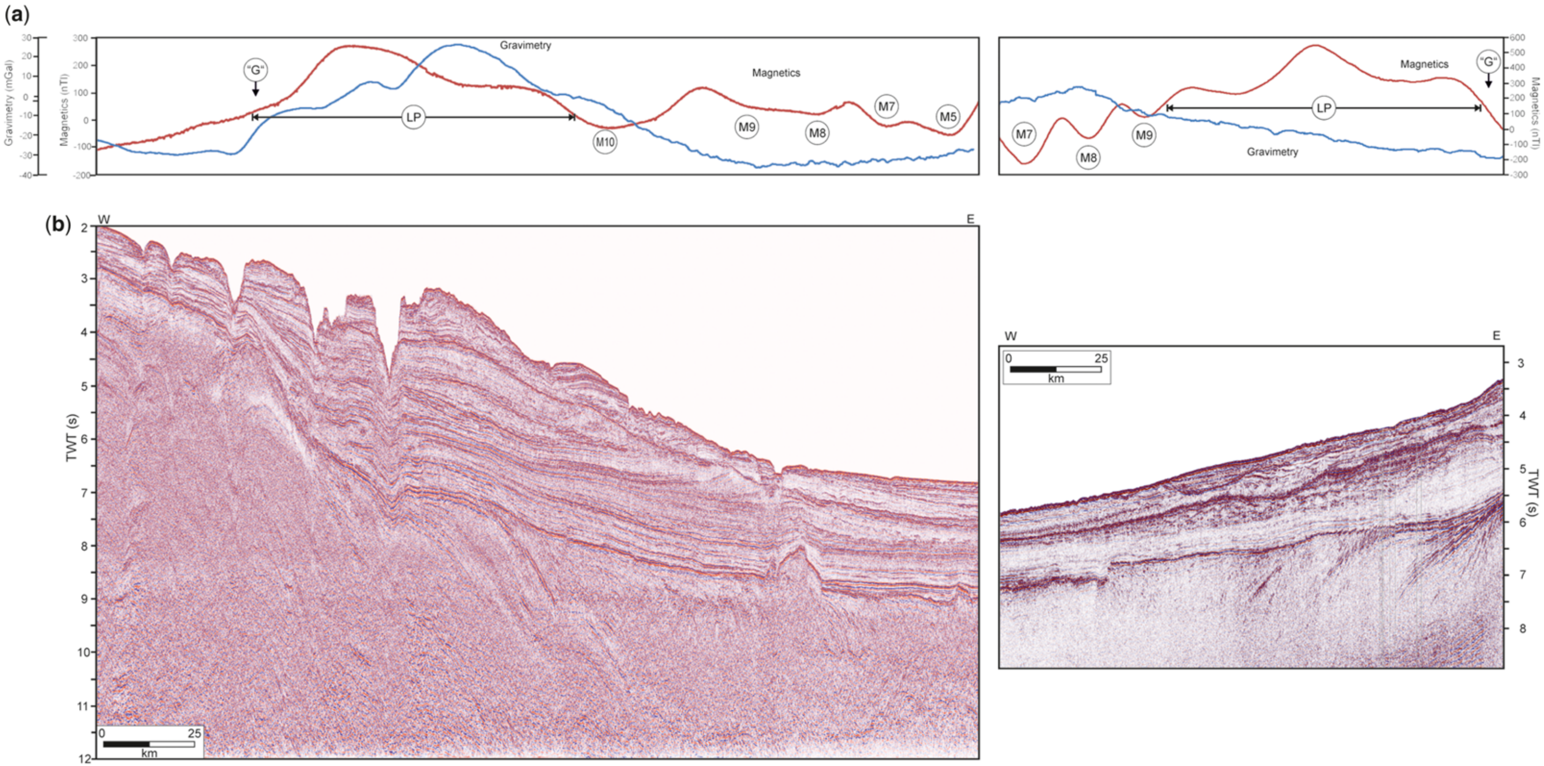

Fig. 4. Approximately conjugated sections of BGR marine geophysical data profiles BGR98-20 (left, South America) and BGR03-12 (right, South Africa) (see Figs 1 and 2 for location): (**a**) ship-track potential field data; (**b**) uninterpreted MCS profile.

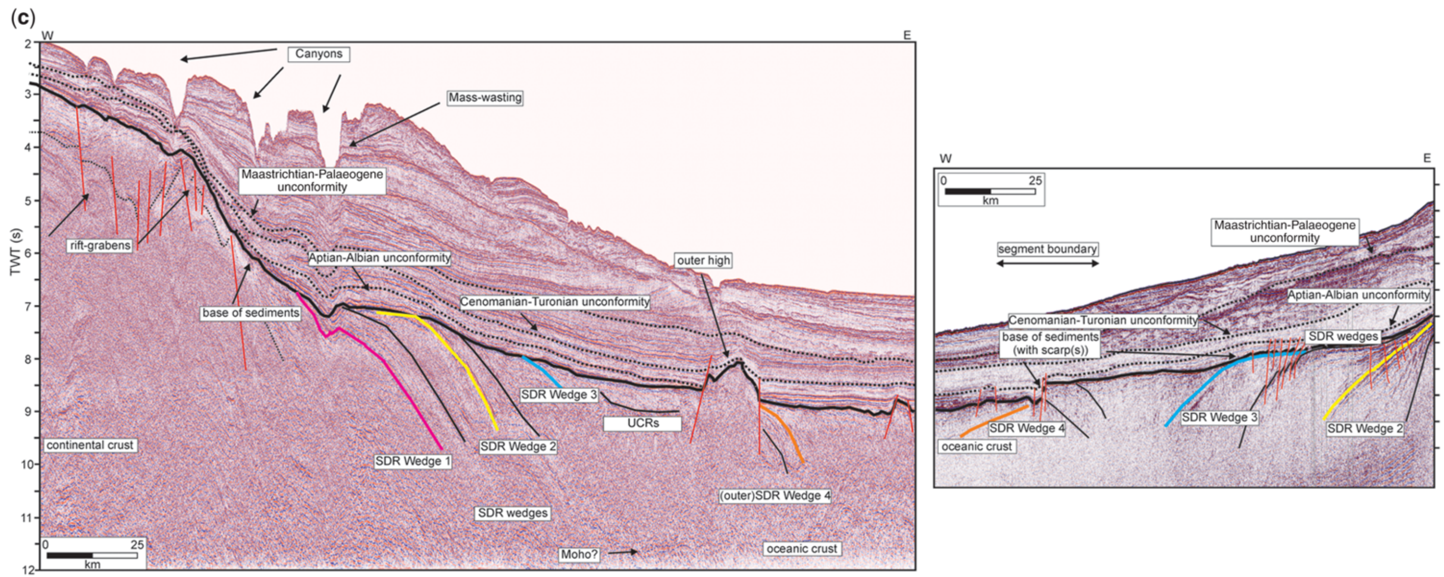

Fig. 4. (*Continued*) (**c**) interpreted MCS profile. These conjugated profiles (*c.* 80 km north of the profiles shown in Fig. 3) are remarkably different towards the more southern profiles regardless of the spatial proximity. On both margins, huge wedges of arcuate, seaward-dipping reflector sequences (SDRS) are easily recognizable. The more landward SDR wedges 1–3 show a good fit to a positive magnetic anomaly (LP) next to the 'G-anomaly' of Rabinowitz & LaBrecque (1979). Further offshore, less prominent outer wedges (SDR wedge 4) are seen, approximately correlating to magnetic chrons M7r to M5r. Also note the prominently fractured SDRS on the African profile and the much thinner sedimentary column on the African margin, which again appears about 2 s (TWT) higher than the American conjugate. The large positive magnetic anomaly is marked 'LP', the linear 'G-anomaly' from Rabinowitz & LaBrecque (1979) is indicated at the landward end of that zone.

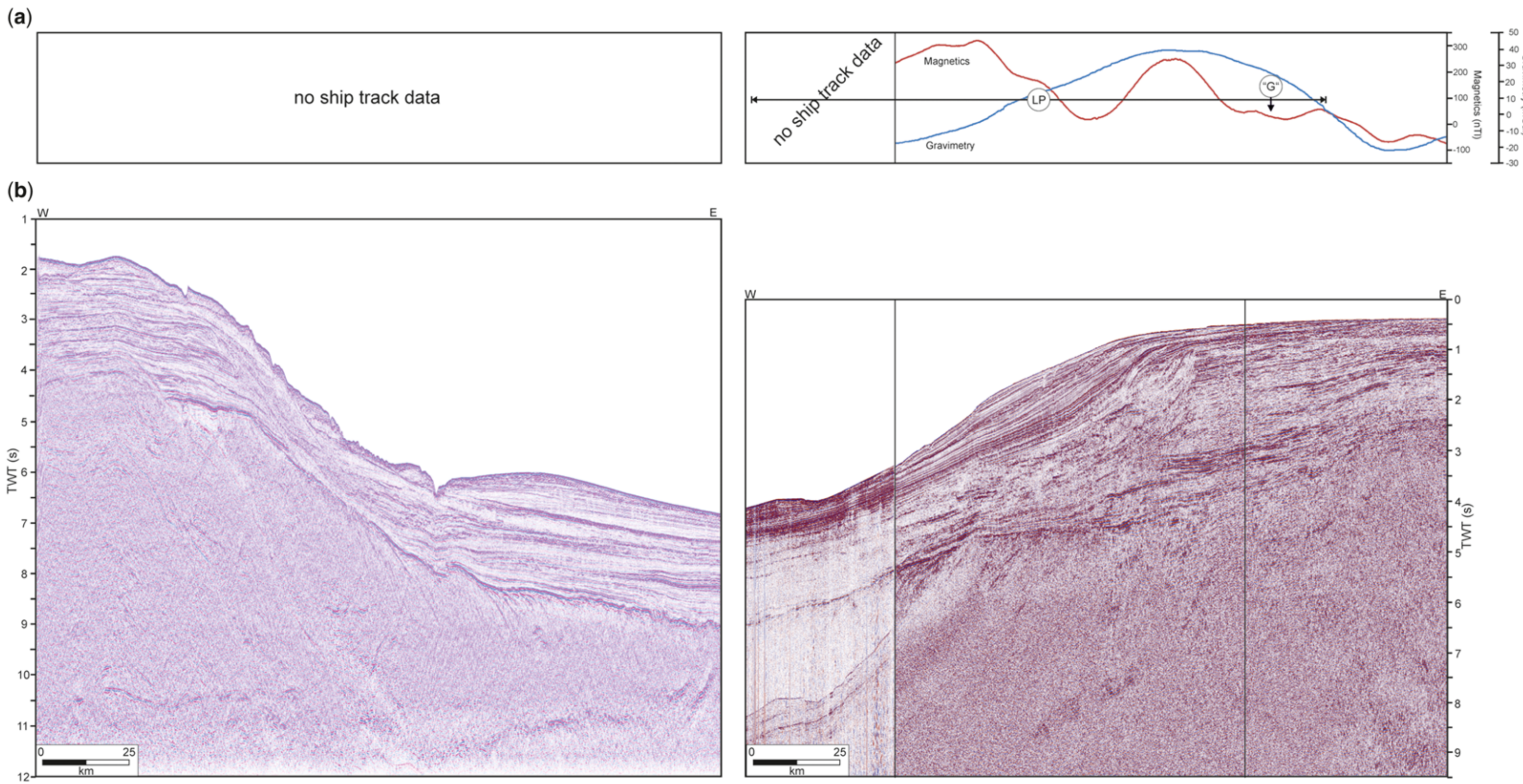

Fig. 5. Approximately conjugated sections of BGR marine geophysical data profiles BGR98-39 (left, South America) and BGR03-02A-04-04A (right, South Africa) (see Figs 1 & 2 for location): (**a**) ship-track potential field data (no data were recorded for the Argentinean profile and BGR03-02A); (**b**) uninterpreted MCS profile.

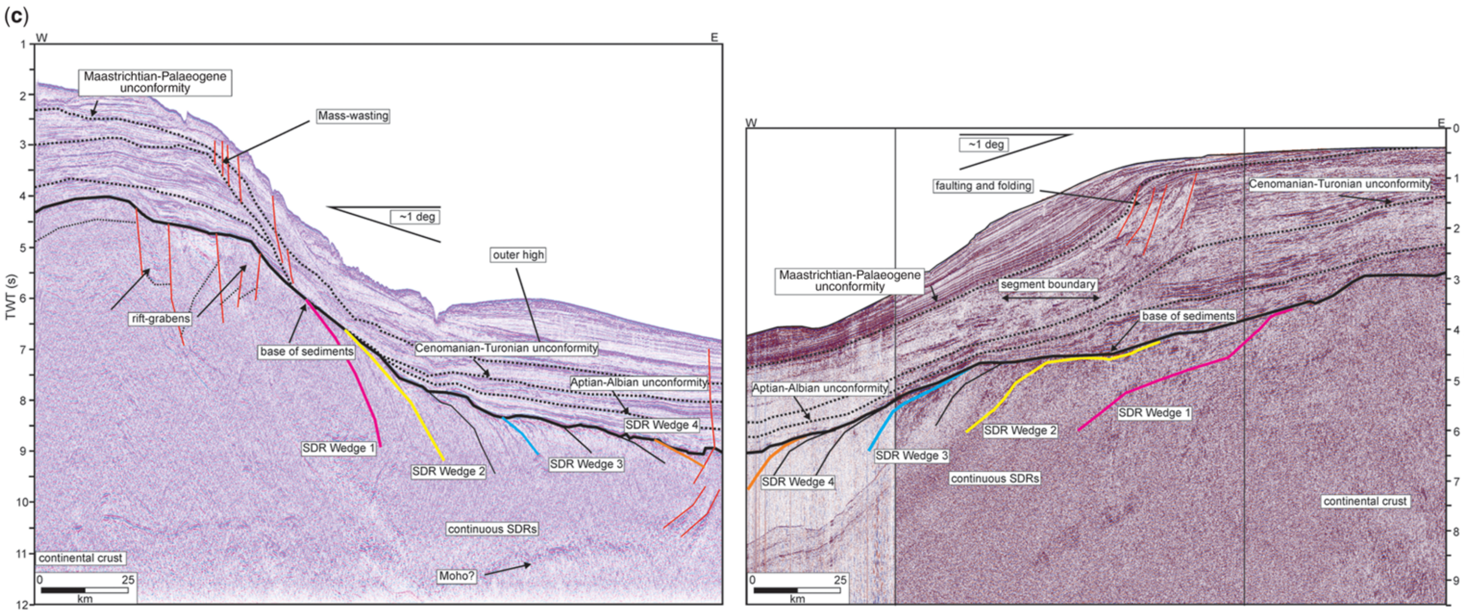

Fig. 5. (*Continued*) (**c**) interpreted MCS profile. Compared to the more southerly profiles showing volcanics, the conjugated sections shown here (*c.* 300 km north of the ones shown in Fig. 4) show less distinct SDRS reflectors and definition of individual wedges is more difficult. The arcuate reflectors now appear more continuous and rather as a wide sequence than the sharply defined wedges further south. The width of the SDRS has increased up to 150 km on either margin. Dip of the basement slope has decreased further to very shallow angles of less than one degree. The profiles appear more symmetrical than further south. From the ship-track potential field data available for the landward part of the African profile, the SDRS again correlate nicely with the positive magnetic anomaly. Again, different subsidence and uplift history submerged the South American margin about two seconds (TWT) lower than its African counterpart. The large positive magnetic anomaly is marked ‘LP’, and the linear ‘G-anomaly’ from Rabinowitz & LaBrecque (1979) is indicated at the landward end of that zone.

amplitude becomes continuously reduced to the north until they are virtually absent from about 32°S northward.

Landward of M9 and north of 35°S we see a broad mostly positive magnetic anomaly over the continental margin, which changes at a sharp but not straight line into a magnetically quiet area over the shelf area that extends up to the coastline showing a negative anomaly level. The strong positive anomaly, or the transition to the landward quiet zone, was originally named the G-anomaly (Larson & Ladd 1973). It is a linear feature and marked 'G' in Figures 2, 3, 4 and 5, whereas the large positive margin-parallel magnetic anomaly is marked 'LP'.

At 35°S the broad positive anomaly is abruptly terminated to the south at a magnetic low. South of 35°S, down to the Agulhas–Falkland Fracture Zone (AFFZ), the magnetic field over the margin is inconspicuous. Except for a broad low amplitude signal at 35°S/17.5°E and some local anomalies between 36° and 37°S the margin does not show a magnetic signature.

South American margin. On the Argentine side the anomalies show basically the same structure but with generally much lower anomaly amplitudes. There are indications for linear anomalies south of 43°S and east of 57°W. There is also a distinct positive anomaly parallel to the edge of the margin but it is much narrower than on the conjugate margin. Except for some local anomalies the shelf areas are smooth at a slightly negative level. Similar to the situation offshore South Africa the positive margin anomaly is terminated abruptly to the south at 44°S on the South American margin.

Seafloor-spreading lineations

Rabinowitz & LaBrecque (1979) interpreted Chron M11 (*c.* 136 Ma; Gradstein & Ogg 2004), from off Cape Town to the Orange Basin, as the earliest spreading anomaly along the African margin. Elsewhere (Nürnberg & Müller 1991), the rift phase has been proposed to have lasted from 150–130 Ma, to Chron M4. More recently, the actual presence or determinability of Chron M11 (*c.* 136 Ma) has been doubted and M7 has been suggested as the oldest determinable Chron in the southern part of the Orange Basin and the conjugate Rawson Basin (Eagles 2007; Moulin *et al.* 2010).

Comparing Figures 2a, b, c, d, it is obvious why the magnetic lineations on the African side were the first to be detected (Larson & Ladd 1973; Talwani & Eldholm 1973), as they have much higher amplitudes and are easier to correlate. Rabinowitz & LaBrecque (1979) identified anomalies M0 to M9 as shown in Figure 2c, d, as well as anomalies back to M11. However, the location of pre-M7/pre-M9 anomalies in the shelf region and the appearance of the anomalies do not suggest a typical seafloor-spreading origin (see Discussion). Rabinowitz & LaBrecque (1979) suggested a correlation with oceanic crust back to M11, but we feel that the more landward anomalies require a different explanation. We propose that voluminous volcanic extrusives of the SDRS type provide an explanation more suitable to account for the shape and the enlarged amplitudes of the earliest margin-parallel magnetic anomalies at this margin. This proposal is derived from comparison with the extent of SDRSs as mapped with the help of reflection seismic data (Franke *et al.* 2007; Koopmann *et al.* 2013). There is a nearly perfect fit at the African margin and to a somewhat lesser but still convincing extent on the Argentine margin.

On the Argentine side, Rabinowitz & LaBrecque (1979) identified only magnetic anomalies M0 to M4. The dense line spacing of the BGR survey allows the interpretation of older lineations on the southern American continental margin despite the fact that the anomalies are distinctively weaker than those offshore South Africa. These weaker anomalies, however, are predicted by our magnetic source model calculations. The reasons are the greater depth of the basement as the magnetic source layer (8 km in contrast to 6 km in the Cape Basin) and different magnetization and strike directions. On the other hand, all these parameters do not explain the full extent of the amplitude reduction. The already known anomaly M2 and M4 identifications are distinctively recognizable and serve, together with some indications for M0, as fixed points from where the identification of the older lineations can be extended. The model for the much better constrained identifications in the Cape Basin served as a first guess. The identification process starts at the two southern profiles BGR98-21 and BGR98-09 where a distinct similarity between anomalies M4 to M10 with the model can be recognized. From here, we continued the correlations to the more northern profiles along some prominent anomalies. These are the negative part of M7 that can be followed to line BGR98-18 and the positive anomaly M10, which can be followed until line BGR98-07 and possibly to BGR98-06. M6 and M7 can not be distinguished, but together they seem to be visible until line BGR98-06. M8 and M9 merge to one positive anomaly between lines BGR98-07 and BGR98-18. This is also visible in the magnetic map (Fig. 2a, b). Although there are some uncertainties, we consider that it is the most probable interpretation for the weakly lineated anomalies in this area.

The oldest negative anomaly (M9), which can be recognized and modelled with certainty on the southern profiles (BGR98-21 and BGR98-09)

(Figs 2a, b & 4), turns into a wide negative anomaly on the adjacent lines to the north, interfering with the area of the SDRS.

The analysis of the most landward interpreted magnetic lineations ends at M9 on the South African side of the Atlantic and at M10 on the Argentinian side. The striking positive anomalies landward of these lineations (Fig. 2) seem to include normal intervals M10 and M11. These intervals are possibly identifiable within the large positive margin-parallel magnetic anomaly (Fig. 4a) as long-wavelength highs. Large parts of these anomalies are found at the continental slope and on the shelf, which excludes that their source is normal oceanic crust.

Earlier lineations than M4 at the South Atlantic margins merge with the large positive margin-parallel anomaly. Successively, younger magnetic lineations reach further north until finally M0 can be followed along the whole margin section between the AFFZ and the Rio Grande Fracture Zone. For example, Chron M4 merges with the LP at about 33°S on the Argentine margin and 24°S on the African margin, about 600 km south of the Rio Grande Fracture Zone.

Discussion

Margin symmetries and asymmetries: implications of magnetic anomalies on early opening history

Comparison of the margins reveals distinct similarities, as well as striking differences. Magnetic lineations on the African side (Rabinowitz & LaBrecque 1979), which can be clearly recognized, are only tentatively seen off Argentina with much lower amplitudes. It is also remarkable that the amplitudes of the earliest eastern lineations (African side) become weaker to the north where they seemingly disappear somewhere between 32°S and 33°S.

Magnetic lineations are an important proxy used to deduce spreading rates and infer opening ages for a given study area and for comparing plate motions on a global scale (Gradstein & Ogg 2004; Torsvik *et al.* 2008). For the limited study area investigated here, however, the disappearance of magnetic lineations along the conjugate margins seems equally important. Together with the mapped SDRS, the successive merging of lineations with the large positive margin-parallel magnetic anomaly northward on both conjugate margins (i.e. in the north–south direction of the opening of the South Atlantic) strongly supports the notion by previous authors (Uchupi 1989; Jackson *et al.* 2000) that the South Atlantic indeed opened successively from south to north (sometimes referred to as 'like an opening zipper', Jackson *et al.* (2000)). The oldest encountered true seafloor spreading anomaly in the southernmost volcanic rifted margin segment is proposed here to be M9, whereas 185 km northwards, the oldest magnetic lineation seen seaward of the SDRS is M7, representing an age difference for the seaward-most wedge of the SDRS and implying a delay in rift propagation, possibly at segment boundaries. The varying interpretation of anomalies on the conjugate margins might quite simply be a systematic problem related to lower magnetic amplitudes off Argentina and a lesser degree of certainty in interpretation. Besides the thicker cover of magnetized material, lower amplitudes might also be a reflection of generally smaller volumes of magnetized material preserved on the South American margin.

The presence of magnetic anomalies Chron M4 (*c.* 130 Ma) and younger is widely accepted in the southern South Atlantic. From that date on, conventional seafloor spreading continues to separate the two continents.

The G-anomalies

Rabinowitz & LaBrecque (1979) interpreted the G-anomalies at the conjugated passive margins of the South Atlantic in a general sense as edge anomalies mostly coincident with an isostatic gravity anomaly. The G-anomaly was defined as a line near the strongest gradient at the landward side of the distinct positive anomaly. Virtually everything seaward of these lines was interpreted in the sense of magnetic seafloor spreading lineations back to M11 in the Cape Basin. Figure 2 now shows that this large positive margin-parallel anomaly has very distinct meaning along the margins and was in the past also defined in places south of 44°S off Argentina and everywhere south of Cape Town, where no prominence in the magnetic anomalies can be detected from the new data. For the positive margin-parallel 'J-anomaly' on the magma-poor Iberian margin, Bronner *et al.* (2011) proposed a pre-seafloor spreading magmatic intrusion pulse that possibly triggered continental break-up without the formation of a massive SDRS. Our re-interpretation of the large positive anomaly proposed here, is rather similar, with the difference being that additional volcanic material was emplaced. These effusives explain most of the extent of the large positive margin-parallel anomaly. Further, Bridges *et al.* (2012) propose that the concept of using the first linear magnetic feature to date the onset of oceanic seafloor spreading overlooks the possibility of forming linear magnetic features by presenting such features as late-stage rift basalts in the transitional continental East African rift system. Our interpretation is another example for this problem. SDRSs in our data can be viewed as equivalents of the axial-rift volcanic basalts of Bridges *et al.* (2012). Our reflection and refraction

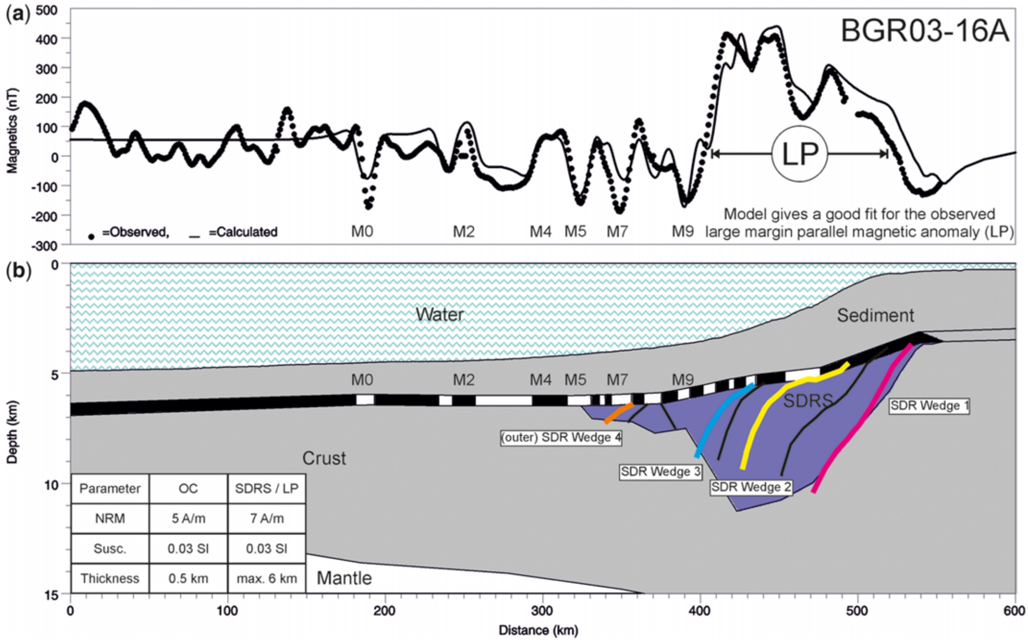

Fig. 6. Magnetic model for profile BGR03-16A (see Figs 1 & 2 for location): (**a**) observed ship-track magnetic data and modelling results with the extent of the large margin-parallel magnetic anomaly (LP) marked by arrows; (**b**) magnetic model bodies with magnetic polarity intervals of the oceanic crust indicated in black (normal) and white (reversed). The model shows it is feasibile to explain the long-wavelength character of the distinct, margin-parallel positive magnetic anomaly with a magnetic source body (purple) with a natural remnant magnetization (NRM) intensity of 7 A m^{-1}, a susceptibility (Susc.) of 0.03 SI and a triangular cross-sectional area of about 600 km^2. Oceanic crust (OC) was modelled with an NRM value of 5 A m^{-1} and a susceptibility of 0.03 SI as well. As the mostly extrusive volcanic origin of the SDRS suggests a strong magnetization, the magnetization intensity is regarded as plausible. Also plotted are the results of SDRS mapping in seismic data, showing that the calculated size of the magnetic body fits the dimensions of the observed SDRS wedges. Similar investigations on profiles on the Argentine margin revealed comparable results (Schreckenberger 1997; Hinz *et al.* 1999).

seismic data allow us to model magnetic anomalies in more detail (Fig. 6).

Therefore, a new definition of the G-anomaly as a (mostly positive) large margin anomaly that cannot be explained by normal seafloor spreading is proposed. This proposition is based on the shape of the anomalies, the lack of actual, clear lineations and on their location over the slope and the shelf. As can be seen in Figure 2, it is not feasible to define it by a simple, single line on a map. A simple explanation as an edge anomaly at the transition between continental and oceanic crust cannot generally be applied. Besides the onset of volcanism (Franke *et al.* 2010), no major differences in the general morphology of the margin can be seen between margin segments where the large margin-parallel positive magnetic anomaly is prominent (e.g. north of Cape Town) and where it is not distinct or is absent. The alternative, which was already proposed by Hinz *et al.* (1999), Bauer *et al.* (2000) and Corner *et al.* (2002), is to use the occurrence of the mostly magmatic SDRS to explain the anomalies.

Emplacement of seaward-dipping reflector sequences (SDRSs)

It is widely accepted that SDRSs, as interpreted in seismic reflection data, result from the impedance contrast (Planke & Eldholm 1994) at the top of layers of basic volcanic rocks (Mutter 1985), possibly interbedded with sediments (Eldholm *et al.* 1989), increasing the acoustic prominence of the basaltic layers (Planke *et al.* 2000). A recent study (Bastow & Keir 2011) suggests that for the Ethiopian rift, massive volcanic emplacement occurred as a direct reaction to a recent crustal thinning event, making it likely to occur at the very end of the rifting process prior to continental break-up. This implies that an SDRS would overlie continental crust of varying thickness that thins quite dramatically towards the 'seaward-most' SDRS.

Bauer *et al.* (2000) show for the northern Namibian margin the landward-most SDRS overlies continental crust of about 30 km thickness, and seaward a SDRS overlies a high-velocity lower crustal body (HVLC) of 15–20 km thickness with seismic velocities exceeding 7.0 km s^{-1}. Outer SDRSs are described by these authors above slightly thickened oceanic crust of 15 km thickness and velocities of up to 7.0 km s^{-1}. On the conjugate South American margin, Schnabel *et al.* (2008) propose values of 25–20 km (partly thinned) continental crust underlain by a first high velocity lower crustal body of up to 7.3 km s^{-1} below the SDRS and a still thinning crust seaward of the SDRS. As the nature of the HVLC and timing of their emplacement is under discussion, the apparent thinning of the crust below SDRSs derived from refraction seismic data is potentially not a clear indicator for a continent–ocean boundary (COB) or continent–ocean transition (COT).

At the Argentine margin a good correlation between the landward end of the SDRS and the magnetic anomaly exists north of 43°S (north of line BGR98-017). Southward, the landward fit is not as good and might indicate that the landward-most SDRSs in this area were not deposited during the same time span (magnetic polarity).

The data presented in this study support the general concept of subaerial, axial-parallel emplacement of volcanic effusives following adiabatic decompressional melting. However, the varied widths of the SDRSs on either margin and also across the oceanic basin questions the idea of symmetrical emplacement and/or symmetrical subsidence of SDRSs, while axial-parallel emplacement of the SDRS is still thought to be the correct model. An asymmetrical rift (as witnessed here by the different character of the sedimentary basins), in the sense of simple shear or detachment rifting (Wernicke 1985; Lister *et al.* 1991), appears to be a more probable approach to explain the asymmetry rather than pure-shear extension. However, there is the further complication of a rotational component in the opening history of the South Atlantic proposed, for example, by Will & Frimmel (2013). Thus, a variable strain approach that can be called simple shear-dominated variable strain rifting seems more appropriate. A comparable variable strain rifting has been proposed for the East African Rift system in Ethiopia (Bastow & Keir 2011). These authors suggest variable mechanisms of extensions along the rift axis as being responsible for along-axis variations in the amount of volcanic material. As rotation of extensional direction is implied for the South Atlantic, this would separate the extension forming the rift graben on the African margin mechanically from emplacement of volcanics, and both would relate to two chronologically independent episodes of crustal thinning. Blaich *et al.* (2011) previously developed an asymmetrical model for the South Atlantic. Further, numerical modelling shows that for most scenarios oblique and asymmetrical rifting is aiding break-up processes by reducing the force required for rifting and, in some settings, can almost be considered necessary to achieve break-up (Brune *et al.* 2012). Asymmetrical rifts also complement the fact that Earth itself is an anisotropic natural body and direction of strain changes over time. Such asymmetry and obliquity implies that the relationship of SDRSs to the COB is not homogeneous along the South Atlantic margins and most likely variable on either conjugate section. The proposition here is accordingly not to define a COB but rather a zone of COT, deemed to be most likely between the COB points of Smythe (1983) at the seaward end of the inner SDRS and of Hinz (1981) at the seaward end of the outer SDRS. There is no reason to doubt the existence of mainly mafic (oceanic) crust proper seaward of the SDRS due to magnetic lineations and seismic character, and there is little doubt that thinned continental crust underlies the feather edge of the SDRS landward of the COB point of Smythe (1983).

The origin of SDRSs as extrusive basalt flows makes it likely that they have strong magnetization. Figure 6 shows that a magnetic source body with magnetization intensity of 7 A m^{-1} is able to cause the long-wavelength character of the anomaly. The modelled magnetic body is only reasonably larger than what the interpretation from MCS data suggests, further supporting the concept of magnetized basalt flows as the cause for the large margin-parallel positive magnetic anomaly. Similar investigations on profiles on the Argentine margin (Schreckenberger 1997; Hinz *et al.* 1999) revealed comparable results but slightly smaller volcanic bodies. While for a considerably different geological setting, Bronner *et al.* (2011) suggest the comparable ‘J anomaly’ on the magma-poor Iberian margin reflects final-rift-stage magmatic intrusions emplaced prior to the subsequent commencement of slow seafloor spreading and formation of true oceanic crust. Compared to the volcanic South Atlantic margin, this might imply that principally there is no difference in the evolution of magma-poor and volcanic-rifted margins, and the SDRS could be considered as the result of much higher volumes of final-rift-stage magmatic intrusions.

SDRS and the Paraná-Etendeka LIP and Tristan hotspot

With the added spreading-axis-parallel length of the SDRS along either margin of 1800 km, and widths of up to 400 km, both margins combined, the area (0.5 Mkm^2) mapped as SDRS in the South Atlantic is on a par with other LIPs around the globe, such as the 2 Mkm^2 of the Paraná-Etendeka (Peate 1997; see Fig. 1 for approximate extent), 0.75–1.75 Mkm^2 of the Deccan Traps and Seychelles province (Mahoney 1988; Devey & Stephens 1992; Verma & Banerjee 1992), 2.5 Mkm^2 of the Siberian Traps (Fedorenko *et al.* 1996; Reichow *et al.* 2009) or the >0.2 Mkm^2 of the Columbia River Basaltic Province (Camp *et al.* 2003).

Numerical modelling results recently showed that the impact of a thermal anomaly in the mantle might cause break-up first at the far end of its impact radius (Brune *et al.* 2013). However, the sudden onset of volcanism over merely tens of kilometres shown in this study appears difficult to explain as having been caused by a distant hotspot. Rather, this argues for local variations in melt supply. Further, the Tristan hotspot was located over 2000 km away from the oldest SDRS in the south and even less conservative estimations about mantle plume-head radii of 500 km (Nataf 2000) fail to account for this distance.

The disappearance of magnetic anomalies into the mapped area of SDRSs provides a minimum age estimate for the seaward-most volcanic flows and suggests that the volcanism related to the formation of the South Atlantic propagated from south to north along with the opening of the oceanic basin itself. The emplacement of the volcanics was coupled with the segmented opening of the oceanic basin, and we suggest a link to localized melting that may be related to SBs. For mid-ocean ridge basalts, varying compositions across SBs (Salters 2012) have previously been shown and also support the notion of elongated, bound-to-margin segments, feeder magma chambers.

On either margin, a significant increase of magma production with increasing proximity to the hotspot is not distinct except very close (200 km) to the inferred hotspot position. Both margins show considerable variations in melt volume within individual margin segments and along the margin. We conclude that the influence of the hotspot in terms of excess melt production was limited to around an area with a radius of about 200 km. Data show that volcanic effusives, imaged in MCS data as SDRSs, flowed generally from the spreading centre towards either margin. It is only in close proximity to the hotspot (about 200 km south of Walvis Ridge) that the influence of the hotspot appears to affect excess melt production and SDRSs (3D-SDRSs) with strike directions not only par-allel to the spreading centre are formed (Elliott *et al.* 2009).

Depending on which current geological/ geomagnetic time-scale is used (Fig. 7), the period of maximum emplacement of the Parana Etendeka LIPs (Hawkesworth *et al.* 2000) and thus the peak activity of the hotspot has been either simultaneous to SDRS emplacement (with the M-sequence geomagnetic polarity time (MHTC12) (Malinverno *et al.* 2012)) or post-dating the period of SDRS activity (with the Geologic Time Scale 2012 (GTS 2012) (Gradstein *et al.* 2012)). This proposition is derived from the first oceanic crust seaward of the inner SDRS, which is marked by magnetic anomaly M9 (130 Ma with MHTC12; 134 Ma with GTS 2012) off Cape Town, compared to the peak ages of 133–131 Ma for Paraná activity from Hawkesworth *et al.* (2000). The only timing information on the SDRSs in the South Atlantic is from the Kudu wells at the border between Namibia and South Africa. Sediments directly overlying the drilled basalts are dated as (?Late) Barremian (in the time-scale used here *c.* 122–123 Ma). Sparse microfauna in the lowermost interval interbedded with volcanics may indicate an age no older than Valanginian (Erlank *et al.* 1990). Typically only a few million years (about three million) are supposed for the formation of these features, resulting in an initial emplacement at about middle Valanginian time. Using the Geologic Time Scale 2012 (GTS 2012; Gradstein *et al.* 2012) this would be around 135 Ma. It is worth noting that the Kudu basalts were found to be 'not offshore equivalents of the Etendeka basalts' (Erlank *et al.* 1990). Rather, the Kudu SDRS basalts appear to be most similar to within-plate basalts of asthenospheric origin. Near Walvis Ridge, where the influence of the excess melt production in proximity to the hotspot can be seen in seismic data, the first oceanic crust correlates to magnetic anomaly M4 (126 Ma with MHTC12; 130 Ma with GTS 2012) compared to the peak ages of 133–131 Ma for Paraná activity from Hawkesworth *et al.* (2000). The observed influence of the hotspot renders GTS 2012 more plausible for the study area. With the MHTC12 time-scale, magmatic activity in the north postdates the peak activity of the Paraná volcanic province. However, within a 200 km diameter of the hotspot, the architecture and style of the SDRS implies a direct influence of the hotspot. This period of increased melt production is better covered using GTS 2012. However, the duration of elevated temperature after arrival of the hotspot is unknown and might also increase melt production once the rift has reached this limited area of elevated temperature.

Geometrical difficulties of unidirectional opening of the South Atlantic

A simple reconstruction of the rigid African and American plates causes geometrical problems. If axial-parallel (although asymmetrical in volume) emplacement of SDRSs is assumed, the SDRSs in the South Atlantic should align without

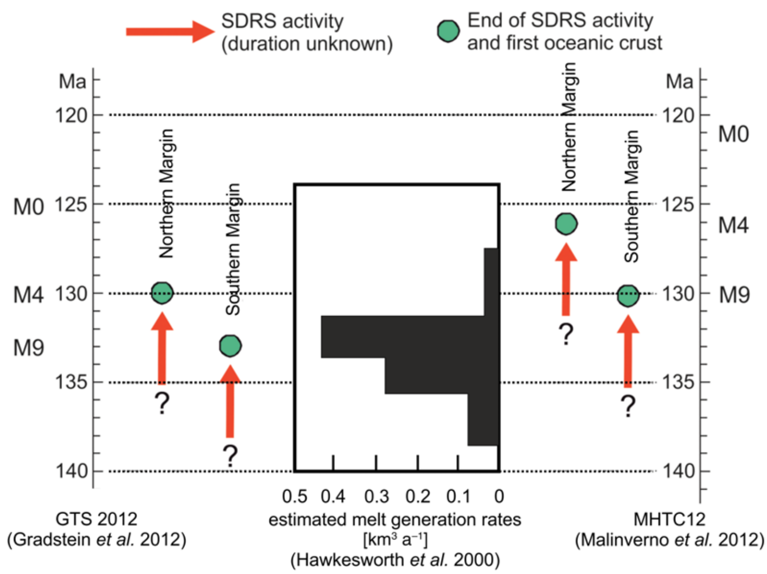

Fig. 7. Comparison of the effect of uncertainties in global time-scales for the temporal relationship of SDR emplacement and peak activity of the Paraná LIP. Depending upon whether the Global Time Scale 2012 (GTS12) (Gradstein *et al.* 2012) or the M-sequence geomagnetic polarity time (MHTC12) (Malinverno *et al.* 2012) is used, the emplacement of SDRS happened prior to or simultaneously with the peak activity of the Paraná LIP (Hawkesworth *et al.* 2000). The southern margin indicates a location approximately offshore Cape Town and the northern margin indicates a location approximately offshore Walvis Ridge. Volcanics offshore Walvis Ridge were likely directly influenced in their abundance by the hot spot, meaning that peak activity pre-dating the volcanics in this area as indicated by MHTC12 seems less probable than with GTS12.

north–south 'offset' on both margins once reconstructed (Fig. 8). However, a unidirectional east–west reconstruction leads to a significant north–south 'offset' in the distribution of the southernmost SDRS on either margin. The southernmost, magma-poor margin segments are not of the same length between the AFFZ and the Colorado TZ/Cape SB on opposite sides of the South Atlantic (Fig. 1). The location of this across-margin segment boundary (Colorado TZ/Cape SB) is well defined from magnetic and seismic data. The difference in length between this structural discontinuity and the AFFZ may be explained by southward intraplate movements within the South American plate relative to Africa prior to the beginning of regular seafloor spreading but after the emplacement of the southernmost (earliest) SDRS.

There are several regional or global rotation pole sets (e.gz. Torsvik *et al.* 2009; Moulin *et al.* 2010; Heine *et al.* 2013) for reconstructing models that include the South Atlantic. For the modest scale and comparably small study area of our research, the existing rotation pole sets all show different problems for the earliest phase of southern South Atlantic opening (Fig. 9). For example, poles from Moulin *et al.* (2010) result in a reasonable fit of offshore structures in the study area but at the cost of significant overlap of South American subplates. In contrast, the Heine *et al.* (2013) poles do not produce onshore overlap, but the offshore fit is not as good. The different extensional domains from south to north (Fig. 10) are also reflected in margin-parallel basin axes on the South African side in contrast to margin-perpendicular basin axes on the southern South American basins. For example, Pángaro & Ramos (2012) and Loegering *et al.* (2013) describe a basin axis for the Eastern Colorado Basin offshore South America with a strike of NW–SE and for the Central Colorado Basin they report a west–east-striking basin axis. The Colorado Basin has been argued to represent a failed rift system (Franke *et al.* 2006; Pángaro & Ramos 2012) instead of a sag basin. This notion is supported from the data presented here, according to which the Colorado Basin and similarly oriented sedimentary basins on the southern South American margin may have formed in the earliest stage of crustal thinning and rifting, which favoured north–south extension, prior to the succeeding west–east extension direction still observed today. It is proposed that this extensional regime caused movements within the

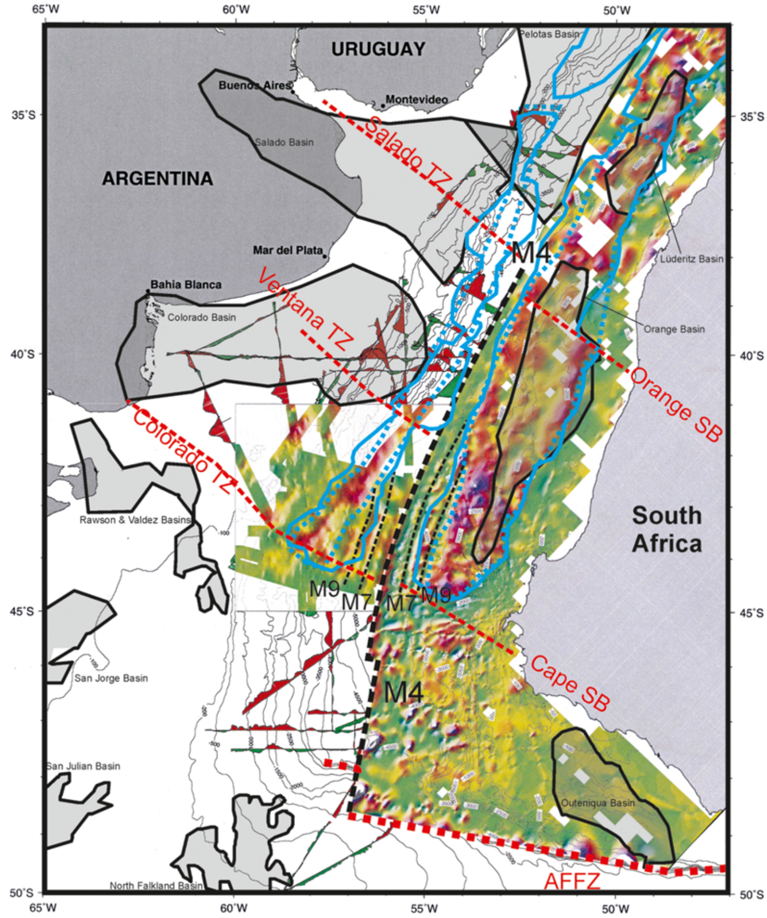

Fig. 8. Manual reconstruction to seafloor spreading anomaly M4 of the southernmost South Atlantic. Detailed SDRS extent: thick blue line; conservative SDRS extent (not including outer highs, flat lying flows or outer wedges): thick blue dots; magnetic anomalies are named and drawn in black dashes. This reconstruction was done manually with special consideration of the newly defined seafloor spreading anomalies on the South American margin. In this reconstruction, the SDRS extent alongside the magnetic anomalies is the main proxy for defining the best fit for the reconstruction. As axial-symmetrical emplacement of volcanics along the spreading axis is the most likely scenario for the SDRS formation, there should be no north–south offset between SDRS on either margin after full reconstruction.

South American plate assembly, allowing for the west–east-orientated sedimentary basins to form. On the South African margin, the sedimentary basins opened the way expected from a west–east-extending rift, i.e. their basin axis is subparallel (north–south) to the main rift axis, indicating west–east extension for these basins. This indicates that the main recipient of the north–south extension was the South American plate (rotational intraplate deformation) and the rift basins on the African margin developed at a later stage during rifting. This is supported by sparse synrift basin infill and mostly post-break-up sediments in the Late Mesozoic basins of the African shelf (Brown *et al.* 1995; Blaich *et al.* 2009). Intraplate deformation of the South American plate along major sutures of limited extent (v. diffuse distribution) within the Brazilian Craton and/or between the Brazilian and Guyana Craton has previously been suggested (Unternehr *et al.* 1988). Eagles (2007) and Moulin *et al.* (2010) also propose intraplate deformation of South America as the main actor within the initial South Atlantic opening theatre. However, as these authors point out, field observations in South America to support this with actual data are scarce.

The proposed changes (Fig. 10) in extensional direction fit onshore findings from South Africa and Namibia describing rotation of the main extensional

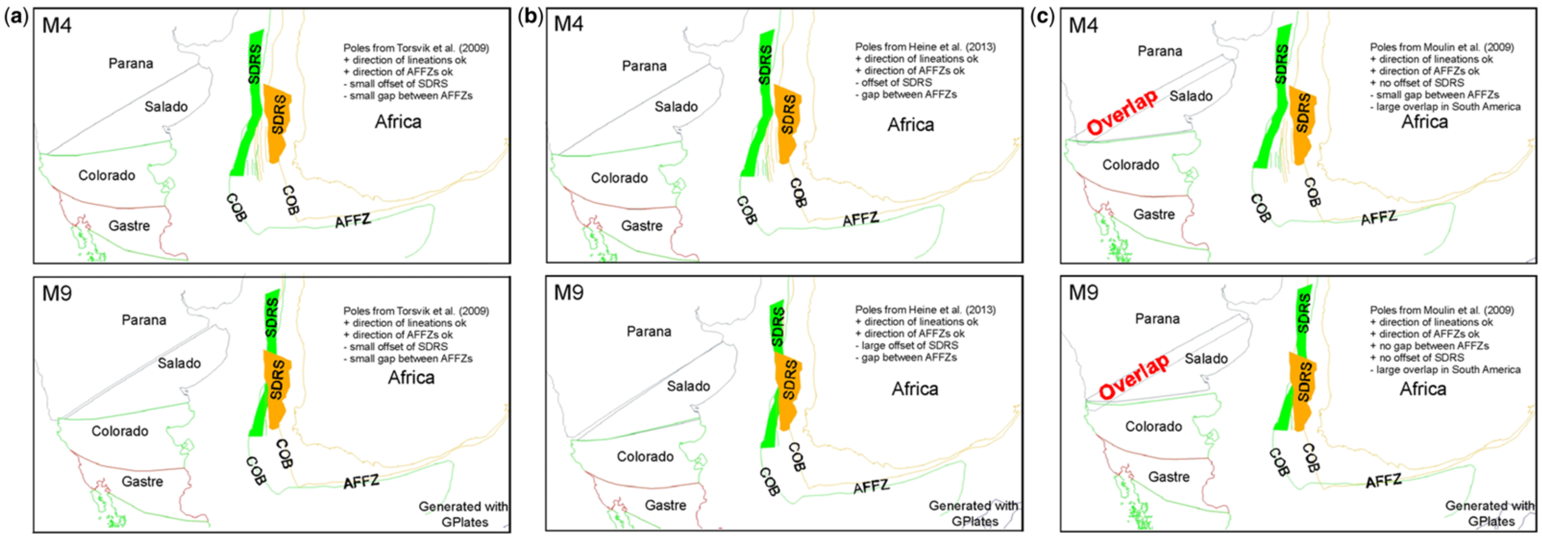

Fig. 9. Comparison of three recently published rotation pole sets in the study area. (**a**) Reconstruction of the study area in the South Atlantic at M4 (126 Ma) and M9 (129 Ma) according to the rotation poles proposed by Torsvik *et al.* (2009). (**b**) Reconstruction of the study area in the South Atlantic at M4 (126 Ma) and M9 (134 Ma) according to the rotation poles proposed by Heine *et al.* (2013). (**c**) Reconstruction of the study area in the South Atlantic at M4 (126 Ma) and M9 (133 Ma) according to the rotation poles proposed by Moulin *et al.* (2010). For the small study area investigated in our research, the along-margin offset of SDRS is the most important proxy for best fit. However, while the Moulin *et al.* (2010) poles work best in that regard, the large overlaps representing intra-plate deformation in the South American plate assemblage are potentially disputable due to lack of field data and are avoided by the Heine *et al.* (2013) model, which instead ends up with a latitudinal offset of the SDRS. It seems as if the possibility for full integration of intra-plate deformation will be the crucial next step in plate reconstruction, but is hampered by the lack of field data.

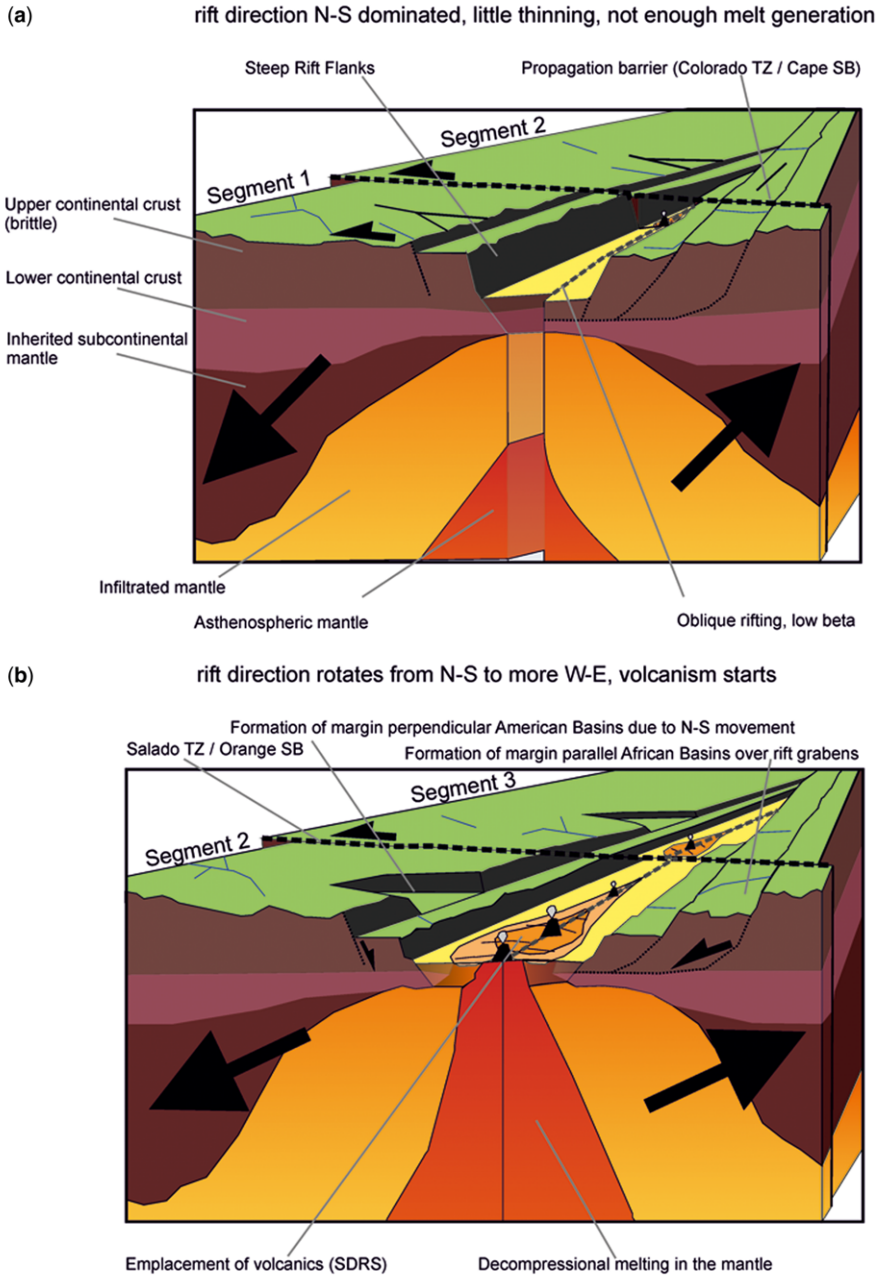

Fig. 10. 4D conceptual sketch model for the opening of the southernmost South Atlantic. (**a**) View of the southernmost, magma-poor Segment 1 of the South Atlantic. Opening of this segment occurred in a dominatingly oblique manner, with the American plate moving mostly southwards relative to the African plate, thus not thinning the crust to the point of adiabatic melting and the emplacement of massive volcanic effusives. (**b**) Northward in Segment 2, across the Colorado Transfer Zone/Cape Segment Boundary, rotation of relative plate movement to an intermediate angle with respect to today's direction enabled the proposed majorly simple shear-dominated break-up with pure shear components. Margin-perpendicular basins on the South American margin are possibly due to the South American plate assemblage accommodating the initial north–south movement by intra-plate deformation. Volcanics were emplaced partially on top of thinned/thinning continental crust. Massive melt production and emplacement of over 400 km (west–east extension) of volcanics on both margins combined was possible due to the more extensively thinned crust.

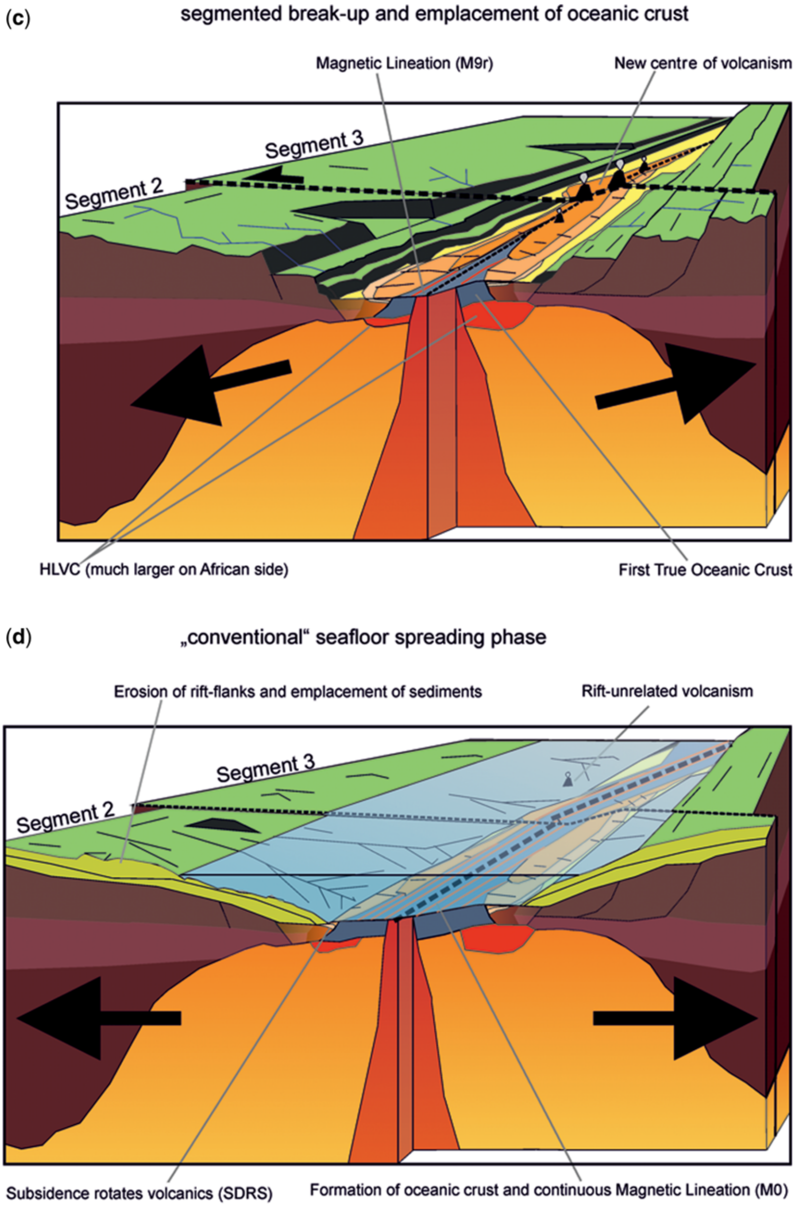

Fig. 10. (*Continued*) (**c**) Seafloor spreading anomalies as old as M9r (thin red line) can be seen seaward of the main volcanic effusives in Segment 2 (southernmost volcanic segment), merging with the mapped area of volcanic effusives northwards, showing a south to north opening of the South Atlantic. Subaerial emplacement of first oceanic crust (implied for example by Bauer *et al.* (2000) and Schnabel *et al.* (2008) to be thickened (15–20 km) compared to regular oceanic crust) is possible. A younger set of volcanics is emplaced in Segment 3, separated from the volcanics in Segment 2 both temporally (magnetic anomalies) and spatially by a shift of the centre of volcanism along the segment boundary. Asymmetrical (simple shear-dominated) rifting is indicated by differences in margin architecture, volume of high-velocity lower crustal bodies (HVLC) and volumes and distribution of SDRS. (**d**) The completion of the South Atlantic opening is indicated by magnetic Chron M0r, the oldest continuous seafloor-spreading anomaly between the Agulhas-Falkland Fracture Zone and the Rio Grande Fracture Zone. Extensional direction has rotated almost 90° compared to the earliest phase. 'Regular' seafloor spreading has commenced along the whole length of the investigated margin section and rift-related volcanism has ceased. Volcanic effusives are inverted to the prominent shape seen in seismic data today as SDRS during their subsidence.

domain from NNE–SSW extension documented in the Saldania Belt near Cape Town to west–east extension from the Gariep Fold Belt northwards to the end of the study area of Will & Frimmel (2013) in northern Namibia. For the South American (Brazilian) margin, recent onshore measurements by Salomon *et al.* (pers. comm., E. Salomon, July 2013) in the region of the Dom Feliciano Belt came up with strike-slip systems synrift or post-dating the Atlantic rift phase, yet with no extensional regime that could be related to the rifting. This stands in contrast to observations from the conjugated Gariep Fold Belt and Kaoko Belt in southern Africa where ENE–WSW-directed extension (Will & Frimmel 2013) and ESE–WNW-directed extension (Salomon *et al.*; pers. comm., E. Salomon, July 2013) are derived from onshore measurements. The margin-perpendicular basins on the South American side shown in Figure 10 also reflect the South American plate assembly as the main recipient of north–south extension and, accordingly, intraplate deformation.

Scrutton (1979) links steep basement slopes to sheared rifted margins. The relatively steep continental basement slope of the southernmost, magma-poor segment might thus be interpreted as representing an extensional direction that was approximately perpendicular to the present-day continental margin.

We thus propose that the opening of this southernmost segment occurred in an oblique manner, with the American plate moving mostly southwards (with a small westerly component) relative to the African plate. This may have resulted in insufficient thinning of the crust to allow considerable adiabatic melting and the emplacement of massive volcanic effusives. Subsequently the direction of relative plate movement rotated to a less extreme angle. When the rift crossed the Colorado TZ/Cape SB, a predominantly simple shear break-up with pure shear components resulted in massive crustal thinning, and with enhanced melt production, led to the emplacement of volcanics.

Conclusions

Based on a large set of new marine geophysical data on the conjugated South American and southern African continental margins, the following main findings were derived in this study.

While the southernmost segment of the South Atlantic lacks magmatism, the northward segments represent classical examples of the volcanic rifted margin type. Huge volumes of volcanic effusives were deposited prior to and during break-up.

The break-up in the South Atlantic occurred asymmetrically, with the larger volumes of magmatic material being emplaced on the African side, based on the distribution and dimensions of SDRS and HVLC. The asymmetry may be better described with a simple shear rifting model than a pure shear model.

New magnetic data allow the interpretation of magnetic anomalies as old as M9r offshore South America in addition to the well known anomalies offshore South Africa and argue against the conclusive interpretation of older anomalies than M9 as true seafloor-spreading lineations on either margin. Further, modelling suggests that a mostly magnetizable composition for the SDRS can be assumed, as it results in a volumetrically reasonable explanation for the large margin-parallel positive magnetic anomaly on both margins.

The break-up in the South Atlantic occurred in distinct segments from south to north. Detailed mapping of SDRSs and magnetic lineations revealed formation of oceanic crust in the south accompanied by emplacement of pre-break-up SDRS further north.

In the very early crustal thinning phase, after emplacement of the southernmost SDRS, parts of the South American plate assemblage likely was affected by southward movement relative to the African plate. This is reflected today in a north–south ‘offset’ in the SDRSs on each margin. The different extensional directions are also reflected in the strike of basin axes offshore South America, which is perpendicular to today’s continental margin, as well as the basin axes on the South African margin. These offshore indications for rotation of the main extensional direction over time are mirrored in onshore findings from both margins.

It is further argued that the influence of the Tristan da Cunha hotspot on the break-up of the South Atlantic and emplacement of the rift-axis-parallel SDRS is less direct than commonly suggested.

The oldest segments within the South Atlantic are magma starved and resemble more a sheared, obliquely-rifted margin than a typical volcanic-passive continental margin. The change from magma-poor sheared to volcanic-passive margin types occurs within tens of kilometres. This is in our view more plausibly explained by a local change in spreading regime than sudden impact of a hotspot centred some 2000 km away.

Magnetic anomalies older than M4 merge into the mapped area of SDRS occurrence. This gives a minimum age for the seaward-most SDR sequence and shows that not only the opening of the South Atlantic started in the south and propagated northwards, but that the volcanism along the continental margin was immediately coupled with this propagation and bound to individual margin segments. Both conjugate margins show segmentation and variations in extrusive melt volumes within segments and along the margin.

Depending on the time-scale used the emplacement of the Parana Etendeka LIPs and peak activity of the hotspot post-date the emplacement of first oceanic crust and thus the emplacement of SDRS.

Only within 200 km of the proposed hotspot location can a consistent relationship between the hotspot and increase in magma production be deduced. Volcanic material is proposed to have flowed from the break-up centre towards the margin, imaged today as SDRS. In closer proximity to the hotspot (about 200 km south of Walvis Ridge), the influence of its excess melt production becomes eminent, resulting in the formation of 3D SDRS. The radius of direct influence of the hotspot is consequently interpreted as limited to about 200 km.

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