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Segmentation and volcano-tectonic characteristics along the SW African continental margin, South Atlantic, as derived from multichannel seismic and potential field data

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A B S T R A C T

Regional seismic reflection and potential field data document the South Atlantic's break-up history, between 39°S and 19°S, from the Early Cretaceous onwards. Previous maps of distribution of volcanics along the margin showed volcanics along the whole African margin based on extrapolation of data. Based on previously unpublished marine geophysical data, we found the southernmost 460 km long margin segment to be lacking huge volumes of break-up related volcanic effusives. Northwards, break-up was accompanied by the emplacement of huge volumes of volcanic material, prominently featured in seismic sections as huge wedge-shaped seaward dipping reflectors (SDRs). Detailed mapping of offsets (left- and right-stepping) and variations in structural character of the volcanics reveal the segmentation along and the break-up history of the margin. Several superimposed SDR sequences, suggesting episodicity of volcanic emplacement (divided by periods of erosion and sedimentation), are distinct along southerly lines, losing prominence northwards.

A main outcome of our study is that this passive margin is not continuously of the volcanic type and that the change from a non-volcanic to a volcanic margin occurs abruptly.

We define four distinct First-order Segments along the 2400 km section of the southwestern African margin covered by our seismic data. From south to north these First-order Segments are: Magma-poor Segment I; Segment II with enormous SDRs volumes; decreasing SDRs volumes in Segment III; Segment IV again with enormous volcanic output, likely influenced by Walvis Ridge volcanism.

Most important is that there is no systematic increase in the volumes of the effusives towards the Tristan da Cunha hot-spot. Rather there is an alternating pattern in the SDRs' volumes and widths.

The boundary between the volcanic and magma-poor margin segments in the southernmost study area is sharp (10s of km), which we propose is reflected in magnetic anomaly data as well. We suggest that this variability along the margin is mainly due to a change in stretching/rifting character from oblique during the early stages of breakup to conventional seafloor spreading from Chron M4 (~130 Ma) onwards.

1. Introduction

The southwestern African continental margin has long been interpreted as a prime example for the volcanic passive margin type (Aslanian et al., 2009; Austin and Uchupi, 1982; Bauer et al., 2000; Blaich et al., 2011, 2009, 2010; Brown et al., 1995; Corner et al., 2002; Eagles, 2007; Elliott et al., 2009; Geoffroy, 2005; Gladczenko et al., 1997, 1998; Hirsch et al, 2009; Jackson et al., 2000; Jokat et al., 2003; Martin, 1987; Maslanyj et al., 1992; Menzies et al., 2002; O'Connor and Duncan, 1990; Parsiegla et al., 2009; Séranne and Anka, 2005; Skogseid, 2001; Trumbull et al., 2007; Unternehr et al., 1988). In this regard it has also been suggested as a case location for the study of a hot-spot related break-up

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history. This study questions both assumptions to a certain degree, as we present evidence that the southwestern African passive continental margin is not continuously of the volcanic type. Further, the change from non-volcanic to volcanic margin occurs abruptly. Based on 3300 km of previously unpublished BGR multichannel seismic data off South Africa along with seismic data provided by industrial partners alongside with publically available geophysical data we study in detail the margin architecture between the Agulhas Falkland Fracture Zone (AFFZ), in the south, and the Rio Grande Fracture Zone (RGFZ), in the north.

Variations in the lateral distribution of break-up related volcanics are used for a detailed investigation of segmentation along the southern African continental margin. We suggest margin segmentation as a prime feature allowing insights into the early break-up histories of continents. We show that the final extension that resulted in breakup was considerably oblique.

Structures that compartmentalize a propagating rift at high angles have long been recognized. Rosendahl (1987) defined a zone, transferring displacement or strain from one rift-graben segment to another with opposite sense via oblique shear along an inter-basinal ridge as accommodation zone. Morley et al. (1990) developed a classification of extensional fault displacement zones and introduced the term “transfer zones”. According to Lister et al. (1991), major transfer faults are required to accommodate a switch in dip of the master detachment fault(s) when the resulting rift-basin segments are alternatively located on either side of the developing margins. The terms transfer zone or segment boundary were widely used in the following, particularly where cross-margin structural elements on the shelf are spatially related to onshore zones of strike-slip faulting. In this work we use the term “segment boundary” to describe linear areas (rather sharply-defined fault lines) localizing major structural differences along the margin, e.g. an offset in the extent of volcanic effusives or the disappearance of intrusive and effusive features.

As deeper structures within the crust along the volcanic-rifted margin are masked by thick wedges of volcanic material (Blaich et al., 2011), volcanic effusives are considered as an important clue in understanding the early break-up and segmentation history of a margin. These effusives are imaged in seismic data as Seaward Dipping Reflector Sequences (SDRs). Offsets and variations in the character of the SDRs have previously been shown to indicate margin segmentation along the southern South American margin (Blaich et al., 2009; Franke et al., 2007). This study investigates the width, architecture and regional distribution of volcanic effusives (SDRs) along the 2400 km of the continental margin between the Agulhas-Falkland Fracture Zone (AFFZ) at 39°S and the Rio Grande Fracture Zone (RGFZ) at 19°S along the African margin of the South Atlantic. We incorporate previous investigations on SDRs (Gladczenko et al., 1997, 1998) and provide an update on an earlier segmentation model for the Namibian part of the study area (Clemson et al., 1997). This results in a consistent and conclusive description of margin segmentation along the entire eastern margin of the southern South Atlantic.

2. Regional geological setting

The South Atlantic continental margins (Fig. 1) resulted from the break-up of Gondwana, with Antarctica separating from Africa and South America at around 155 Ma, forming the Mozambique Basin and Weddell Sea prior to the South Atlantic opening (Jokat et al., 2003). The opening of the South Atlantic took place in the Early Cretaceous with suggested opening ages ranging between 137 and 126 Ma (Gladczenko et al., 1997; Jokat et al., 2003; Nürnberg and Müller, 1991; Rabinowitz and LaBrecque, 1979; Unternehr et al., 1988). The South Atlantic likely opened from South to North in a zipper-like succession along individual rift zones (Austin and Uchupi, 1982; Jackson et al., 2000; Rabinowitz and LaBrecque, 1979; Uchupi, 1989). Just before and during the opening of the ocean basin, large volumes of volcanic effusives were emplaced both on Mesozoic intracratonic basins onshore (Paraná-Etendeka Large Igneous Province (LIP)) and on the incipient rifted crust onshore and offshore (Bauer et al., 2000; Franke et al., 2010, 2007; Franke, 2013; Gladczenko et al., 1997; Hinz et al., 1999; Jackson et al., 2000; Jerram et al., 1999a,b; Moulin et al., 2010; O’Connor and Duncan, 1990; Trumbull et al., 2007).

The presence of magnetic anomalies Chron M4 (~130 Ma; Gradstein and Ogg, 2004) and younger anomalies is widely accepted offshore South Africa, marking the onset of conventional

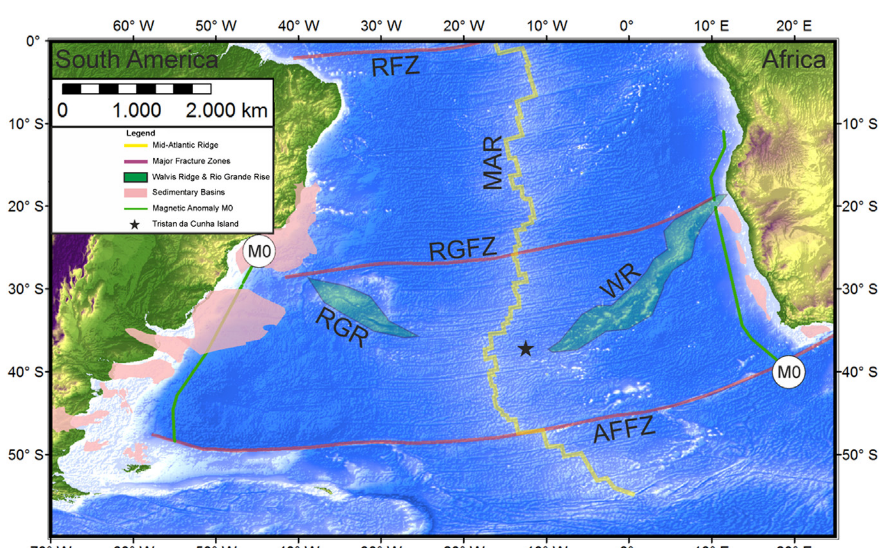

Figure 1. Regional map of the South Atlantic. In this work, we study the volcano-tectonic characteristics along the Namibian and Southern African margin between the Agulhas Falkland Fracture Zone (AFFZ) and the Rio Grande Fracture Zone (RGFZ). The map shows the distribution of the sedimentary basins in the study area on the Namibian and Southern African margin (South to North: Outeniqua Basin; Orange Basin; Lüderitz Basin; Walvis Basin) and on the conjugate South American margin (South to North: North Falkland Basin; San Julian Basin; San Jorge Basin; Rawson Basin; Valdez Basin; Colorado Basin; Salado Basin; Pelotas Basin; Campos Basin; Santos Basin). Further shown: Magnetic Anomaly M0, Mid-Atlantic Ridge (MAR; the spreading axis of the Atlantic Ocean); Walvis Ridge (WR) and Rio Grande Rise (RGR); Tristan da Cunha volcanic Island and the Romanche Fracture Zone (RFZ).

seafloor spreading that finally led to the South Atlantic Ocean between South America and South Africa.

Chron M9N (∼133 Ma) has been suggested as the oldest spreading anomaly (Rabinowitz and LaBrecque, 1979). Rabinowitz and LaBrecque (1979) further interpreted Chron M11 (∼136 Ma) along the African margin close to the Orange Basin. Elsewhere (Nürnberg and Müller, 1991), the rift phase has been proposed to have lasted from 150 to 130 Ma to Chron M4. More recently, the actual presence or determinability of Chron M11 (∼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 offshore South America (Eagles, 2007; Moulin et al., 2010).

Previously, the African margin of the southern South Atlantic had been interpreted as being entirely of the volcanic rifted type. Thick offshore volcanic units are imaged in seismic data as SDRs, corresponding to thick wedges of convex-up reflectors with an arcuate internal reflection pattern (Eldholm et al., 1995; Elliott and Parson, 2008; Franke et al., 2010; Gladczenko et al., 1998; Hinz, 1981; Mutter, 1985; Planke et al., 2000). Strong reflectors separating individual stacked SDR sequences across the slope may be an expression of episodicity in their emplacement (Franke et al., 2007). Other explanations for the unconformities may be the volumes and rates of magma production, the volcanic environment, synvolcanic and postvolcanic deformation and subsidence (Eldholm et al., 1995) as well as sedimentary interbeds. Only in the Orange Basin (Hirsch et al., 2009) off Namibia (Kudu Field) SDR related volcanic units were encountered by wells and it has been suggested that the lavas were erupted subaerially (Clemson et al., 1997; Wickens and McLachlan, 1990). It is likely that the majority of the SDRs along the eastern margin of the southern South Atlantic were emplaced subaerially.

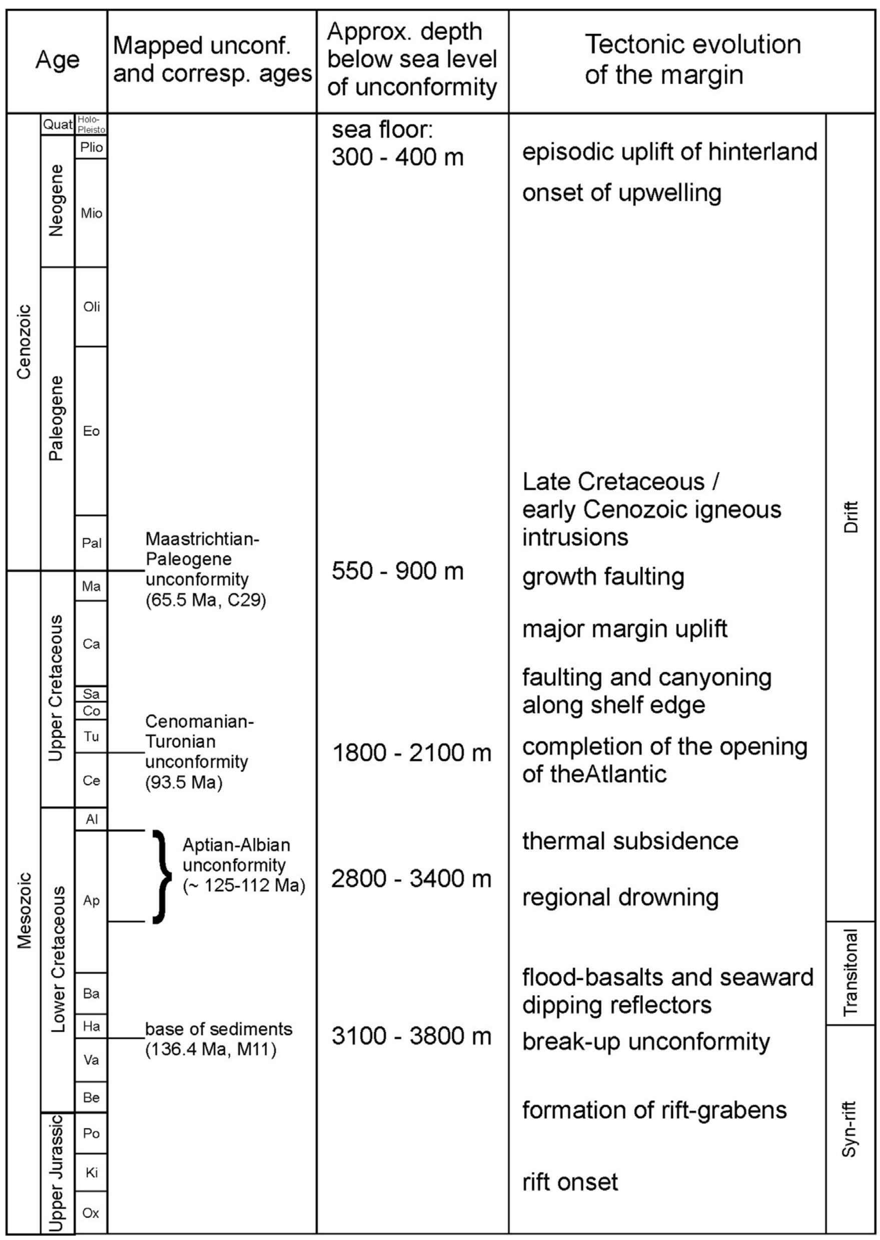

Figure 2. Generalized tectonostratigraphic chart for the southern African margin. Ages according to Gradstein and Ogg (2004), regional events as suggested by Hartwig et al. (2012), depths from four distal wells (A-C1, A-C2, A-C3, A-N1) within the Orange Basin (Hirsch et al., 2010).

The African margin of the South Atlantic has developed parallel to N-NNW trending coastal branches of the Proterozoic Damara and Gariep mobile belts. It is separated by the NE–SW trending Damara inland branch (Frimmel and Hartnady, 1992; Corner et al., 2002) where structures are considered to have influenced margin segmentation (Clemson et al., 1999). Such segmentation of the Namibian margin was suggested by Clemson et al. (1997) claiming that segment boundaries are thinned-lithosphere penetrating lineaments separating segments of initial oceanic crust from continental rifting. Jungslager (1999) suggested a linkage between oceanic fracture zones in the southern South Atlantic and transfer zones along the margin without further discussing possible implications.

3. Dataset

Between 1991 and 2003, four scientific cruises were accomplished by the German Federal Institute for Geosciences and Natural Resources (BGR) along the continental margin of western Africa and a total of 12,200 km of MCS data were acquired (Figs. 3 and 4; BGR91: 4200 km of MCS data; SO85: 1900 km; BGR95: 2800 km; BGR03: 3300 km). Magnetic and gravimetric data were recorded simultaneously along BGR MCS lines. BGR seismic data were acquired using different setups of the multichannel streamer system 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 a pre-stack deconvolution, frequency filtering, multiple attenuation by radon filtering and surface related multiple elimination, post-stack deconvolution and post-stack Kirchhoff time migration. The National Petroleum Corporation of Namibia (NAMCOR) provided a large set of seismic data to their GZN partners out of which four seismic lines were chosen for presentation in this paper. These data cover with a dense grid (margin cross line spacing 5–15 km, margin parallel line spacing 10–20 km) mostly the northern part of Namibia's continental margin, alongside a less densely covered (cross line spacing 5–15 km, parallel line spacing 50 km) area to the north of the Orange River. Forest Exploration International (South Africa) (PTY) Ltd (Forest Oil) and the Petroleum Oil and Gas Corporation of South Africa (PTY) (Ltd) (PASA) provided data to their GFZ partners for interpretation and subsequent publication within the scope of this research project. These data densely cover (cross line spacing 5–15 km, parallel line spacing 5–20 km) mostly the northern part of South Africa's continental margin, particularly the Orange Basin. Data were acquired by varying contractors with varying recording set-ups and processing parameters. In addition to the aforementioned data, seismic data from cruises FM0103 and FM0104 (Austin and Uchupi, 1982) were incorporated via the public-access Marine Seismic Data Center of the University of Texas Institute for Geophysics (Shipley et al., 2005). Areas that are not fully covered by seismic data, were interpreted on the basis of previous publications (Clemson et al., 1997; Corner et al., 2002; Jungslager, 1999) covering the aspect of margin segmentation.

The seismic data were supplemented by the EMAG2 2-arc min Earth Magnetic anomaly grid (Maus et al., 2009) and the DTU10 Gravity field and Mean sea surface (Andersen, 2010) for supporting the interpretation of the extent and segmentation of the effusive volcanics and the investigated margin section.

4. Interpretation

4.1. Age constraints

Post-rift sediments provide information on the timing of segment boundary activation or reactivation. These sediments were deposited along the southwestern African continental margin in four distinct basins (Fig. 4) which later connected during the Upper Cretaceous (Gerrard and Smith, 1982). The change from rifting to drifting and onset of oceanic spreading is marked by a prominent break-up unconformity that can be traced from the shallow shelves to the top of the SDRs before it merges with the top of the igneous oceanic crust (Franke, 2013). This author showed that the age of the break-up unconformity decreases from late Valanginian (137 Ma) in the Outeniqua Basin off South Africa to the Aptian–Albian in the Brazilian – West-African segment.

In the Orange and Lüderitz basins the break-up unconformity has been suggested to be of Hauterivian age (Brown et al., 1995; de Vera et al., 2010; McMillan, 2003). Based on DSDP wells drilled at the Walvis Ridge the unconformity was dated to the Barremian/Aptian boundary (Sibuet et al., 1984).

Three further unconformities were mapped between the break-up unconformity and the seafloor along the margin (Fig. 2). These are an unconformity within Aptian–Albian sediments, the Cenomanian-Turonian unconformity and the Maastrichtian–Paleocene unconformity (Brown et al., 1995; Gradstein and Ogg, 2004; Hartwig et al., 2012). Especially for the BGR data, correlation has to be considered tentative because line-ties are rarely at hand.

Another age constraint is given by magnetic seafloor spreading anomalies. Magnetic Chron M4 is the earliest anomaly that could be traced along the entire margin under study (Fig. 3). Both M4 and M0 anomalies show a change in intensity along the margin. They are weaker between 33°S and 28°S. Pre-M4 anomalies merge successively with the G-anomaly (Rabinowitz, 1976; Rabinowitz and LaBrecque, 1979) between 32°S and about 30°S while M4 intersects with the G-anomaly at about 23°S (Fig. 3). Earlier anomalies (M7–M11) were found particularly in an area that is well covered by ship-track magnetic data close to Cape Town. In this area and further north these early anomalies may be located partly within the SDR wedges (Bauer et al., 2000; Schreckenberger et al., 2002; Séranne and Anka, 2005) and not within the oceanic crust. The occurrence of these earlier anomalies at other locations is still possible, particularly further south.

4.2. Margin segment I

The continental margin of First-order Segment I, between the AFFZ and the Cape Segment Boundary (Cape SB), is the area where the large magnetic anomaly (G-anomaly), extending from the Walvis Ridge to about 34°50′ S offshore Cape Town, is not present (Fig. 3). This margin segment is crossed by two MCS lines. A comparatively steep basement slope (>4.5°) is exclusive to this segment. Along the MCS lines there are neither indications for SDRs, nor for intrusive complexes, sills or dikes except for the isolated volcanic mount seen in Figure 5. The architecture of this margin segment is different from the volcanic rifted type further north along the margin and elsewhere. Thus we interpret this margin segment not as volcanic rifted (Fig. 5).

The lack of break-up related magmatism, however, did not result in a typical magma-poor margin. Typical magma-poor margins are characterized by the occurrence of high-angle listric faults related to fault-bounded rift basins and seaward by extremely thinned crust that potentially is separated from the oceanic crust by a domain of exhumed subcontinental mantle (Franke, 2013; Lavier and Manatschal, 2006; Péron-Pinvidic and Manatschal, 2009; Reston, 2009; Whitmarsh et al., 2001). Rather the architecture of this margin segment points towards an interpretation as sheared margin, controlled by a major transform fault zone as has been described for example for the Central Atlantic (Antobreh et al., 2009) but at a high angle to the subsequent predominant direction of rifting.

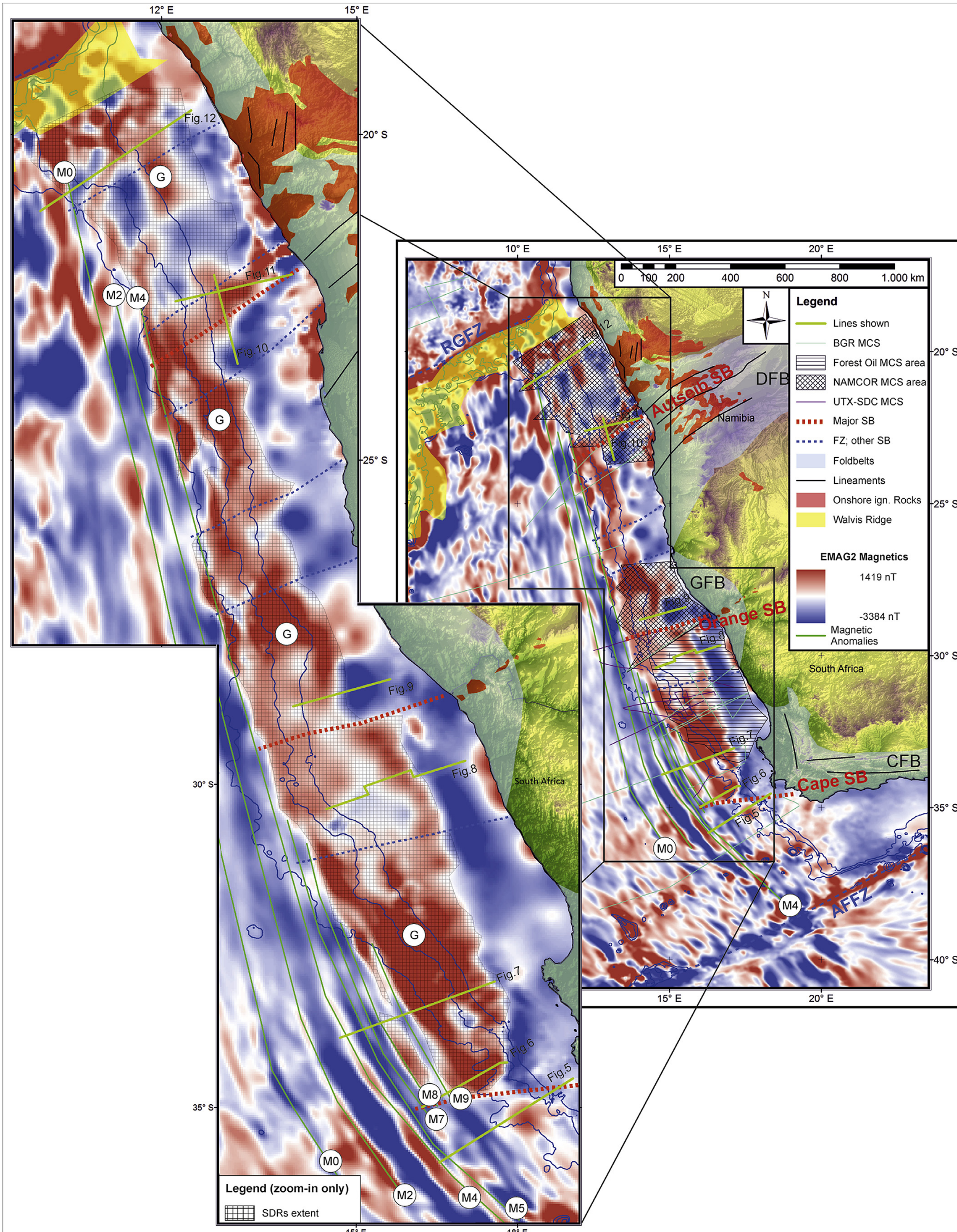
12° E
15° E
20° S
25° S
30° S
35° S
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Fig.12
Fig.11
Fig.10
Fig.9
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Fig.6
Fig.5
M0
M2
M4
M5
M7
M8
M9
G
South Africa
Legend (zoom-in only)
SDRs extent
10° E
20° E
40° S
0 100 200 400 600 800 1.000 km
N
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Lines shown
BGR MCS
Forest Oil MCS area
NAMCOR MCS area
UTX-SDC MCS
Major SB
FZ; other SB
Foldbelts
Lineaments
Onshore ign. Rocks
Walvis Ridge
EMAG2 Magnetics
1419 nT
-3384 nT
Magnetic Anomalies
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Autseib SB
DFB
Namibia
GFB
Orange SB
South Africa
CFB
Cape SB
AFFZ

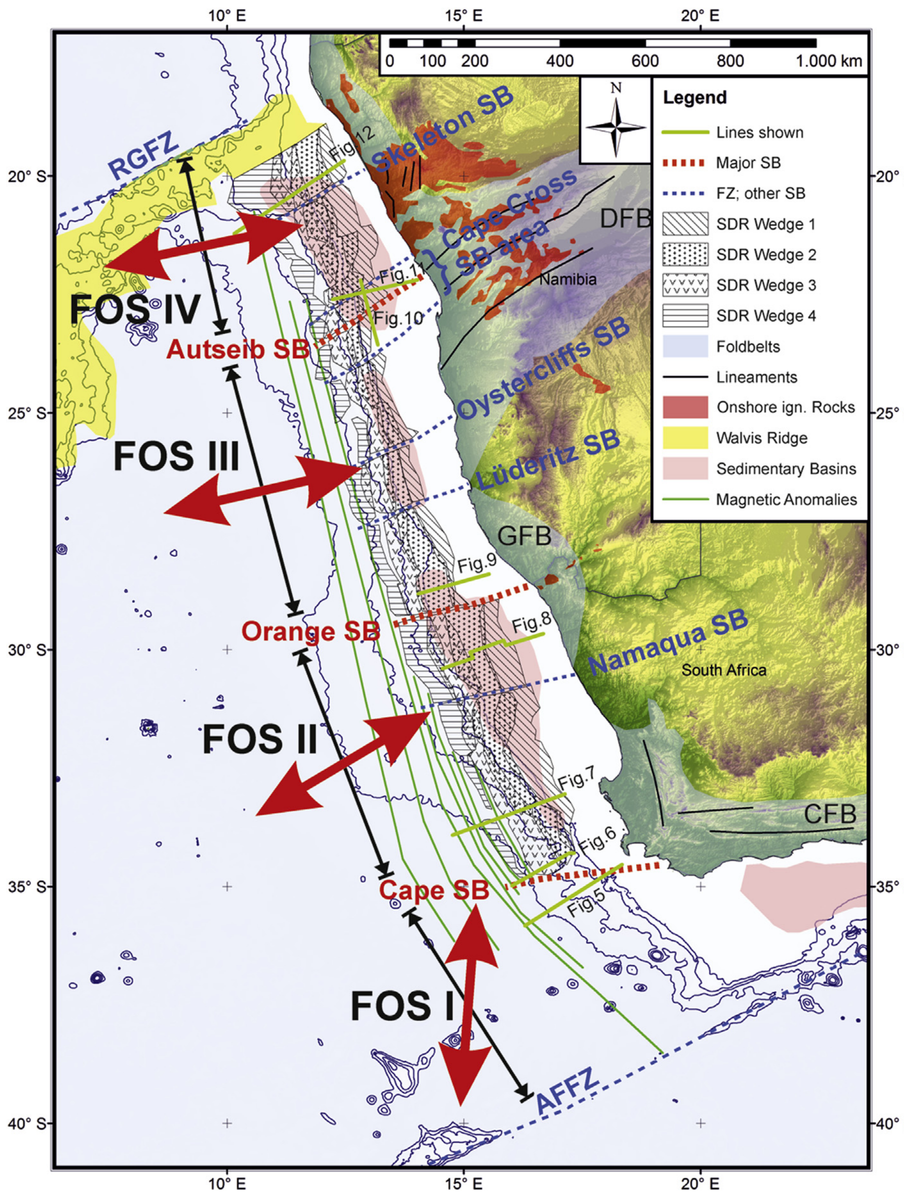

Figure 4. Structural Map of the South Western African passive continental margin between the AFFZ and the RGFZ. Along this section of margin, we identified four First-order Segments (FOS). Shown are the SDR wedges mapped as seen of the seismic data along the margin, with the three major segment boundaries (Cape, Orange and Autseib SB) marked in bold dashed red. In dashed blue, both fracture zones and segment internal boundaries are shown. These internal boundaries are either marked by significant offsets in the SDRs extent or significant margin architectural changes or were previously described (Lüderitz SB/Oystercliffs SB from Clemson et al. (1997)). The changes at these FOS internal boundaries were ruled as not significant enough to define another FOS in this study. Bold red arrows indicate the proposed relative plate motion during initial stretching/rifting of each segment. Note the proposed oblique movement in FOS I. Annotations: see Figure 3; further shown: the four main sedimentary basins on the southwestern African margin; from south to north: Outeniqua Basin; Orange Basin, Lüderitz Basin, Walvis Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As there are only 80 km between the two MCS lines shown in Figs. 5 and 6, we conclude that the transition between the sheared and the volcanic rifted margin is taking place within several tens of kilometers only. On the basis of the magnetic data it may even be proposed that the transition occurs over a less wide region (compare Figs. 3, 5 and 6 for change in magnetic pattern at the shelf break). At the conjugate margin off the coast of Argentina, Franke et al. (2010) concluded from a dense grid of MCS data that in fact the large, margin parallel anomaly in the magnetic data marks the distribution of the SDRs and that this transition occurs over less than 20 km.

Figure 3. EMAG2 Earth Magnetic Anomaly Grid (Maus et al., 2009) at the southwestern African margin. The large margin parallel positive anomaly correlates well with the extent of Seaward Dipping Reflector Sequences (SDRs), especially in the southern part of the study area. It also reflects the sudden change from non-volcanic to volcanic margin at the Cape Segment Boundary (SB). The zoom-in map further shows some of the less clear Magnetic anomalies older than M4, some of them apparently reaching into the margin parallel G-anomaly and thus, the SDRs. Annotations: For orientation also shown are MCS lines of BGR and the University of Texas Seismic Data Center (Shipley et al., 2005) and areas covered by MCS data provided by industry partners. Onshore structural information compiled from Clemson et al. (1997), Hirsch et al. (2009) and Blaich et al. (2011); CFB = Cape Fold Belt; DFB = Damara Fold Belt; GFB = Gariep Fold Belt; FOS = First-order Segment; SB = Segment Boundary; RGFZ = Rio Grande Fracture Zone; AFFZ = Agulhas Falkland Fracture Zone. Deep blue contours are the −1000 m, −2000 m and −3000 m isobaths; for clarity, magnetic anomalies M2, M5, M7, M8, M9 are only indicated on the zoom-in map inset.

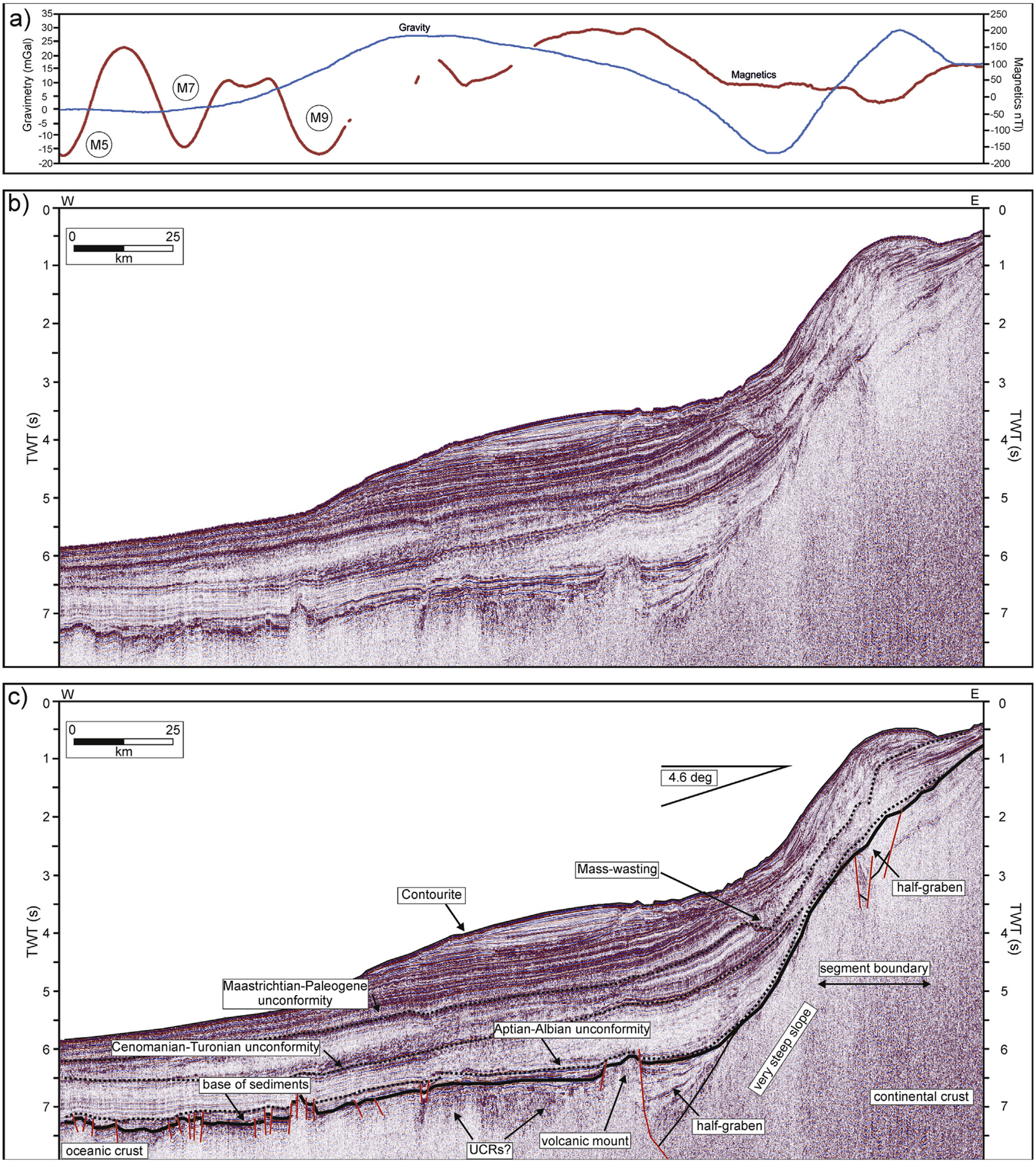

Figure 5. 235 km section of BGR migrated MCS line BGR03_11 (see Figs. 3 and 4 for location); a) cross-plot of ship-track potential field data; b) uninterpreted, c) interpreted. Located in the North of First-order Segment I. An example of the Magma-poor segment of the Southern African continental margin. Note the steep slope, unusual for a passive continental margin and a feature of sheared margins (Scrutton, 1979). The measured gravity data seem to largely follow the sedimentary buildups and waste events on the slope. The magnetic data show a response to the volcanic mount seaward of the half-graben. This positive magnetic anomaly is also visible on satellite derived magnetic data (Fig. 3).

4.3. Margin segment II

The boundary between First-order Segments I and II is at the position where the continental margin changes to the volcanic rifted type. First-order Segment II, bound by Cape SB in the south and Orange Segment Boundary (Orange SB) in the north (Fig. 3) is characterized by widespread volcanic effusives, reflected on seismic images as SDRs and correlating to the large positive

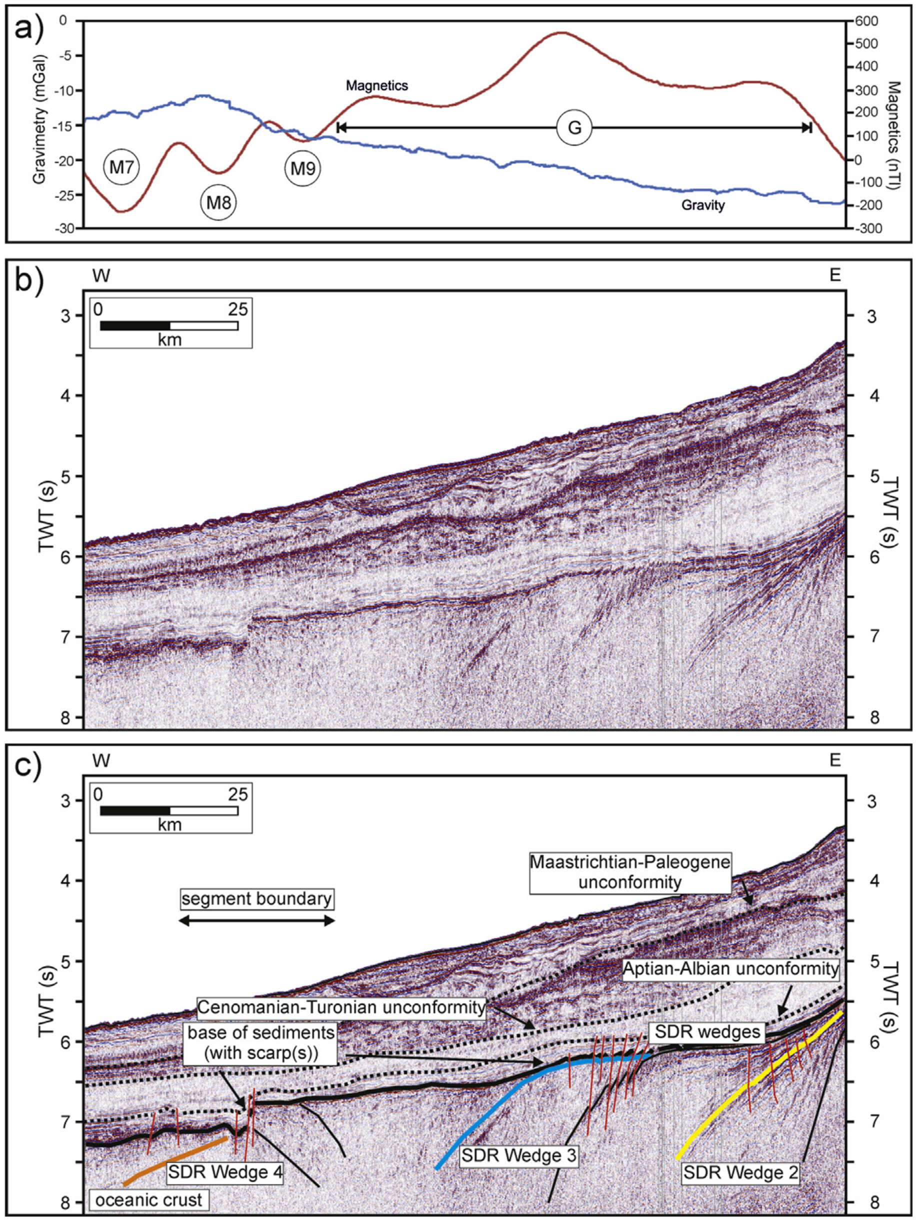

Figure 6. 140 km section of BGR migrated MCS line BGR03_12 (see Figs. 3 and 4 for location); a) cross-plot of ship-track potential field data; b) uninterpreted, c) interpreted. Southernmost section within First-order Segment II. Note the strong Seaward Dipping Reflectors, separating individual wedges. SDRs are highly dissected, with some faults affecting Aptian–Albian sediments. The main set of SDRs largely corresponds to a large positive magnetic anomaly (G-anomaly, Rabinowitz and LaBrecque, 1979). The outer SDR wedge 4 is already within an area of polarity changes, indicating a much later emplacement. The gravity data for this line shows an unexpected low in the area of SDRs.

margin-parallel magnetic anomaly (compare Figs. 3, 5, 6, 7 for the magnetic response of the SDRs). The outer SDR wedge 4 frequently falls outside this large magnetic anomaly. A seaward continuation of the southern segment boundary may correspond to a scarp, offsetting the oceanic crust and overlying sediments, as young as Aptian (Fig. 6). Within First-order Segment II, the across margin lateral extent of the emplaced volcanics exceeds 200 km. This enormous width is the binding trait of its sub-segments. North of the Cape SB, at least 2 s TWT (or 5 km at a velocity of 5000 m/s) thick wedges of SDRs are imaged.

The SDRs were interpreted as of volcanic origin according to analogies with well-studied areas such as offshore Norway and Greenland (e.g. Hopper et al., 2003; Planke et al., 2000; Roberts et al., 2005) or South America (e.g. Franke et al., 2007; Hinz, 1981) and their correlation with magnetic, gravity and velocity anomalies offshore Namibia (Bauer et al., 2000) and Argentina (Schnabel et al., 2008). Common features of SDRs seismic facies are their typical convex shapes associated with increasing dips with depth and flat and narrow “tails” landwards (e.g. Fig. 7). As a characteristic trait (Franke et al., 2007; Hinz, 1981; Mutter et al., 1982; Planke et al., 2000), the SDRs share an arcuate, internally diverging reflection pattern. Usually, more landward emplaced SDRs tend to be steeper than underlying flows, due to relatively larger subsidence. Separation of individual SDR wedges by strong unconformities is characteristic for the southern area of this segment (Fig. 6). Northwards, SDR reflections show a more continuous pattern (Fig. 7). The basement slope angle is much less steep than in First-order Segment I ($<1°$) and further decreases

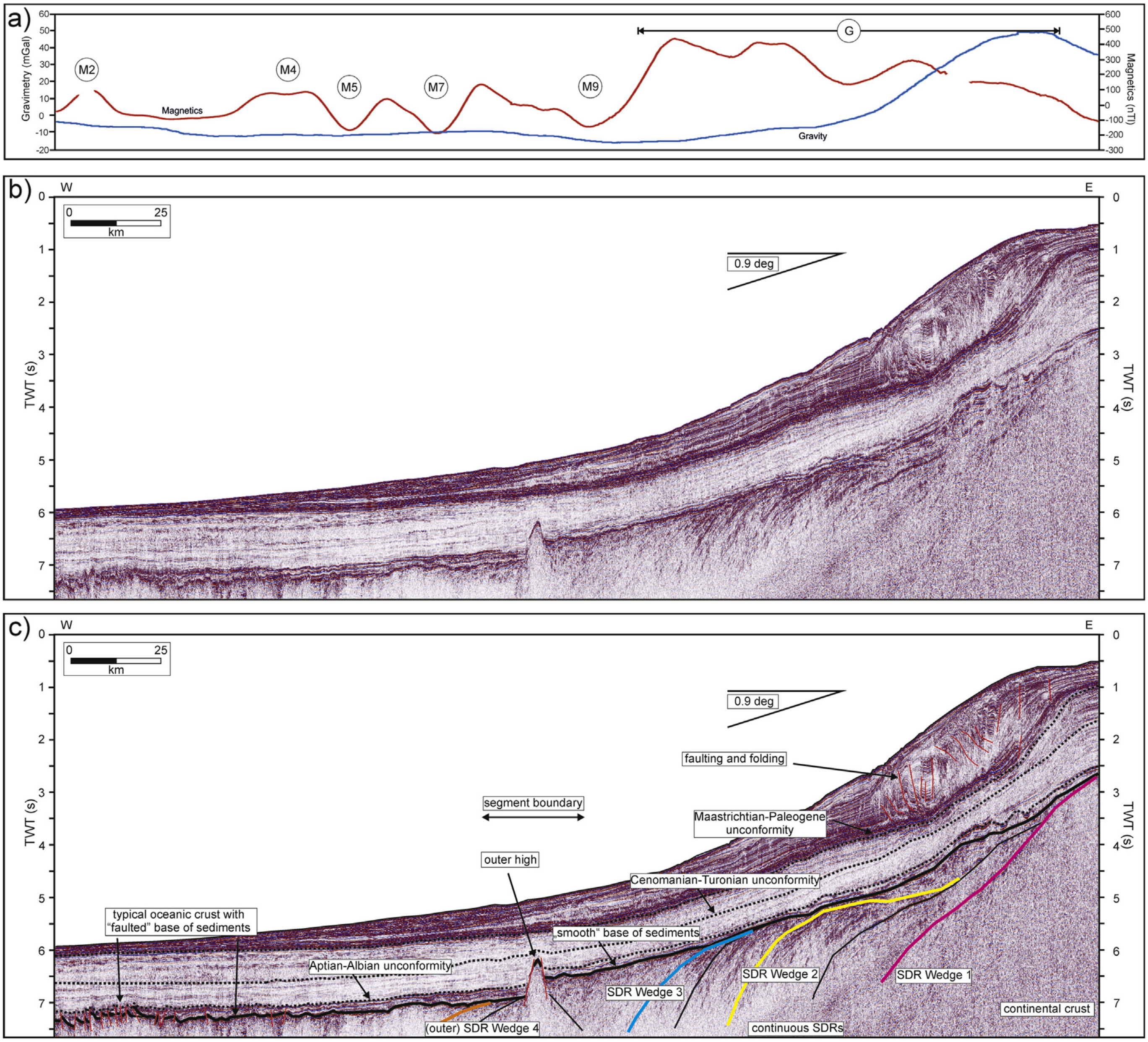

Figure 7. 290 km section of BGR migrated MCS line BGR03_16A (see Figs. 3 and 4 for location); a) cross-plot of ship-track potential field data; b) uninterpreted, c) interpreted. Note that the SDR wedges are less characterized by strong reflectors separating individual wedges instead showing a more continuous reflection character, without the intense deformation of the more southerly profile in Fig. 6. Further shown is the transition from the continental towards the oceanic domain with the typical intensely faulted top of the oceanic crust. The main set of SDRs largely corresponds to a large positive magnetic anomaly (G-anomaly, Rabinowitz and LaBrecque, 1979). The outer SDR wedge 4 is already within an area of polarity changes, indicating a much later emplacement accompanying the change towards normal seafloor spreading.

towards the north (compare Figs. 5, 7 and 8). Outer highs and outer SDRs sensu Planke et al. (2000) as an integral part of the succession of inner SDRs (e.g. Fig. 7) are not as frequently imaged as offshore Argentina (Franke et al., 2007). This may be related to the smaller MCS data coverage in the far offshore off South Africa compared to the South American datasets used in previous studies (Franke et al., 2010, 2007). On the profiles that show outer highs in this sense, the outer SDR sequence is also less prominent than on the conjugate margin. The across-margin width of the SDRs increases from about 75 km at the Cape SB northwards and reaches a maximum width of 200 km at the Orange SB (Fig. 4). Within the Orange Basin we observe two distinct left-lateral offsets within the lateral extent of the SDRs (Namaqua SB and Orange SB; Fig. 4). Furthermore, a remarkable feature within this margin segment and exclusive to this segment is the (across margin) dissection of the SDRs (Fig. 6). The dissecting faults partly affect also overlying Aptian sediments, providing an age estimate for the timing of deformation. From margin-parallel data, we confirm the general continuity of SDR reflectors along the margin, with undulations and apparent northerly and southerly dip of the packages (margin parallel dipping) instead of simple, subhorizontal reflectors. This suggests a deviation from the simplified SDRs subsidence model in which spreading axis orthogonal flows are homogenously subsidized to form subhorizontal reflectors seen in margin-parallel seismic data and might accordingly suggest varying pre-rift relief and inhomogeneous subsidence along the African margin. The formation of actual margin parallel northwards dipping SDR wedges in the way shown by Elliott et al. (2009) for the Walvis Ridge volcanism in the

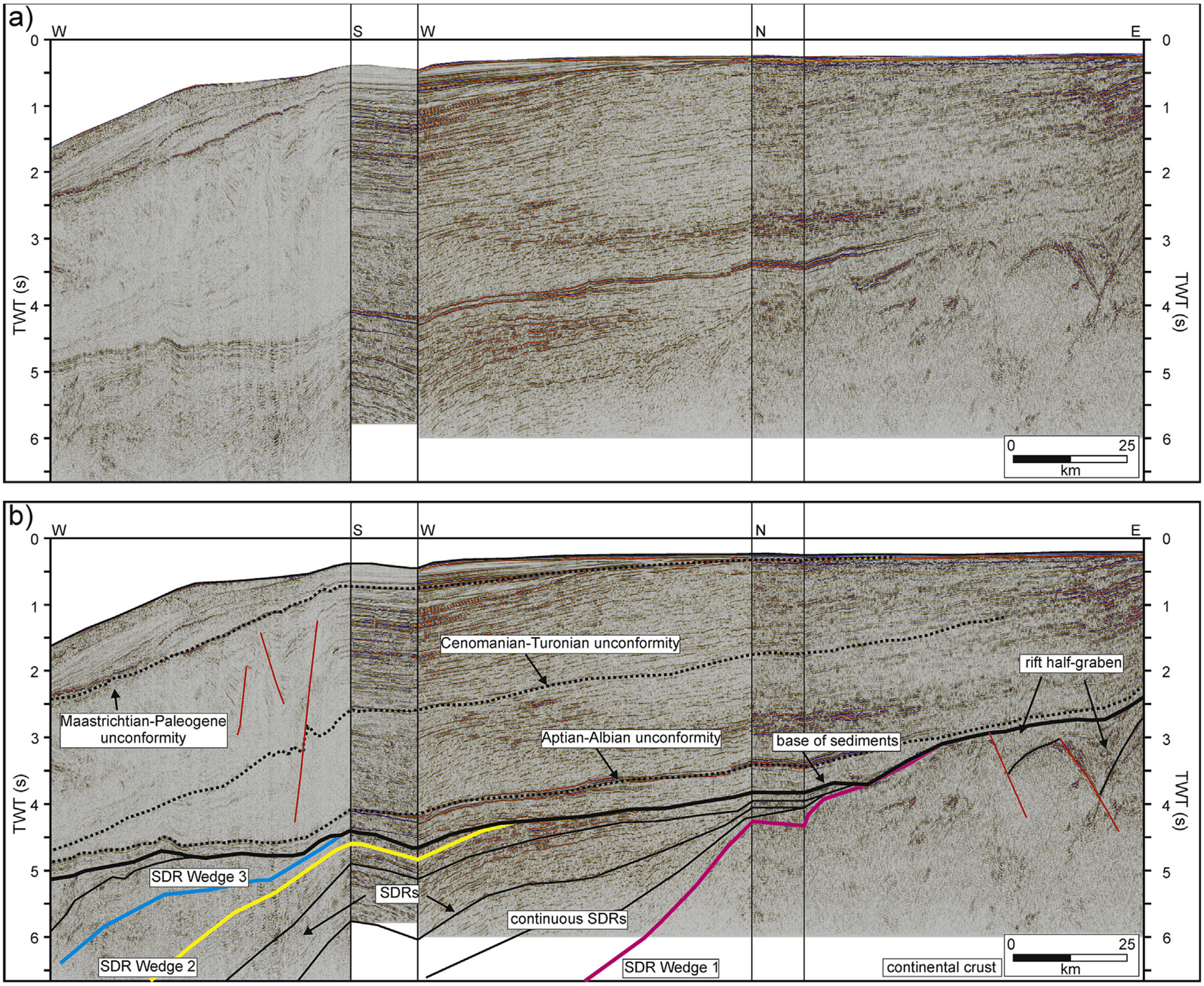

Figure 8. 240 km composite section (directional changes!) of migrated MCS lines provided by Forest Oil (see Figs. 3 and 4 for location); a) uninterpreted, b) interpreted. This profile shows an almost ideal succession of SDR wedges with the typical (Hinz, 1981; Mutter et al., 1982; Franke et al., 2010) convex-up, arcuate reflection pattern. Basement dip is very shallow. We interpret the half-grabens as results of crustal stretching during break-up, as opposed to the half-grabens shown in Fig. 5, which we suggest to result from oblique extension.

northern part of our study area (see 4.5 margin segment IV) is confirmed by us to be limited to that area.

4.4. Margin segment III

The segment boundary between First-order Segment II and First-order Segment III is combined with a major left-lateral offset (80 km) within the lateral extent of the SDRs in the Orange Basin (Orange SB in Fig. 4). The Orange SB may originate from a structure which hindered rift propagation. In the seismic data, a structural high is clearly imaged at this position (Fig. 9), which may have forced the rift to a westerly position resulting in the corresponding offset of the volcanic flow units. At this position we also observe a change in the strike of the transfer zones from W–E to SW–NE from here on northwards.

First-order Segment III is bound by the Orange SB in the south and a prominent but diffuse segment boundary west of Cape Cross. Within this previously described (Clemson et al., 1997) area of about 150 km N–S extent we found one major right lateral offset in the distribution of the SDRs, the Autseib Segment Boundary (Fig. 4). This comes along with a significant vertical offset along faults affecting the SDR sequences, which is best imaged on margin-parallel MCS lines (Fig. 10). Similarly at the southern end of the diffuse Cape Cross segment boundary area, vertical dissection of the SDR sequences is distinct. Looking at the corresponding strike line (Fig. 11), it becomes apparent that what might resemble sedimentary sequences below 3.5s TWT in Figure 10 is indeed the margin-parallel seismic image of SDRs. In across margin lines such vertical throw is imaged as distinct undulation in the elsewhere arcuate shape of the SDR wedges (Fig. 11). Across the Autseib SB we observe a considerable increase in the width of the SDRs (Fig. 4).

First-order Segment III shows an overall decline in the width of the volcanic deposits along the margin in comparison to First-order Segment II. The across-margin width of the volcanic sequence changes from ~200 km south of the Orange SB to merely ~100 km north of the segment boundary. Previously defined segment

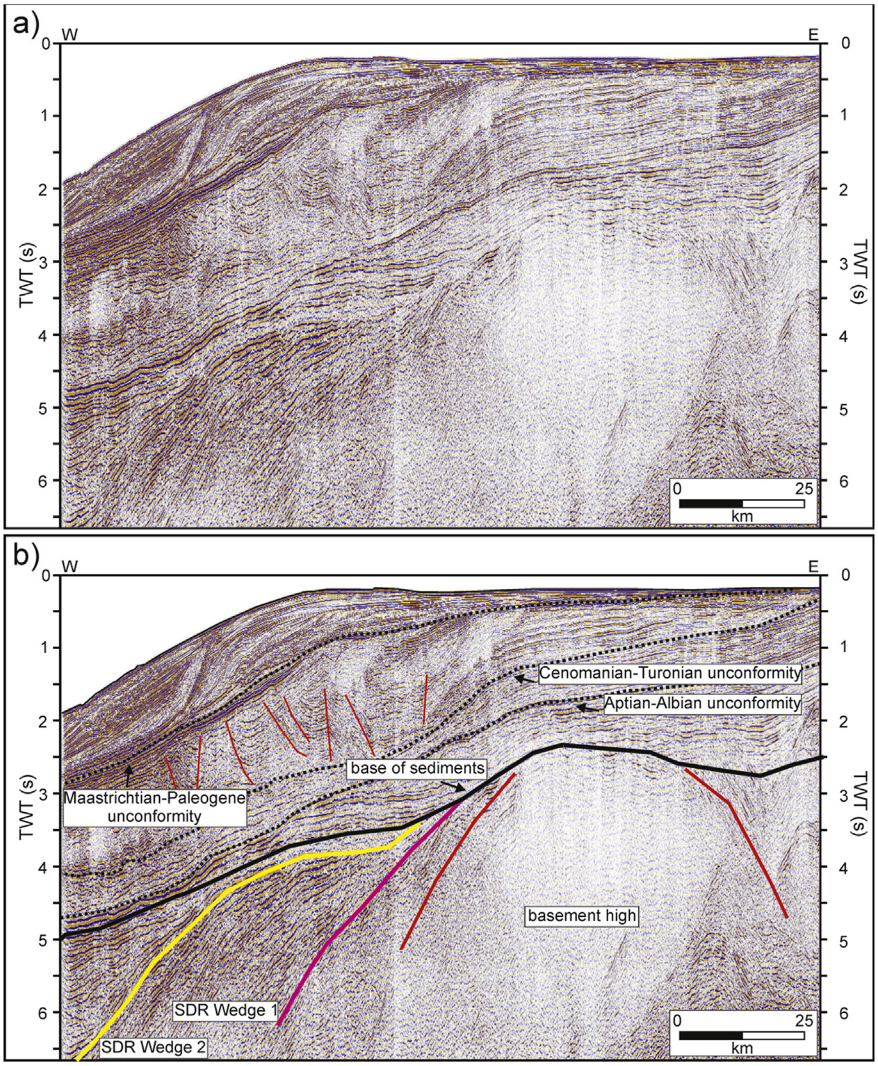

Figure 9. 155 km section of migrated MCS line provided by NAMCOR (see Figs. 3 and 4 for location); a) uninterpreted, b) interpreted. The decrease in width of magnetic anomaly G is reflected in the decrease of the width of the SDRs north of Orange SB. Note the structural high, proposed to be the reason for inhibited rift propagation and subsequent change from predominantly left- to right-stepping offsets in the SDRs extent at segment boundaries. Note that Fig. 3 shows the basement high corresponding to a negative magnetic signal.

boundaries within this First-order Segment III comprise the Lüderitz Segment Boundary (Lüderitz SB), 250 km north of the Orange SB, at the southern end of the Lüderitz Basin and the Oystercliffs Segment Boundary in the center of the Lüderitz Basin (Clemson et al., 1997). A minor right-lateral offset in the landward limit of the SDRs corresponds with the Oystercliffs SB; the Lüderitz Segment Boundary does not reflect in the volcanics.

4.5. Margin segment IV

First-order Segment IV, bound by Autseib Segment Boundary (Autseib SB) in the south and the Rio Grande Fracture Zone (RGFZ) in the north (Fig. 4) is characterized by an overall northwards increase in the width of the volcanic effusives and further by the fact that the SDRs do no longer conclusively correlate with the G magnetic anomaly. For example SDR wedge 3 extends over areas of both positive and negative magnetic anomalies. In this segment, there are large spots of negative magnetic anomalies which correspond to clearly imaged SDRs (Fig. 3). When approaching the Walvis Ridge, from about 400 km away (Skeleton SB; Fig. 4), the extent of emplaced volcanics increases to over 270 km across margin width. The Walvis Ridge is likely completely made up of volcanics with individual volcanic wedges covering an across margin area of more than 300 km (Fig. 12). North of the Skeleton SB, the seaward end of volcanics was not reached by our MCS data. The fact that the SDRs do not univocally correlate with the G anomaly may imply a longer duration of the emplacement of these effusives in comparison with the SDRs further south. An increasing influence of Walvis Ridge volcanism is suggested. Seismic data presented by Elliott et al. (2009) clearly show northward dipping SDR wedges on margin parallel lines in this area, further indicating volcanic flows from the Walvis Ridge alongside volcanic flow from the spreading center near Walvis Ridge.

5. Discussion

5.1. SDRs

Along the margin, we found distinct variations in volcanic output rates and volumes, imaged by varying thicknesses (compare Figs. 6 and 8), overall SDR wedge widths (compare Figs. 8 and 12) and spacings of prominent SDR reflectors. However, there are some consistent findings along the volcanic rifted margin off southern Africa. Four main SDR wedges, bound by strong unconformities were found to be at similar relative position within each segments'

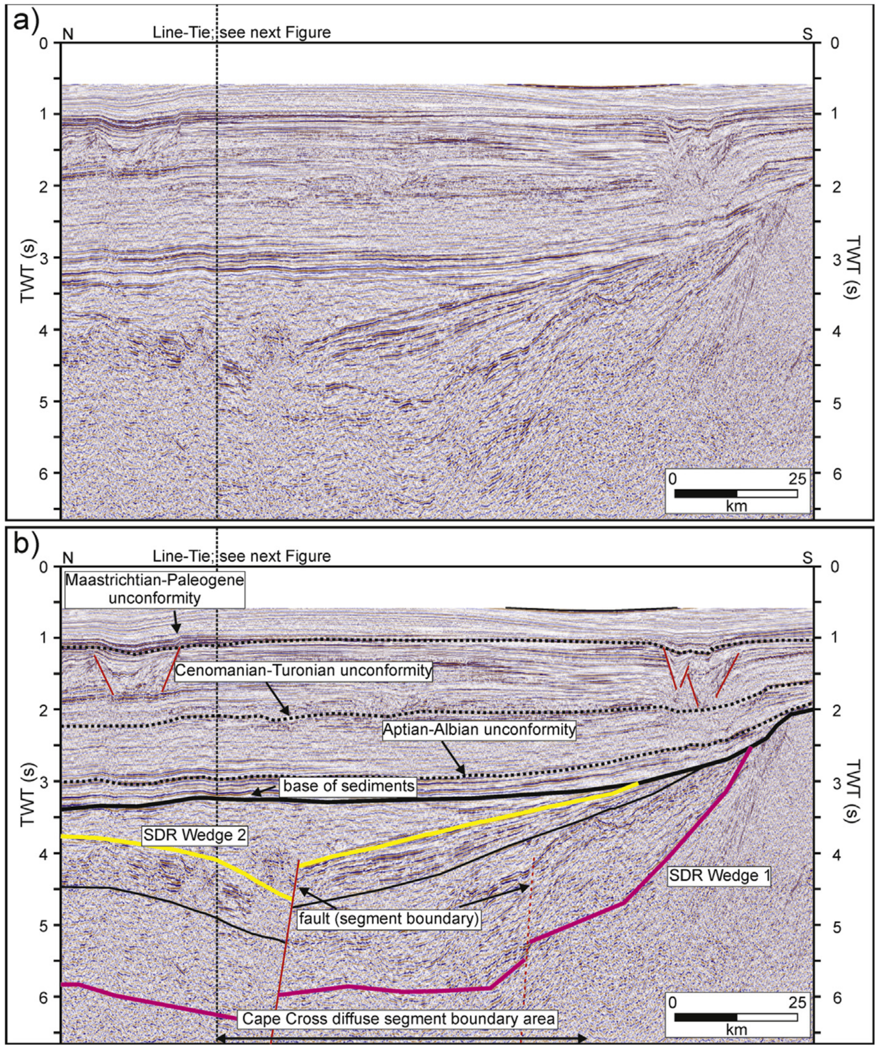

Figure 10. 155 km composite section of migrated MCS lines provided by NAMCOR (see Figs. 3 and 4 for location); a) uninterpreted, b) interpreted. This margin parallel profile shows evidence that movement along segment boundaries in this area was at least partly after the emplacement of Seaward Dipping Reflector Sequences but before extensive sedimentation commenced, as only the SDRS are affected by movement along the transfer zone faults. We do not think, however, that this finding should lead us to expect geologically sharp contact all along the margin.

SDRs set. However, this does not mean that the individual wedges have the same age along the entire margin. Rather, an age trend is suggested placing for example SDR wedge 1 in the northern part of the study area alongside SDR wedge 2 from further south with respect to their relative age.

From the intense internal deformation of the SDRs wedges in the south of the study area, we conclude that the unconformities, separating individual SDR wedges formed earlier than this deformation. The most landward SDR wedge was the first that has been emplaced because it records maximum subsidence and is partly overlain by the subsequent seaward SDR wedges. Thus, after emplacement, erosion and initial subsidence, subsequent wedges were emplaced, located partly on top and mostly seaward of the previous wedge. The formation of distinct unconformities separating individual SDRs wedges indicates erosion and thus implies a subaerial emplacement of the entire inner SDRs. This reveals a considerable symmetry to the conjugated South American volcanic rifted margin (Franke et al., 2010, 2007; Hinz et al., 1999). However, our data from the African margin do not confirm the systematically decreasing volumes of effusives towards the next northward segment boundary as have been described for the conjugated margin (Franke et al., 2010, 2007). Most important is that there is no evidence of a systematic increase in volume of the effusives towards the earlier proposed Tristan da Cunha hot-spot. Rather there is an alternating pattern in the volumes and widths of the SDRs. The relatively large volumes of SDRs in the southernmost volcanic rifted margin segment are not compatible with assumption that activity of the Tristan da Cunha hot-spot is the main cause for the magmatism.

The largest volumes of volcanic effusives were found proximal to the Walvis Ridge in an area of less than 400 km away from the ridge axis. This is probably due to the longer-lasting Walvis Ridge volcanism with respect to the volcanic activity further south.

Elliott et al. (2009) conclude from a series of northerly dipping SDRs next to the Walvis Ridge that these SDR wedges resulted from eruptions along an east-west orientated spreading center or fracture zone. Northerly dipping SDRs indicate a southerly paleo-flow direction: a northward directed flow would contradict the suggested origin of thermal uplift and melt volume derived from the Tristan da Cunha hot-spot because the center of the hot-spot, and thus the most elevated area would have been located to the north of the observed northerly dipping SDR hindering such flow direction.

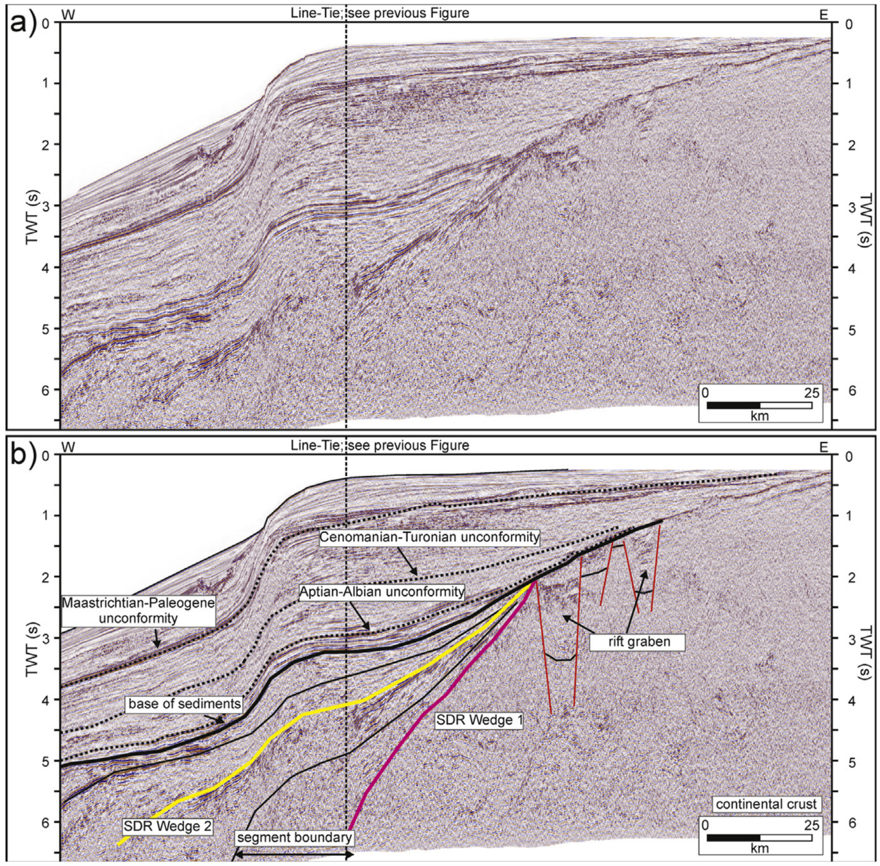

Figure 11. 185 km composite section of migrated MCS lines provided by NAMCOR (see Figs. 3 and 4 for location); a) uninterpreted, b) interpreted. Autseib SB, northernmost of the segment boundaries defined in the intensely segmented area due west of Cape Cross, is identified on this cross-section by the abrupt change in basement convexity, which we presume to mark the transfer zone in which the segments moved relative to the other.

We confirm the presence of both northerly and southerly undulations of SDR packages not only close to, but also far away from the Walvis Ridge. This deviates from the assumption that SDR packages are subparallel along margin parallel seismic lines, thus emphasizing that they are in fact not merely seaward-dipping. Such undulations may be related to pre-rift relief, encouraging (or hindering) the flow of SDR related magma in directions other than simply away from the spreading center towards areas of deep (or shallow) rift relief. This relief may have been increased by movement along segment boundaries. During the subsidence phase, thicker and heavier flows might then have undergone larger amount of subsidence, creating 3D-dip effects in parts of the study area.

5.2. Margin segmentation

Variations in the margins volcano-tectonic architecture may be related to margin-crossing discontinuities or lineaments, termed segment boundaries in this study. Segment boundaries may not necessarily be considered as geologically brittle faults, but rather reflect partly ductile crustal reactions to a previously impaired crustal structure during rifting. Arguments for locating segment boundaries across the margin were mainly lateral offsets in any direction of the spatial extent of the SDRs. Such offsets were consistently confirmed by spatial variations in magnetic data. Along-margin profiles usually image the SDRs as flat-lying reflectors. Major faults, dissecting the SDR reflectors were therefore used as additional indications for segment boundaries. These structural lineaments often coincide with a steeper than average basement slope, implying that they are deeply rooted. This is also supported by the fact that segment boundaries coincide with areas, where we found drastic changes in the volume of volcanic effusives.

The herein defined segment boundaries are well in line with the trend of known onshore structures (e.g. Clemson et al., 1997; Corner, 1983; Holzförster et al., 1999; Stollhofen, 1999; Stollhofen et al., 2000). By extrapolating the NE–SW trends of e.g. the Cape Fold Belt or the Damara Inland Branch to the adjacent offshore areas we resolve a good fit with the trend of the proposed segment boundaries. Clemson et al. (1997) suggested that the Autseib SB represents the offshore continuation of the Autseib Lineament within the Damara Fold Belt. We further suggest that the segment boundary area off Cape Cross might be structurally related to the structural line of Messum and Brandberg intrusive complexes in the north and the Omaruru Lineament in the south. Orange SB is possibly related to the structural line of the (albeit much older at ~520 Ma (Reid, 1991)) Kuboos-Bremen-Igneous province within the Gariep Fold Belt. All this may imply that the formation of segment boundaries before and during the opening of the South Atlantic was guided by structural inheritance.

Around the Orange SB, a structural high is quite distinct in the seismic profiles (Fig. 9) and it is suggested that this reflects hindered rift propagation. Evidence for this is shown by changes in the strike of segment boundaries and also by the margin architecture which changes from there on northward. In that case, a pre-rift structure may result in a segment boundary forming at this location, influencing the system particularly during rifting.

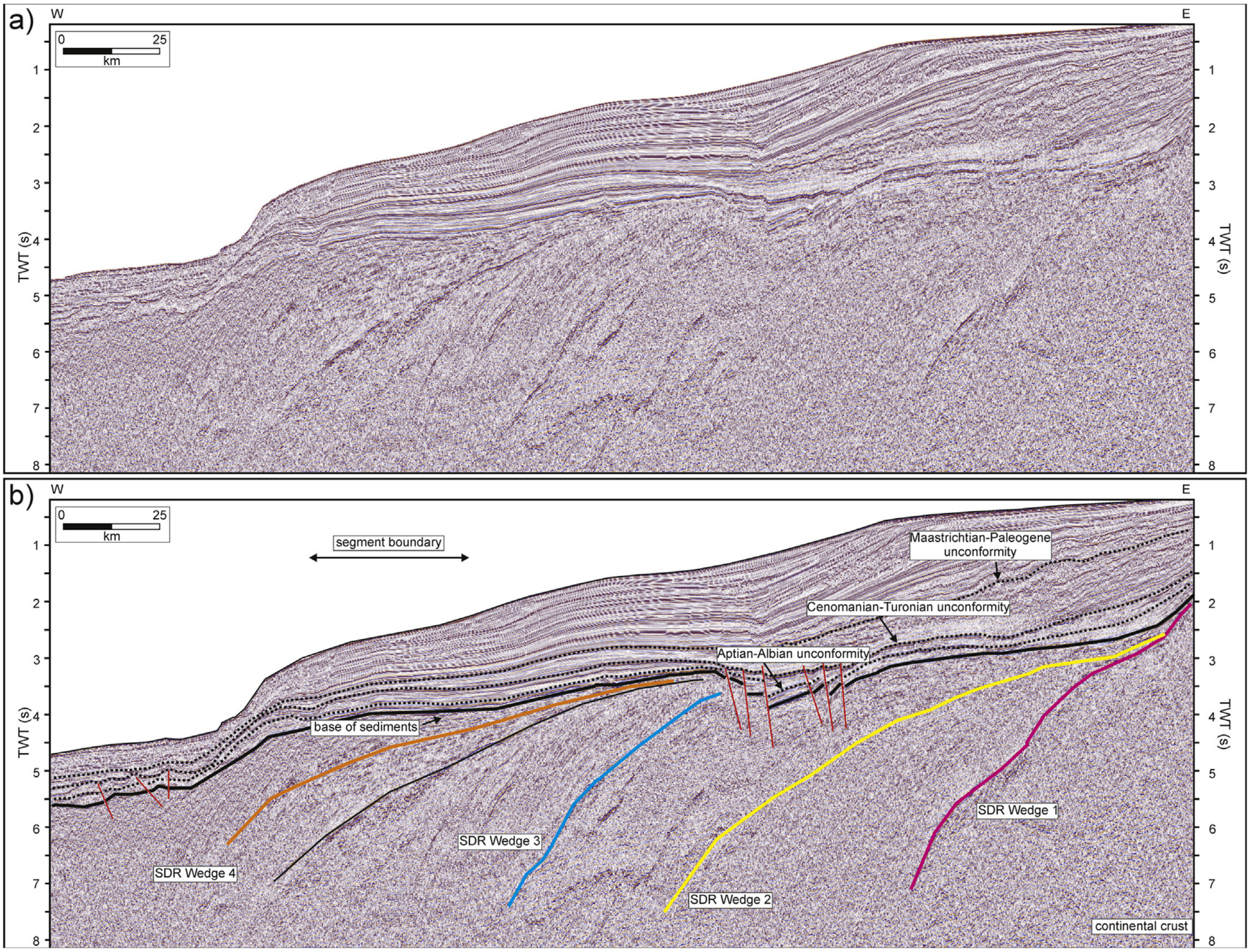

Figure 12. 300 km section of migrated MCS line provided by NAMCOR (see Figs. 3 and 4 for location); a) uninterpreted, b) interpreted. On the northernmost profile shown in our study, the influence of Walvis Ridge volcanism is reflected in the tremendous width of the SDRs which cannot be followed to their seaward termination on our data.

Further offshore, oceanic fracture zones are clearly visible in gravimetric data. However, it is unclear if there is a link between oceanic fracture zones and segment boundaries. Lister et al. (1991) suggested that continental break-up utilizes preexisting structures such as transfer zones, so that oceanic fracture zones may be features largely inherited from preceding phases of continental extension. At the northern Norway margin it was found that the fracture zone trends may differ from that of the transfer zone (Tsikalas et al., 2001). Similarly, at the southern African margin a conclusive extrapolation of oceanic fracture zones appears geometrically implausible at the furthest south of the margin. Accordingly, we suggest that the classical symmetrical approach seems to be only valid northwards of Orange SB and from M4/M0 on onwards. The symmetric opening of the South Atlantic after M0 is well documented by magnetic data (Rabinowitz and LaBrecque, 1979) and accordingly implemented in plate reconstruction models (e.g. Moulin et al., 2010; Nürnberg and Müller, 1991). A shift in relative plate motion from a more north-south trending towards the conventional east–west direction has recently been proposed, based on a very different set of data and a plate reconstruction model (Heine et al., 2013). Nevertheless, segment boundaries are still likely to influence the formation of oceanic transform faults by passing along structural inheritances from the continental crust, albeit at different trend due to changes in plate motion directions.

5.3. Magma-poor rifting in the South and implication for the early opening of the South Atlantic

We found that the seismic lines in the southernmost segment of the African margin do not reveal typical features of volcanic rifted margins. Instead the volcanic rifted margin type is confined to the area where magnetic data reveal high amplitudes, resulting in the margin parallel G-anomaly. This resembles the situation at the conjugate margin, where also a sharp transition from magma-poor to volcanic rifting was found (Becker et al., 2012; Franke et al., 2010). We conclude that at both sides of the South Atlantic the volcanic rifted margin type is confined to the extent of the G large magnetic anomaly. Along the Canadian east coast a similar situation exists. Keen and Potter (1995) found the overall width of the magnetic anomaly being similar to the width of the SDR unit and considered it as highly likely that the volcanic wedge represented by the SDRs is at least partly responsible for generating the East Coast Magnetic Anomaly. The strong linear character of the magnetic anomaly diminishes significantly within about 20 km along-strike where regional deep seismic reflection studies show that the wedge of the SDRs also vanishes. In agreement with Keen and Potter (1995) we suggest that the position of the volcanic-magma-poor transition along the margin is associated with a crustal-scale structural boundary. Becker et al. (2012) described the conjugate Argentine continental slope as being inclined seawards at an angle of about 5° with seaward dipping extensional faults that developed at the slope. Similar to the southernmost area investigated in our study, these authors found no SDRs. The almost complete absence of volcanics and the relatively steep slopes imply an evolution as sheared margin before the onset of oceanic spreading (e.g. Scrutton, 1979).

It is important to note that there is a difference in length of the magma-poor segment on both sides of the South Atlantic. According to previous publications (Franke et al., 2010, 2007; Hinz et al., 1999) offshore South America SDR wedges were emplaced ~380 km north of the AFFZ. In contrast, our results show a distance of ~460 km between the AFFZ and the first occurrence of SDRs offshore the African margin, resulting in a difference of 80 km. This difference leads obviously to geometrical difficulties if a likewise symmetric break-up and uniform sea-floor spreading for the magma-poor segment is assumed. We suggest that the AFFZ, which developed after the formation of the SDRs, originated under a different angle of extension. The asymmetry may reflect rather the direction of extension of the proto-South Atlantic than an asymmetry in length of both margins. Thus a change in the direction of extension affecting the area of the future South Atlantic is proposed here. Extension is suggested to have started in an N–S direction and successively turned clockwise towards an E–W direction. This suggests that the initial opening of the South Atlantic occurred under considerable north-south extension before the extension changed to the present east-west direction (Fig. 13). The north–south extension was possibly realized by rotation of the southern South American subplate, a notion recently also suggested by Heine et al. (2013). This may also explain the formation of huge sedimentary basins at the South American shelf, namely the Colorado and the Salado Basins (Pángaro and Ramos, 2012) which developed under a high angle to the present margin of the South Atlantic (Franke et al., 2007) during a major extensional period of the early opening phase of the Atlantic Ocean (Nürnberg and Müller, 1991). The steep slope angle on both sides of this southern segment is an indication for margin-parallel shear movements during opening. We suggest that this obliquity hindered substantial melt supply to the evolving rift. Previous investigations of the Central Atlantic sheared margin offshore French Guiana (Greenroyd et al., 2008) and its conjugate offshore Ghana (Antobreh et al., 2009) also reveal a lack of signs of widespread magmatism such as SDRs or high-velocity lower crustal bodies. Once the axis of extension had rotated to its east–west direction and thus was symmetrical, vast amounts of volcanics were emplaced resulting in the observed sharp boundary between the magma-poor rifted margin and the volcanic rifted margin type.

Towards the Walvis Ridge the clear correlation between the margin-parallel magnetic anomaly G and the extent of SDRs diminishes. This may indicate a later emplacement of volcanic

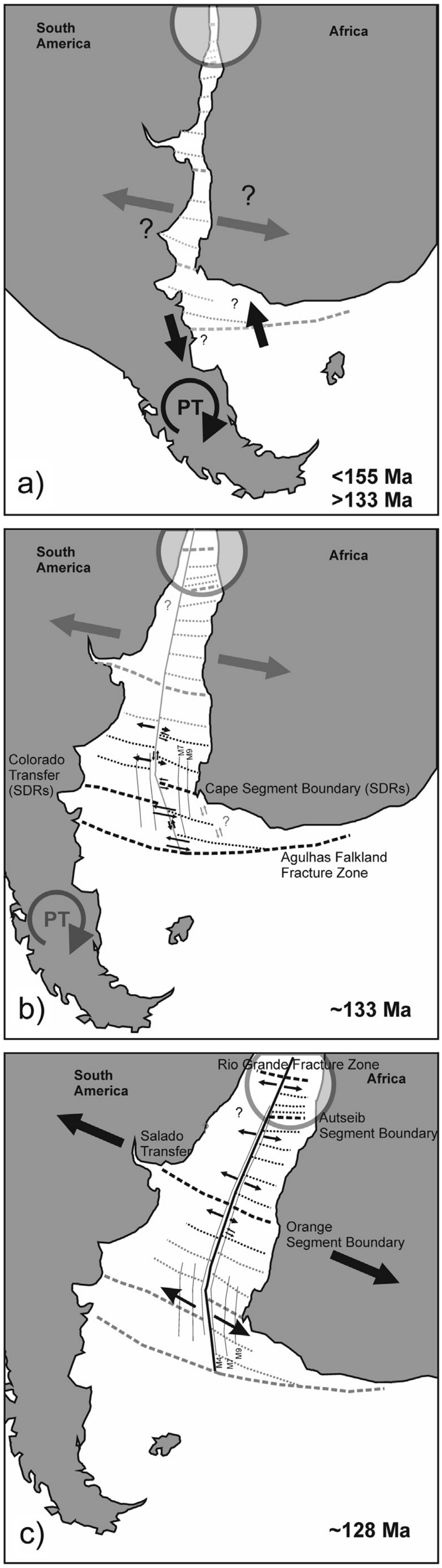

Figure 13. Plate reconstruction of the South Atlantic at <155 Ma >133 Ma (a), ~133 Ma (b) and ~128 Ma (c) (modified from Jokat et al., 2003; Macdonald et al., 2003). Segment boundary locations and names of the South American margin as interpreted by Franke et al. (2007). Semitransparent circles mark the proposed extent (diameter: 800 km) of Tristan da Cunha hotspot related volcanism. Fracture zones, segment boundaries and movement directions are drawn in more pronounced gray shades up-to black with increasing certainty and impact. Starting with Fig. 13a, this sketch shows the beginning of the opening by oblique-sheared or strike-slip dominated stretching via a clockwise-rotation of the Patagonian (PT) subplate (Heine et al., 2013), resulting in spatial and geometric offsets partially indicated in Fig. 13b. Magnetic Anomaly M4 is assumed to be equivalent to the onset of conventional seafloor spreading as indicated in Fig. 13c. As suggested in this contribution for the South African side, onshore continuation of segment boundaries has also been proposed for the South American side (Franke et al., 2007, 2010).

effusives. Here, some SDRs are mapped in areas with a negative magnetic signal. Further, Chron M0 (125 Ma) is closest to the volcanic effusives in the north of the study area, indicating that these volcanic effusives were emplaced subsequently after the SDRs in the South. This indicates that the South Atlantic did not open instantaneously but is better described as successive unzipping of rift-segments from south to north, as previously suggested (e.g. Austin and Uchupi, 1982; Jackson et al., 2000; Rabinowitz and LaBrecque, 1979; Uchupi, 1989).

6. Conclusions

A striking finding of this study is that the 460 km long, southernmost African margin between the AFFZ and the Cape SB is lacking major volcanic effusives. Given the steep slope and the presence of only minor rift basins, the margin nevertheless does not resemble the style of typical magma-poor margins. We propose that the architecture of this margin segment originates from oblique rifting, resulting in sheared margin architecture. From magnetic data and two close MCS profiles it is concluded that the boundary between magma-poor and volcanic rifted margin to the west of the Cape Peninsula occurs abrupt (10s of km).

Segment boundaries are interpreted as zones that hindered the continuous opening of the northward propagating rift. In the southern study area, this resulted in a predominant left-stepping pattern of the SDRs extent, and, from the Orange SB northwards, in a predominant right-stepping pattern of the SDRs extent. Several of the segment boundaries are at positions that imply a relationship to preexisting crustal structures that can be traced onshore. Correlation of segment boundaries with onshore structures is possible with some confidence in the Damara Fold Belt region of Namibia (Oystercliffs SB to Autseib SB). Cape SB to Orange SB seem to parallel a W-E trend possibly inherited by structures within the Cape and Gariep Fold Belts. The close relationship of SBs and onshore structures suggests that segment boundaries formed in zones of inherited structures in the lithosphere.

These segment boundaries define four First-order Segments of major structural and architectural differences along the 2400 km long passive continental margin of southwest Africa. From the architecture of the southernmost margin segment, which resembles a sheared margin, we suggest that the early crustal stretching phase was dominated by oblique movements and shearing, possibly resulting in spatial differences in the apparent onset of SDRs on both sides of the South Atlantic, relative to the AFFZ today.

Characteristics of the SDRs in the study area vary immensely, with differences in lateral continuity, steepness, thickness and length. The earliest volcanics in the south of the study area also cover the largest area, decreasing drastically in width north of the Orange SB before regaining width under the presumably influence of Walvis Ridge volcanism towards the northern end of the study area. There is no evidence for a systematic increase in effusive volumes towards the Tristan da Cunha hot-spot. Rather there is an alternating pattern in volumes and widths of the SDRs. The influence of the Tristan da Cunha on break-up related magmatism appears to be limited to a maximum of about 400 km distance from the hot-spot.

Towards the Walvis Ridge, the clear correlation between the margin-parallel magnetic anomaly G and the extent of SDRs diminishes. This indicates a later emplacement of volcanic effusives and some SDRs with a negative magnetic signal. Magnetic anomaly M0 (125 Ma) is closest to the volcanic effusives in the north of the study area, indicating that these volcanic effusives were emplaced subsequently after the SDRs in the South. This underlines that the South Atlantic did not open instantaneously but is better described as successive unzipping of rift-segments from south to north.

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