Break-up of the South Atlantic: A geophysical image of the continent-ocean transition zone and implications on lithospheric controls and mantle dynamics

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An investment in knowledge pays the best interest

Benjamin Franklin

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SUMMARY

Ever since the concept of plate tectonics was developed, continental margins have been a focus for scientists and researchers worldwide. Structures along continental margins are an excellent archive of the development of sedimentary basins and the evolution of break-up systems.

The continental margins of Africa and South America in the South Atlantic between the Rio Grande / Florianópolis Fracture Zone and the Agulhas-Falkland Fracture Zone cover a particularly complicated and variable section of the Atlantic Ocean. Due to its relevance and complexity this area is the focus of academic research. Because of continued finds within the sedimentary basins it is being investigated intensively by the oil and gas industry as well.

Based on a unique set of geophysical data, the South Atlantic between 39°C and 19°S is also the focus of this thesis. Continental break-up in the South Atlantic during the Early Cretaceous was accompanied by episodes of magmatism. From marine seismic data, the distribution of volcanic material along the African margin is investigated and described here. Offshore, volcanic episodes are featured in seismic sections as prominent wedge-shaped seaward dipping reflectors (SDRs). This investigation reveals a segmentation of the margin similar (but not identical) to what has been previously described for the Argentinean margin. Four major segments are defined along the investigated 2400 km section of the southwestern African margin, based on variations in the distribution and structural character of the volcanics. A major find of this investigation is that the South Atlantic African margin is not continuously of the volcanic type as previously suggested.

Further, the transition from the magma-poor southernmost segment to clearly volcanic margin further north occurs abruptly within 10s of km. As there is also no systematic increase of volcanism towards the Tristan hot-spot this casts doubts on the importance of large thermal anomalies for continental break-up and break-up related volcanism. Further, the emplacement of the SDRs in the southern volcanic segment happened prior to the main magmatic pulse of the hot-spot which emplaced the Paraná-Etendeka onshore large igneous provinces.

Conjugate margin profiles are investigated in this thesis to study continental break-up mechanisms. As the findings show asymmetries across the margins, an asymmetric simple shear-dominated variable strain rifting model is proposed. A rotation of spreading- and rifting-direction explains the asymmetries along the margins. Initial oblique stretching and rifting also explains the formation of the magma-poor southernmost segments. The transition from oblique stretching and rifting to regular seafloor spreading was completed around magnetic Chron M4 (~130 Ma). Pre-M5 magnetic seafloor spreading lineations on both margins constrain the timing of volcanism and the transition to regular seafloor spreading. Older magnetic anomalies terminate within the seaward dipping reflector units. This underlines the emplacement of the volcanics during the early rift and opening stages. It also shows that the South Atlantic opened from south to north in a propagating manner. Magnetic anomaly Chron M9 (~133 Ma) is shown to be the oldest seafloor spreading anomaly in the study area. Chron M0 (~125 Ma) is the first continuous Chron along the investigated margin section. This means the South Atlantic opened successively over a timespan of about 10 Ma, depending on the geological timescale used.

Investigations of volcanic structures, abundance and variability along South Atlantic and comparable North Atlantic volcanic margins reveal a spatial link of volcanics to transfer fault zones. Transfer fault zones segment the juvenile rift and act as rift propagation barriers. This concept is tested in this thesis using numerical modelling. Rift parallel material flow and locally enhanced rates of volcanism caused by delayed, segmented opening are two of the main model results. Local structures and rift propagation delay play a large role in the distribution of break-up related volcanism, independent of deeper (mantle) processes. Duration of delay is an important factor in controlling melt supply in segmented continental rift settings.

KEYWORDS: CONTINENTAL BREAK-UP; PLATE TECTONICS; MAGMATISM

KURZFASSUNG

Seit der Entwicklung des Konzepts der Plattentektonik sind Kontinentalränder ein wichtiges Arbeitsgebiet für Wissenschaftler und Forscher weltweit. Die Strukturen entlang der Kontinentalränder sind ein ausgezeichnetes Archiv der Entwicklung von Sedimentbecken und der Entwicklung von auseinanderbrechenden Kontinenten.

Die Kontinentalränder von Afrika und Südamerika im Südatlantik zwischen der Rio Grande / Florianópolis Fracture Zone und der Agulhas-Falkland Fracture Zone umfassen einen besonders komplizierten und vielfältigen Bereich des Atlantiks. Aufgrund der Relevanz und Komplexität dieses Abschnitts ist er im Fokus vielfältiger wissenschaftlicher Untersuchungen. Wegen fortlaufender Funde in den Sedimentbecken entlang der Ränder wird der Südatlantik auch von der Öl und Gas Industrie stark untersucht.

Basierend auf einem umfassenden geophysikalischen Datensatz steht der Südatlantik zwischen 39°S und 19°S auch im Fokus dieser Arbeit. Das Auseinanderbrechen der Kontinente im Bereich des Südatlantiks während der frühen Kreidezeit wurde von magmatischen Episoden begleitet. Die Verbreitung von vulkanischem Material entlang des Afrikanischen Kontinentalrandes wird hier anhand mariner seismischer Daten untersucht und beschrieben. Vor der Küste Afrikas sind die vulkanischen Episoden sichtbar in den seismischen Daten in Form auffälliger, keilförmiger, seewärts einfallender Reflektorfolgen. Die hier vorgestellte Untersuchung zeigt eine Segmentierung des Kontinentalrandes ähnlich (aber nicht identisch) zu den vom argentinischen Rand zuvor beschriebenen Verhältnissen. Vier Hauptsegmente können entlang des 2400 km langen Teils des südwestlichen afrikanischen Kontinentalrandes beschrieben werden, ausgehend von Variationen in der Verteilung und im strukturellen Charakter der Vulkanite. Ein wichtiger Fund dieser Untersuchung ist, dass der afrikanische Rand des Südatlantiks nicht durchgängig ein vulkanischer Rand ist, wie zuvor aufgrund von Interpolationsstudien vermutet wurde.

Darüber hinaus ist der Übergang vom magma-armen, südlichsten Segment zum eindeutig vulkanischen Kontinentalrandtyp weiter nördlich abrupt und findet innerhalb weniger Zehnerkilometer statt. Da außerdem kein systematischer Anstieg von vulkanischer Aktivität in Richtung des Tristan Hot-spot zu erkennen ist, kommen Zweifel an der Wichtigkeit von großen thermischen Anomalien für das Auseinanderbrechen von Kontinenten und dem damit verbundenen Vulkanismus auf. Außerdem fand die Ablagerung der Vulkanite im südlichsten vulkanischen Segment vor der Hauptaktivitätsphase des Hot-spots statt, der die magmatische Großprovinz Paraná-Etendeka auf den beiden auseinanderbrechenden Kontinenten verursachte.

Konjugierte Profile über die Kontinentalränder werden in dieser Arbeit benutzt um das Auseinanderbrechen zweier Kontinente im Detail untersuchen zu können. Da die Untersuchungen neben einigen Ähnlichkeiten auch starke Asymmetrien zeigen, wird ein asymmetrisches, simple-shear dominiertes Modell mit variabler Belastungsrichtung für das Auseinanderbrechen vorgeschlagen. Eine Rotation der Divergenzrichtung wird darüber hinaus genannt um die Asymmetrien entlang der Ränder und die Bildung der magmaarmen südlichsten Segmente während der schrägen anfänglichen Phase des Auseinanderbrechens zu erklären. Der Übergang von diesem schrägen zum regulären divergenten Modus war zur Zeit der magnetischen Spreizungsanomalie M4 (~130 Ma) abgeschlossen. Spreizungsanomalien vor M5 können an beiden Ränder die Zeitlichkeit des Vulkanismus und den Übergang zur normalen Divergenz eingrenzen. Ältere magnetische Anomalien enden in den Vulkaniten, was sowohl die Ablagerung dieser Vulkanite während der frühen Phase des Spreizens und Auseinanderbrechens als auch die Öffnung des Südatlantiks von Süd nach Nord in einer propagierenden Art und Weise bestätigt. Die Spreizungsanomalie M9 (~133 Ma) ist die älteste Spreizungsanomalie im Untersuchungsgebiet. Die erste durchgehende Anomalie entlang der untersuchten Kontinentalränder ist M0 (~125 Ma). Der Südatlantik öffnete sich also sukzessive über einen Zeitraum von 10 Millionen Jahren, abhängig auch von der verwendeten geologischen Zeitskala.

Untersuchungen der Strukturen, der Häufigkeit sowie der Variabilität der Vulkanite entlang der südatlantischen und der vergleichbaren nordatlantischen vulkanischen Kontinentalränder zeigt eine räumliche Verbindung der Vulkanite zu Transferstörungszonen. Diese Zonen segmentieren die sich entwickelnde kontinentale Spreizungszone und werden als Hindernisse der Fortschreitung der Spreizung betrachtet. Dieses Konzept wird in dieser Arbeit mit Hilfe von numerischer Modellierung getestet. Materialfluss parallel zur Rift-Fortschreitungsrichtung und lokal erhöhte Raten des Vulkanismus die durch das verzögerte, segmentierte Öffnen ausgelöst werden sind zwei der der Hauptresultate der Modellierung. Räumlich begrenzte Strukturen und das verzögerte Öffnen spielen eine große Rolle für die Verteilung von zum kontinentalen Auseinanderbrechen gehörigem Vulkanismus, unabhängig von tieferen (Mantel) Prozessen. Die Dauer der Verzögerung ist ein wichtiger Faktor zur Kontrolle der Schmelzbildung und Schmelzverteilung in segmentierten Kontinental-divergenzsystemen.

SCHLAGWÖRTER: KONTINENTALDIVERGENZ; PLATTENTEKTONIK; MAGMATISMUS

1. INTRODUCTION: WHY, WHAT AND HOW TO LEARN FROM THE SOUTH ATLANTIC

1.1 Thesis outline

The thesis is divided into five chapters. Chapter 1 acts as an Introduction to both study area in the South Atlantic and methodology. Chapter 2 presents a study of geophysical (mainly multi-channel seismic) data along the southern African continental margin, whereas in Chapter 3 the conjugate margins of South American and South Africa are compared and the formation of the South Atlantic is discussed. In Chapter 4, ideas regarding the relationship of volcanism and transfer zones based on findings in the Atlantic Ocean are tested by numerical modelling. In Chapter 5, the results of this thesis are synthesized.

1.2 Plate tectonics, rifted margins and the (South) Atlantic Ocean

This thesis mainly describes and discusses the evolution and structural features of the rifted continental margins of the South Atlantic. However, the Atlantic Ocean (Fig. 1) as a whole offers a unique variability in structural architecture along its margins. For example, recent studies (Péron-Pinvidic & Manatschal (2009) reveal a far more complex development of continental margins with regard to rather simple mono-phase rifting and a selection seemingly limited to either pure- or simple-shear mechanism. Research (e.g. Wilson et al., 2001; Sibuet et al., 2007; Péron-Pinvidic et al., 2010; Mohriak & Leroy, 2013) on the well-described Iberian-Newfoundland margins describes a system involving mantle exhumation, hyperextension and deep reaching listric faults (Fig. 2). It is easily recognizable in Fig.1 that there is a large difference about both the South and North Atlantic margins when compared to Iberian-Newfoundland system. And indeed, recognizing the work of e.g. Mutter et al. (1982) and Planke & Eldholm (1994), there is: In marine geophysical data, the North and South Atlantic show a unique set of seismic reflections (Fig. 3), appropriately named seaward-dipping reflectors (e.g. Hinz, 1981; Mutter, 1985). Based on few drill-results and comparison with onshore observations, it is agreed for the most part that these features are largely of volcanic origin and that margins with these features are to be called volcanic rifted margins.

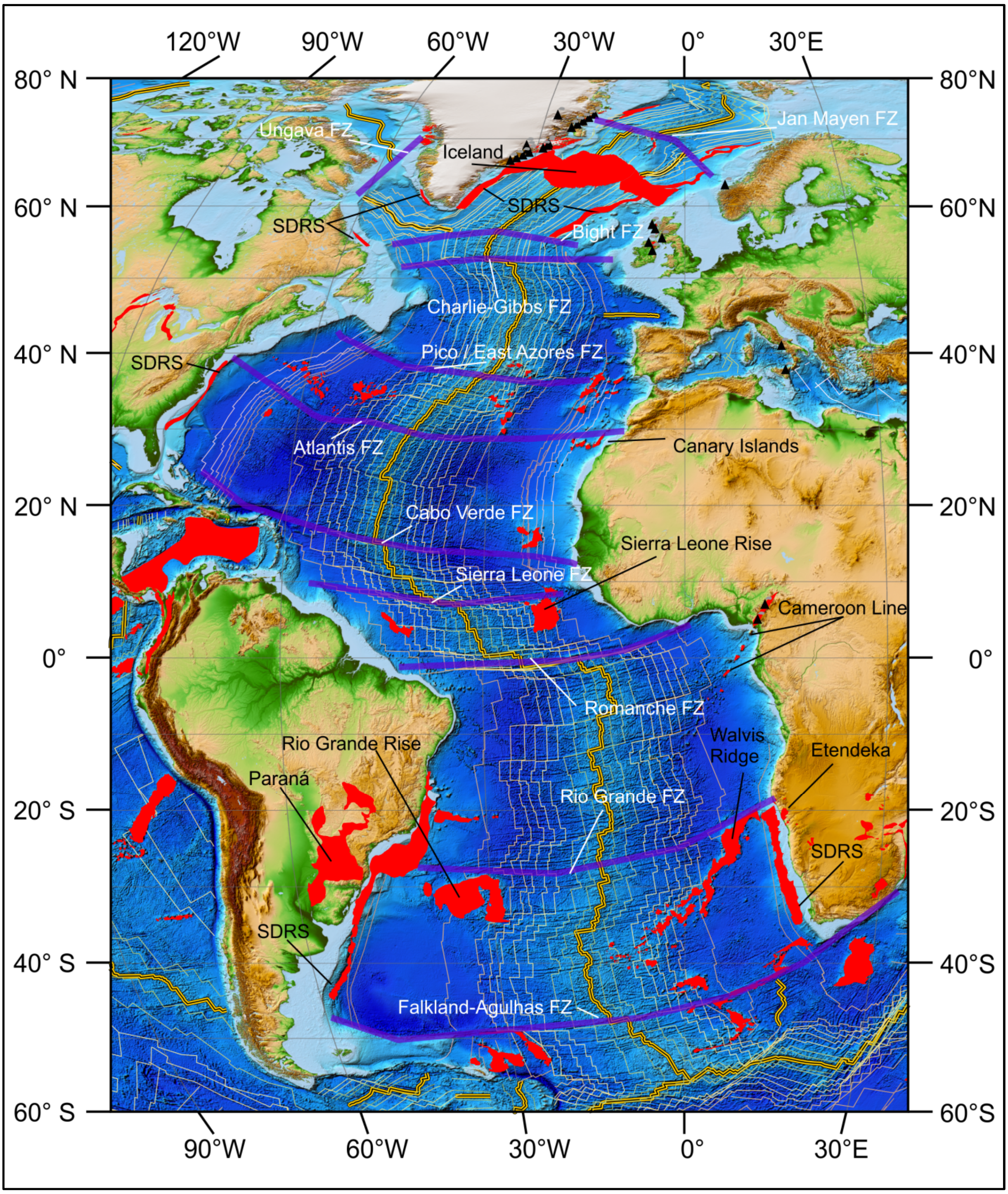


Fig. 1.1: Topobathymetric (ETOPO1) map of the Atlantic Ocean. Indicated on the map are the locations of relevant off- and onshore Large Igneous Provinces (LIPs) alongside major oceanic fracture zones, Marine Magnetic Anomalies and other structural elements of Atlantic. Structural information compiled from Bryan et al. (2010), Courtillot et al. (2003), Franke et al. (2007) and Koopmann et al. (2014b).

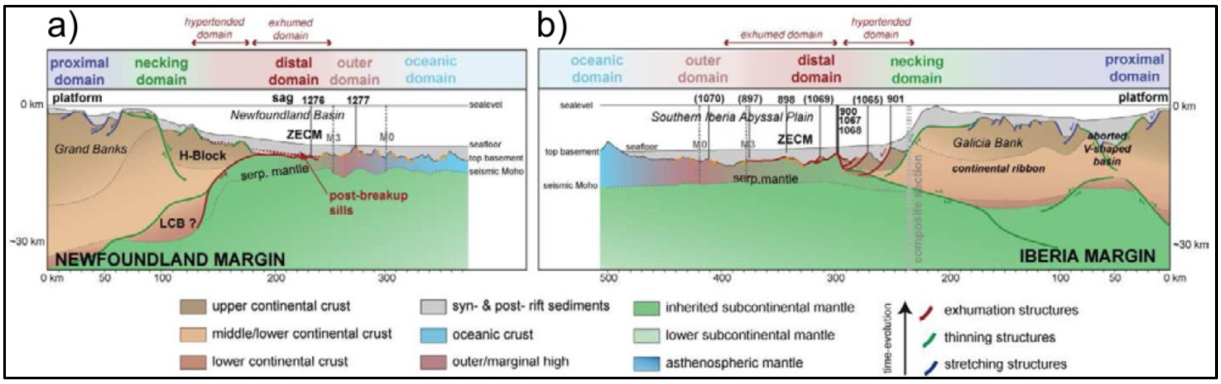


Fig. 1.2: Simplified composite margin section across the Iberia-Newfoundland passive non-volcanic continental margin system (from: Péron-Pinvidic et al., 2013; therein after Péron-Pinvidic and Manatschal, 2009).

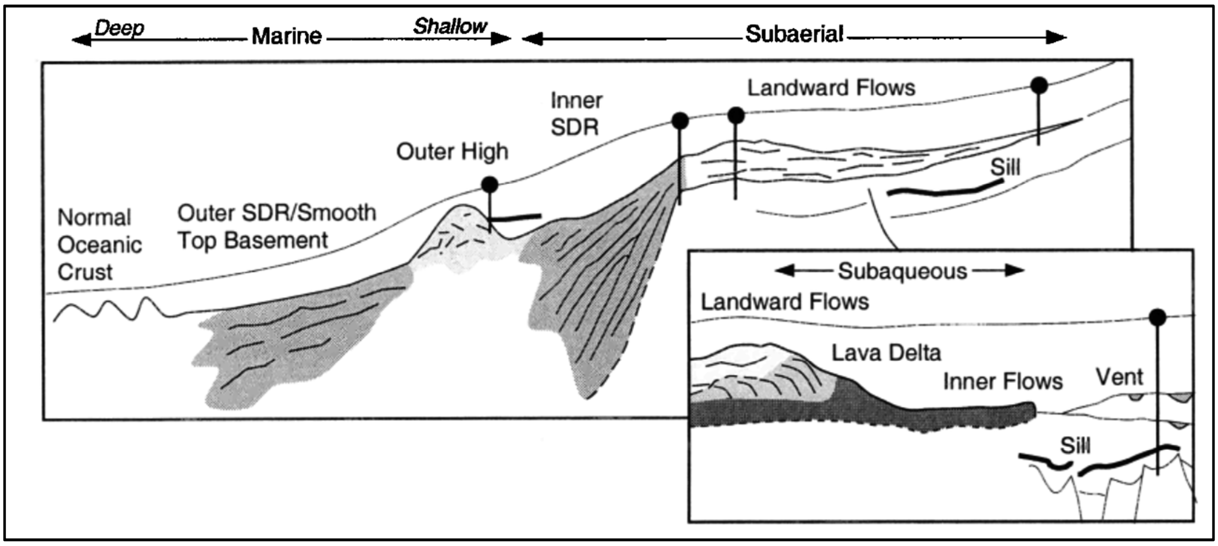


Fig. 1.3: Simplified margin section illustrating the seismic sequence of volcanic extrusives (shaded) at the northeast Atlantic volcanic continental margin; inset shows other seismic facies observed in the northeast Atlantic (from: Planke et al., 2000).

Ever since Wegener (1912) postulated and refined (Wegener, 1929) a movement of continents and an according break-up of them, oceanic islands (e.g. Wilson, 1963; Morgan, 1971) and continental margins form a key research area of scientists looking to restore former plate assemblages (e.g. Gondwana) to their pre-break-up style. One of the key features for restoration is the continent-ocean transition between true oceanic crust and (possibly deformed) continental crust. The structures behind this continent-ocean transition is as of yet not conclusively described. There is a continuing debate whether this is a sharp boundary (continent-ocean boundary, COB) or a transition (continent-ocean transition, COT) (e.g. Franke et al., 2011). Comparing volcanic rifted margins to hyper-extended magma poor ones, the abruptness of the COT and comparatively low amount of thinning (50 - 100 km) on the volcanic margins becomes obvious. The relationship of the SDRs and the COT is one of the topics of this thesis, as previous authors (e.g. Hinz, 1981; Smythe, 1983) have placed the COT at seaward edge, landward edge or in the center of the SDRs. Plate tectonic reconstruction possibly including consideration of ductile deformation can be both beneficial to and benefit from a more precise location of the COT.

Possibly the most conclusive proofs for the validity of Wegener's (1912) concept were the discovery, description and interpretation of magnetic seafloor striping (Vine & Matthews, 1963). This phenomenon reflects reversals of the Earth's magnetic field embedded in magnetizable rocks and due to the continuing work on geologic timescales can be used to date almost any given section of oceanic crust on the planet. The stripes are called magnetic Chrons or seafloor spreading magnetic anomalies, as they are dependent on the onset and later speed of seafloor spreading and thus the production of oceanic crust. However, especially important for the South Atlantic, the dating of individual Chrons is subject for debate, as varying absolute ages are applied to the same anomaly by different authors. For example, Gradstein et al. (1994) suggested an age of 121 Ma for Chron M0 but changed this to 125 Ma in later versions of their timescale (Gradstein et al., 2004; Gradstein et al., 2012). Their rearrangement was disputed by some authors (e.g. He et al., 2008; Torsvik et al., 2009). For the vast majority of the scientific community this discussion means an inclusive use of timelines and no real bias towards either version is noticeable (e.g. Seton et al, 2009; Tominaga and Sager, 2010; Malinverno et al., 2012; Heine et al., 2013).

While the research presented in this thesis is far from being on a small or local scale, there have been a number of far more regional plate reconstruction publications (e.g. Rabinowitz and LaBrecque, 1979; Campan, 1995; Marks and Tikku, 2001; Eagles, 2007; Torsvik et al., 2009; Moulin et al., 2010; Heine et al., 2013) on the opening of the South Atlantic (or more). The further backwards in time the reconstructions go, the fewer data can be used for calibration, resulting in a necessary loss of complexity and / or resolution in time and / or space. Younger Chrons than M7 typically are covered by more publications (e.g. Curie, 1984). Especially magnetic data for the early phase of seafloor spreading are sparse, demanding the use of proxies such as structural and stratigraphic data. The reconstruction for the South Atlantic presented by Heine et al. (2013) is the first to cover Base Cretaceous, and the shown reconstruction to magnetic Chron M4 (Fig. 4) from that publication underlines the importance of magnetic data in the south of the area studied in this thesis, where the break-up was more complex than further north. Moulin et al. (2010) propose the onset of strike-slip movements with the South American basins for magnetic Chron M7. Nürnberg and Müller (1991) and Lawver et al. (1998) both implicate the Paraná Basin in Brazil as the main recipient of tectonic deformation. As most large-scale reconstructions do not include ductile deformation and work with constant plate and / or sub-plate sizes, Torsvik et al. (2009) defined the COB from calculated stretching values and gravity maps. The non-deformational model proposed early on by Martin et al. (1982) was refined by König & Jokat (2006). Quirk et al. (2013) propose a break-up at the start of the Aptian (123 Ma) which is 10 Ma before what was previously suggested by other authors.

The extensive survey presented by Moulin et al. (2010) on possible intraplate deformation within South America and Africa achieves misfits below 30 km which the authors mostly blame on the lack of quality magnetic data. On the other hand, as onshore geologic proof for their pr oposed deformation zones is also weak a larger actual misfit seems realistic. While there are fewer models for the less prominent Chron M2 (Nürnberg & Müller, 1991; König & Jokat, 2006; Moulin et al., 2010), Chron M0r received a lot of scientific attention due to its importance for the proto-South Atlantic (Rabinowitz & LaBrecque, 1979; Nürnberg & Müller, 1991; Schettino & Scotese, 2005; König & Jokat, 2006; Eagles, 2007; Torsvik et al., 2009; Moulin et al., 2010; Heine et al., 2013). M0r is commonly regarded as the first magnetic anomaly in all of the South Atlantic. According to Moulin et al. (2010), the widespread salt distribution, or rather the not properly confined limits of the salt provinces, in the Central and Equatorial Atlantic segments lead to gaps and overlaps in most reconstruction models (Rabinowitz & LaBrecque, 1979; Unternehr et al, 1988; Moulin et al., 2010). Even with the more prominent seafloor spreading anomalies after the magnetic quiet zone, slight differences in plate reconstruction model results are evident, with at times huge difficulties to correctly match magnetic chrons and fractures zones (Chron C34; Campan, 1995).

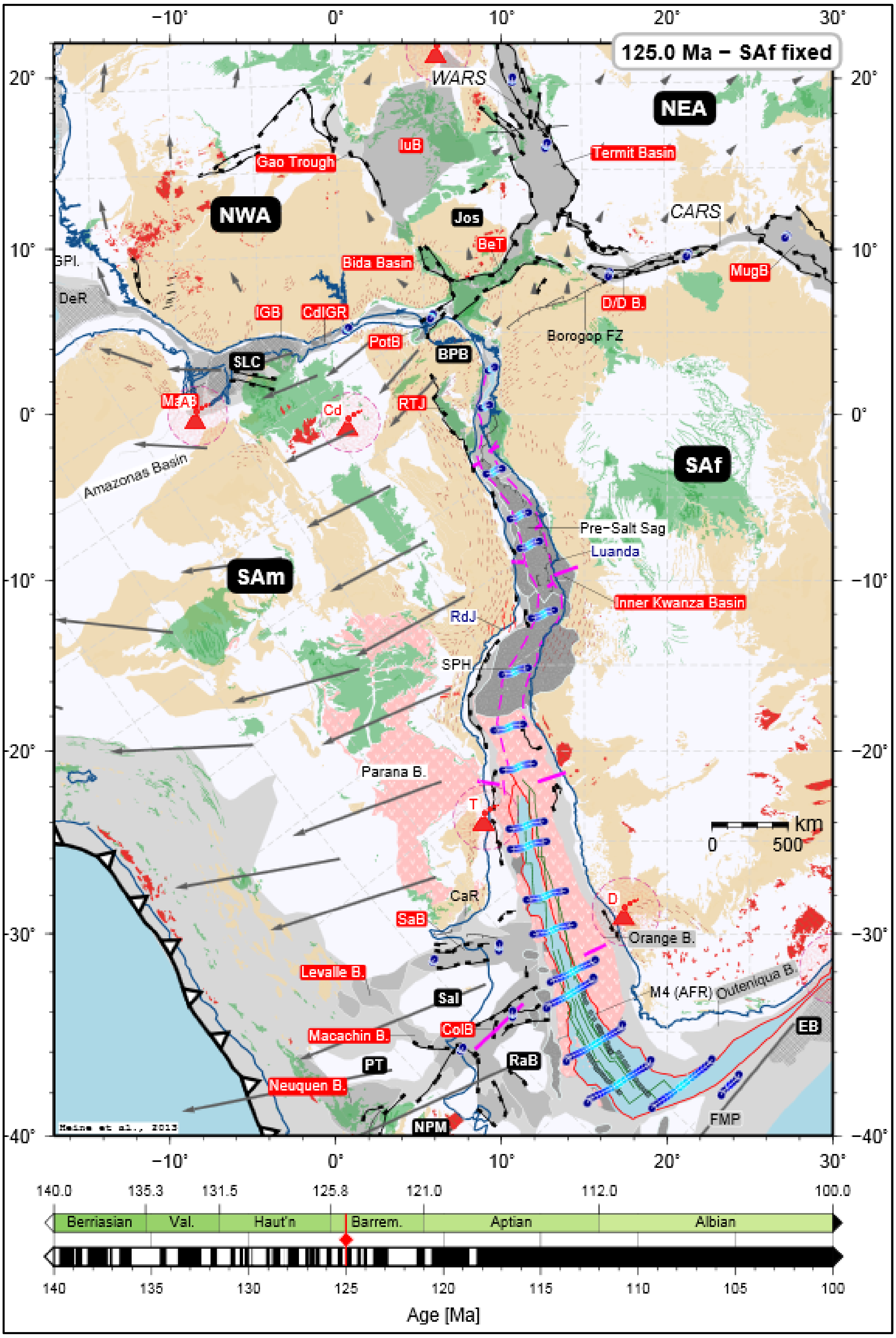


Fig. 1.4: Example of a recent publication on South Atlantic plate reconstruction (from: Heine et al., 2013): Reconstruction to Magnetic Anomaly Chron M4 (125 Ma in Heine et al., 2013; 130 Ma based on the timescale from Gradstein et al., 2004). Note the importance of magnetic anomaly information in the south of the South Atlantic (older part of the oceanic basin), where the opening history is more complex than after successful opening of the whole South Atlantic.

To further increase plate reconstruction models, more structural data in better quality is necessary and has been made available for the South Atlantic in recent years both on- and offshore. Margin-parallel structures and geology have been studied recently along the conjugate margins (e.g. Becker et al., 2012; Blaich et al., 2009; Blaich et al., 2011; Fernàndez et al., 2010; Franke et al., 2007; Franke et al., 2010; Hartwig et al., 2012; Heine et al., 2013; Hirsch et al., 2009; Hirsch et al., 2007; Koopmann et al., 2014b; Moulin et al., 2010; Paton et al., 2007; Schnabel et al., 2008; Soto et al., 2011; Will & Frimmel, 2013). The importance of Cretaceous-aged basin orientation for the start of the rift phase has been pointed out by Moulin et al. (2010) and Heine et al. (2013) and is also discussed regarding its implications on mono-phase rifting in Chapter 3 of this thesis.

The dataset available for the compilation of this thesis offers a unique opportunity in both coverage and previous data unavailability to address the poorly constrained initial rifting phase of the South Atlantic rift system. The main proxies for this are the thick layers of volcanic material and the magnetic anomalies. Together with the deep, refraction seismic profiles (Bauer et al., 2000; Schnabel et al., 2008; Becker et al., 2014), the seismic dataset can be used for insights of the very early rift phase of the South Atlantic before 130 Ma (Magnetic Chron M4). While the most important proxy is the distribution of extrusive volcanics offshore South America (as described by Franke et al., 2007) and South Africa (Chapter 2), the magnetic data (Chapter 3) are a much welcomed fill for the data gap previously existing offshore Argentina. With the data this early phase of rifting can be investigated with confidence on the conjugated margins of South Africa and South America and the quality of previously published reconstructions on this comparably small scale can now be evaluated. Due to their large regional scope and the previous lack of magnetic lineations as old as M9 in the southernmost South Atlantic, significant shortcomings of existing models can be expected.

While the exact mode of SDRs emplacement remains up for debate, the most common agreement is that the SDRs should be mostly symmetrical for conjugate margin sections (see Chapter 3 for discussion on (a)symmetry). Most models assume that the landward most SDRs cover (albeit extended) continental crust. For the South American margin, the analysis of the internal structure and segmentation proved to be a great proxy for margin development (Franke et al., 2010). Studying the symmetry of the two margins therefore is the obvious choice to achieve improvement of the break-up models. Segments along the margin are separated by lithosphere-scale transfer zones, which can but not necessarily have to coincide with the strike (i.e. direction) of present-day oceanic fracture zones and might be depending on inherited crustal structures. The symmetry of high-velocity lower crustal bodies (HVLC; Becker et al., 2014) along the margins can further be linked to break-up processes such as variations in the amount of extension and melt produced, potentially testing the proposal of localization of crustal thinning to be the focus for melt production instead of mantle temperatures (Armitage et al., 2010). Since rift basins seem to be only present on one of the South Atlantic margins (i.e. the Orange and Walvis Basins on the African side), the South Atlantic rift has been proposed to have employed a simple-shear rift mechanism. As no rift-graben proper has been described from the data on either margin, there is debate about whether it is an imaging problem beneath the SDRs units, similar to the masking of structures beneath salt structures. It is evident that conjugate studies are crucial for the understanding of the complex rift system in the South Atlantic (Chapter 3). Focus points of conjugate studies have to be on symmetry and asymmetry of lithospheric thinning, HLVCs, SDRs as well as sedimentary basins along the margins. While not part of this thesis, a brief comparison of the magnetic data presented in Chapter 3 with published reconstruction poles (Eagles, 2007; Heine et al., 2013; Moulin et al., 2010; Nürnberg and Müller, 1991; Rabinowitz and LaBrecque, 1979; Torsvik et al., 2009) show that these data will improve plate reconstruction models in the future, especially for the very early period of South Atlantic continental break-up. The investigation of the offshore volcanic structures on both conjugate margins should also increase the plate reconstruction, as it can potentially help with defining aligned plate segments.

Break-up of the South Atlantic is widely agreed to have happened in a manner best described as a northward propagating (Martin, 1984) unzipping or “zipper-like” opening (Jackson et al., 2000) of the continental plates. Individual margin segments in this scenario might be more or less triangular with variations in stretching across the margin. Variations in extension rates within each segment have also been linked to variations in apparent melt generation as reflected in the distribution of SDRs (Franke, 2013). Of course, as is the case with most concepts, the zipper notion is not the only model for continental break-up in the South Atlantic (or for all break-up systems). Other popular ideas include the instantaneous break-up of long margin sections, punctual seafloor spreading or asymmetric rifting. And indeed, although large parts of the data in the South Atlantic agree with the zipper model, some features do not, for example the coast-parallel magnetic anomalies north of 32°S offshore South Africa and north of 28°S offshore South America. Poly-phase faulting, depth-dependent stretching, relevance of the detachments faults and behavior of the lower crust might have been part of the South Atlantics continental break-up. Again, with the volcanic units visible as SDRs in the seismic data serving as the main focus of this thesis, their emplacement mechanism and factors playing in their formation are crucial. Break-up velocity has previously been named as one of the most important factors to control the amount of volcanism in rift systems and accordingly the influence of break-up velocities and rift delay at transfer zones is tested in the numerical models presented in Chapter 4. Rift delay at segment boundaries (Chapter 2) or transfer zones (e.g. Franke et al., 2007) is supposedly another important factor in determining volcanic activity. Segment boundaries are discontinuities supposed to decouple margin segments to form individually rifting segments, likely forming at least partially localized melting chambers. The proposal of potentially increased melt production is tested in Chapter 4.

1.3 Volcanism, crustal structures and margin architecture in the South Atlantic

The passive volcanic continental margins (Fig. 5) along the South Atlantic provide an excellent view of fundamental and important geological processes such as continental break-up (e.g. Turner et al., 1994), subsequent subsidence (e.g. Maslanyi et al., 1992), accompanying sedimentation (e.g. Wickens & McLachlan, 1990) and also about the development of oceanic currents (e.g. Gruetzner et al., 2011). The massive volcanic layers along the margins, the seaward-dipping reflector sequences (SDRs; Chapter 2) provide valuable input regarding the importance of the Tristan hot-spot with respect to the opening of the South Atlantic along the Argentinean and southern African conjugate margins. Accordingly, the major aim of this thesis was the processing of the seismic data acquired offshore southern Africa in 2003 by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) during the Break-up Of the South Atlantic expedition (BOSA; Schreckenberger & Shipboard Scientific Party, 2003) and the subsequent detailed interpretation of the data and the integration of the results into revised models, concepts and ideas regarding the continental break-up of the South Atlantic. These data are unique and comparable data have not been published before.

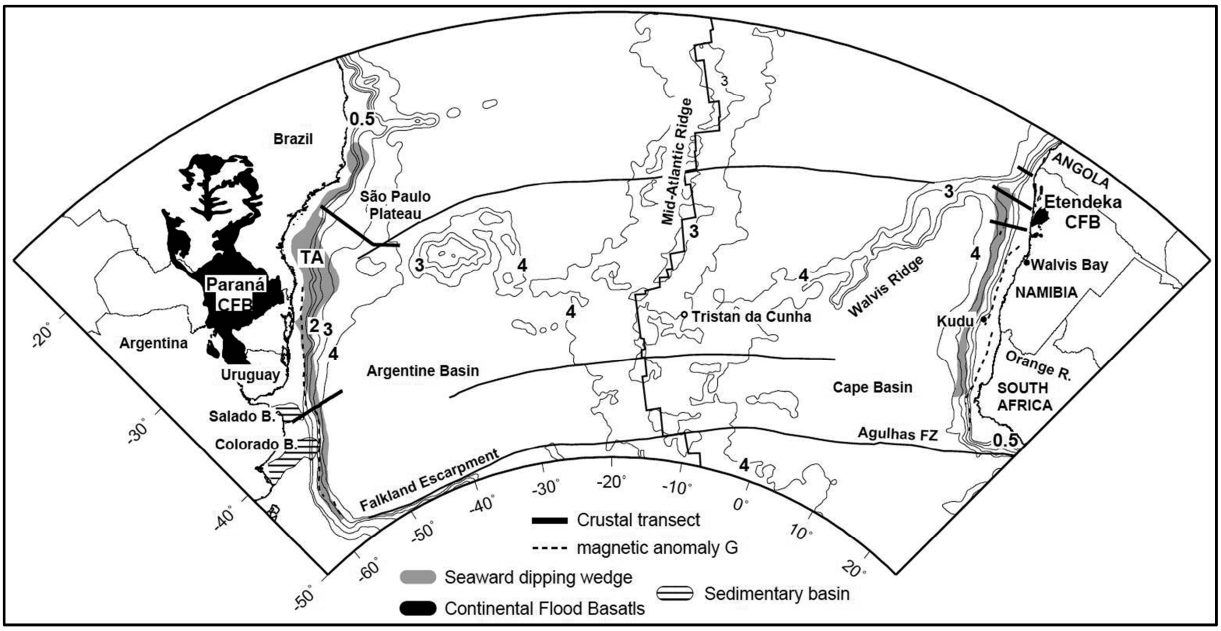


Fig. 1.5: Tectono-magmatic features of the South Atlantic passive continental margins (from: Gladczenko et al., 1997; therein compiled from Rabinowitz & LaBrecque, 1979; Austin & Uchupi, 1982; Andreis et al., 1987; Cande et al., 1989; Goncalves de Souza, 1991; Chang et al., 1992; Milner et al., 1992; Turner et al., 1994; Gladczenko, 1994 and Hinz et al., 1995)

The continental margins of the South Atlantic are important for understanding the continental break-up of Gondwana and the related mantle dynamics. Active, hot-spot related upwelling, increased mantle temperatures with or without hot-spot input and a mainly adiabatic partial melting passive model are the most important concepts for what might be happening beneath disintegrating continents. The area investigated in this study is situated at the very distal end of the Tristan hot-spot diameter suggested by White & McKenzie (1989) and some 1200 km away from the hot-spot trace, i.e. the actual surface expression of the Tristan hot-spot. Accordingly, the question of an active or passive mantle and the importance of deep hot-spots can be addressed partly with the data presented here.

After the break-up of Antarctica from Gondwana in the Upper Jurassic (Jokat et al., 2003), the South Atlantic continued the disintegration of the super-continent when opening northwards in the Early Cretaceous. The break-up of the Atlantic left behind two major structural provinces divided by the Rio Grande (or, used interchangeably in the literature: Florianopolis) Fracture Zone and indicated by changes in bathymetric and lithospheric character. The dominantly volcanic part that is also the focus of this thesis lies between the Falkland-Agulhas Fracture Zone and the Florianopolis Fracture Zone. The volcanic character is shown by the seaward-dipping reflectors in marine seismic data sets on the conjugate southern Africa and Argentinean margins. North of the Florianopolis Fracture Zone, along the passive conjugate margins of Angola, Congo and Gabon and eastern Brazil, the break-up volcanism is overshadowed by syn- and post-rift deposition of massive amounts of salt of Aptian age alongside carbonate platforms and the sedimentation of clastic material.

The continental margins along the South Atlantic are prime examples for the passive volcanic rifted continental margin type which is marked by abundant volcanic activity within a narrow time window (e.g. HInz, 1981; White &McKenzie, 1989; Holbrook & Kelemen, 1993; Eldholm et al., 2000; Menzies et al., 2002; Mjelde et al., 2002). While the existence of thermal anomalies at depth and hot-spot tracks at the surface are widely accepted geological features, it is still unclear if hot-spot activity is connected to large igneous provinces (LIPs) and if these in return are connected to the formation of volcanic continental margins or not. The relevant volcanic provinces in the study area, the Paraná-Etendeka LIPs in Brazil and Namibia were emplaced during a time of peak activity between 133 and 129 Ma (e.g. Renne et al., 1992; Stewart et al., 1996; Peate, 1997; Hawkesworth et al., 2000; Menzies et al., 2002). Recent confirmations of the south to north directed relayed opening of the South Atlantic question the validity of proposing the Tristan hot-spot as the trigger for the South Atlantic continental break-up as for example discussed by White & McKenzie (1989). As further discussed in Chapters 2 and 3, the hot-spot was centered some 2000 km north of the locus of first oceanic crust. There are a number of reasons to doubt a deep hot-spot as the only possible major source of magmatic activity at volcanic margins (Péron-Pinvidic et al., 2009), encouraging the look for different concepts. These could include simple heterogeneities in mantle properties, crustal delamination, small-scale convection or crustal structures which could potentially alter melt properties (e.g. Holbrook et al., 2001; Menzies et al., 2002; Korenaga, 2004; Meyer et al., 2007; Franke et al., 2010; Armitage et al., 2010). The South Atlantic continental margins (Fig. 5) between the Falkland-Agulhas Fracture Zone in the south and the Florianopolis Fracture Zones in the north are classified as of the passive rifted volcanic margin type (Gladczenko et al., 1997; Hinz et al., 1999; Bauer et al., 2000; Franke et al., 2007). This conclusion is derived mainly from geophysical investigations of the massive volcanic extrusive units, observable in seismic data as seaward-dipping reflectors (SDRs) and further in magmatic underplating (Schnabel et al., 2008). These volcanics offer a tremendous amount of information and when properly mapped, can also provide information on the continental break-up history.

The German Federal Institute for Geosciences and Natural Resources (BGR) acquired a total of 39100 km of reflection seismic data between 1978 and 2004 offshore Argentina and Uruguay (BGR78: 2900 km, BGR87: 3700 km, BGR91: 4500 km, SO85: 7000 km, BGR95: 5,100 km, BGR98: 12,100 km, BGR04: 3,800 km).Further, four research cruises were conducted by the BGR between 1991 and 2003 along the continental margin of western Africa and 12200 km of MCS data were gathered (BGR91: 4200 km of MCS data; SO85: 1900 km; BGR95: 2800 km; BGR03: 3300 km). During the research cruises, eight seismic refraction traverses were acquired to further image the study area along the conjugate southern African and South American margins. The datasets formed the basis for an impressive number of research papers (Gladczenko et al., 1997; Hinz et al., 1999; Bauer et al, 2000; Franke et al., 2006; Franke et al., 2007; Schnabel et al., 2008; Hirsch et al., 2009; Franke et al., 2010; Grassmann et al., 2011; Becker et al., 2012) and in addition for the results presented here and in the related research papers (Koopmann et al., 2014b; Koopmann et al., 2014c) forming chapters 2 and 3 of this thesis.

The detailed description of the South American margin based on BGR multi-channel seismic data was unmatched prior on the conjugate African to this project and the writing of this thesis and the corresponding research papers. The processing, interpretation and subsequent integration into geologic models were the main tasks for this thesis. As pointed out in Chapter 1.2, the South Atlantic continental margin show evidence of widespread volcanism related to the Early Cretaceous break-up, dividing a typical margin section in distinct parts, all buried by a sedimentary cover ranging from post-break-up to Cenozoic ages (Figs. 6 & 7): On the outer shelf, syn- and pre-rift features can be observed. The slope is dominated at depth by the seaward-dipping reflectors (see also Chapter 2) and is followed by oceanic crust proper further seaward. The location and depth of the lithosphere-mantle boundary (the Mohorovic discontinuity; Moho) can be described more accurately based on wide-angle refraction seismic data (e.g. Bauer et al., 2000; Temmler, 2005; Schinkel, 2006; Hirsch et al., 2007; Schnabel et al., 2008; Becker et al., 2014) and are not a major focus of this thesis. The wide-angle data were used by Bauer et al. (2000), Temmler (2005), Schinkel (2006), Schnabel et al. (2008) and Becker et al., 2014) to study deeper crustal structures, confirming the deep structure typical for volcanic margins. This architectural style includes a very distinctive high-velocity lower crustal body (HVLC). This body varies in size, seismic velocities (up to 7.5 km/s) and relative location on the continental margin relative to oceanic crust and SDRs.

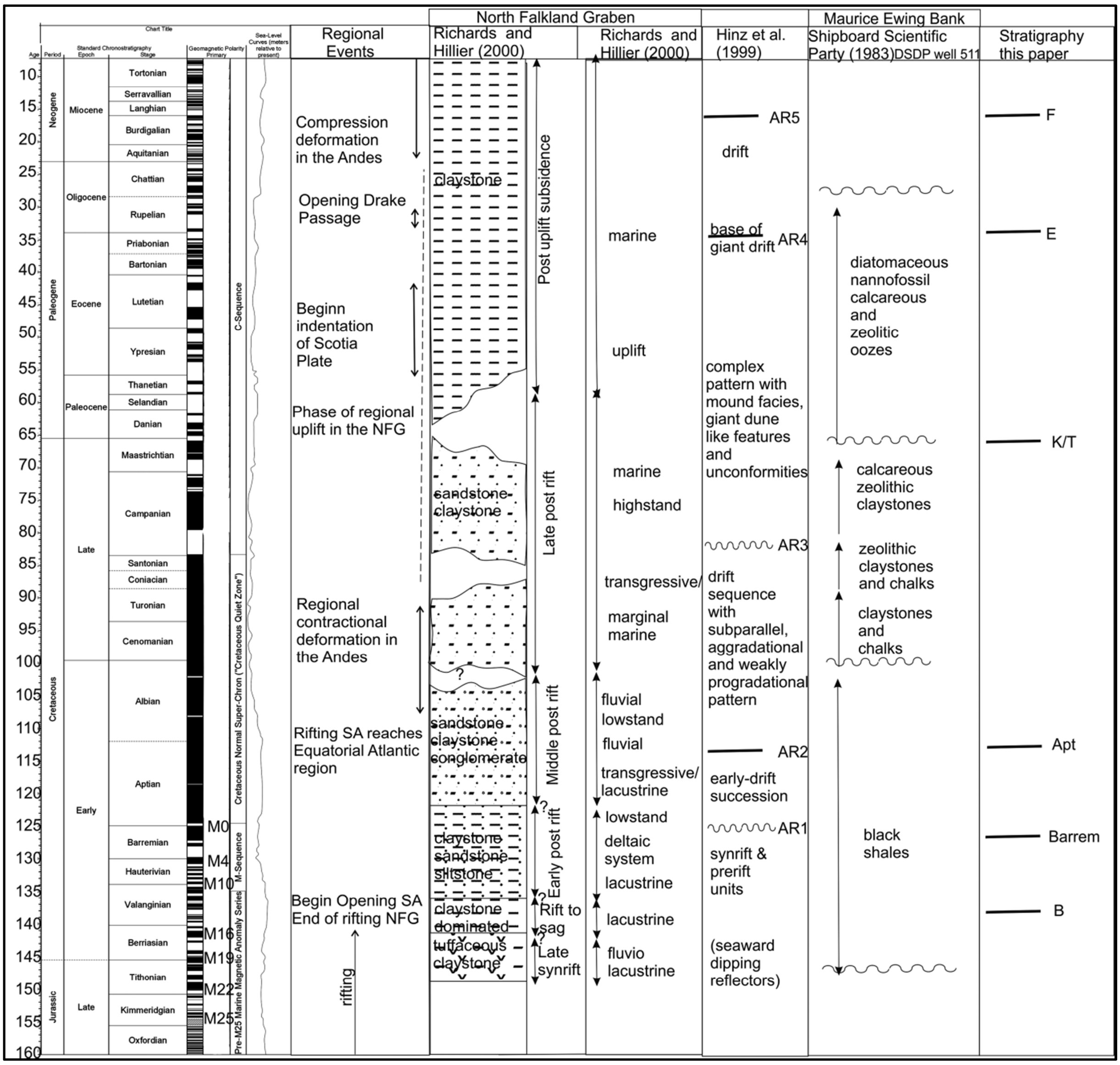
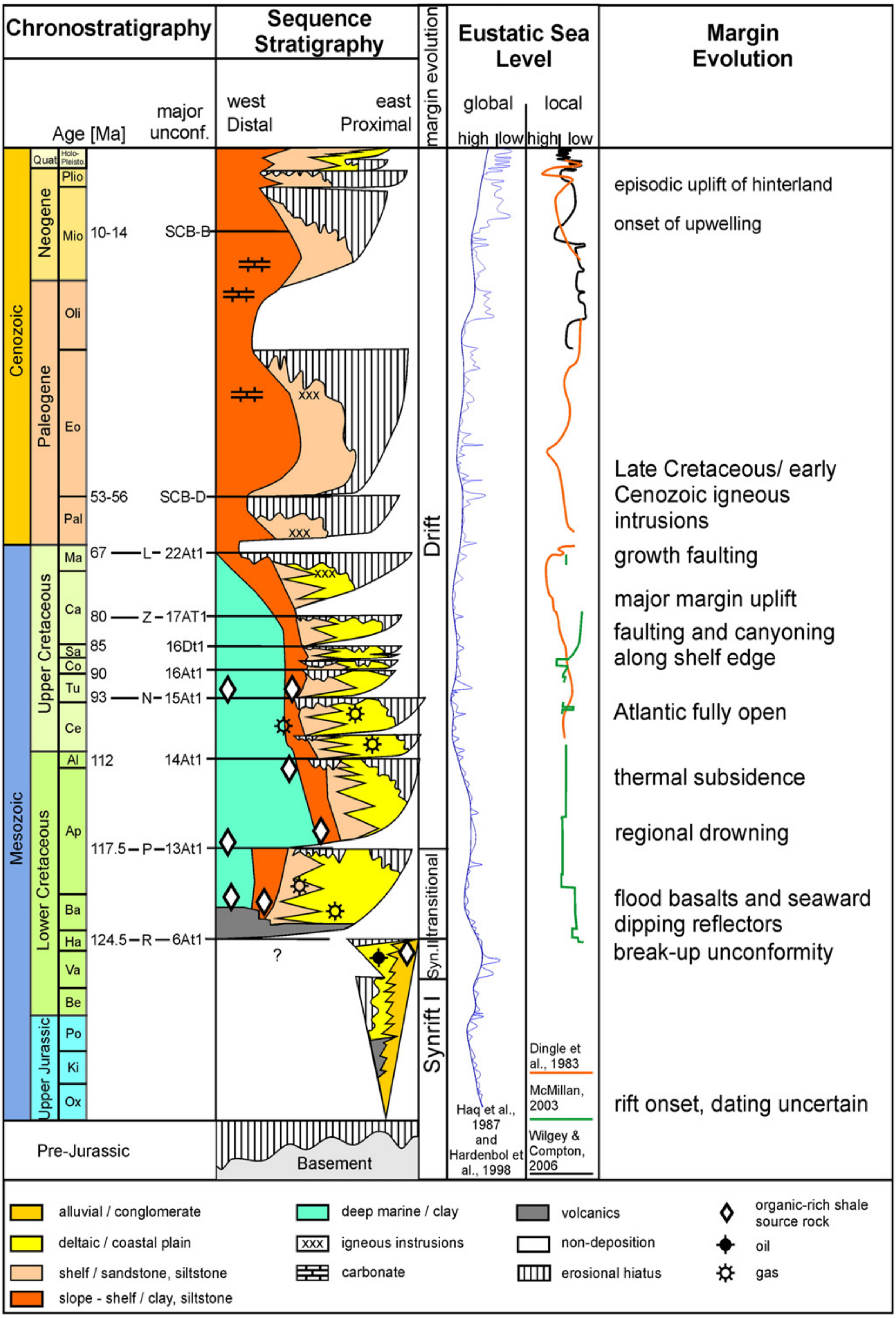


Fig. 1.6: Stratigraphy of the North Falkland Graben (NFG) on the South American showing major sequence stratigraphic horizons and the generalized margin evolution (from: Becker et al., 2012; therein compiled from DSDP well 511 - Shipboard Scientific Party, 1983; Fitzgerald et al., 1990; Hinz et al., 1999; Rodriguez & Littke, 2001; Lawrence et al., 1999; Richards & Hillier, 2000 and Richardson & Underhill, 2002).

Fig. 1.7 (next page): Stratigraphy of the Orange Basin on the southern African margin showing major sequence stratigraphic horizons, sea level variations and the generalized margin evolution (from: Hartwig et al., 2012; therein modified from Broad et al., 2006; with Cenozoic ages from Weigelt & Uenzelmann-Neben, 2004; sea level curves from Dingle et al., 1983, Haq et al., 1987, Hardenbol et al., 1998, McMillan, 2003 and Wigley & Compton, 2006).


Chronostratigraphy
Sequence Stratigraphy
margin evolution
Eustatic Sea Level
Margin Evolution
Age [Ma]
major unconf.
west Distal
east Proximal
global
local
high low
high low
Cenozoic
Neogene
Paleogene
Quat
Holo-Pleisto
Plio
Mio
Oli
Eo
Pal
Mesozoic
Upper Cretaceous
Lower Cretaceous
Upper Jurassic
Ma
Ca
Sa
Co
Tu
Ce
Al
Ap
Ba
Ha
Va
Be
Po
Ki
Ox
10-14 SCB-B
53-56 SCB-D
67 L 22At1
80 Z 17AT1
85 16Dt1
90 16At1
93 N 15At1
112 14At1
117.5 P 13At1
124.5 R 6At1
?
Drift
transitional
Syn.II
Synrift I
Pre-Jurassic
Basement
Haq et al., 1987 and Hardenbol et al., 1998
Dingle et al., 1983
McMillan, 2003
Wilgey & Compton, 2006
episodic uplift of hinterland
onset of upwelling
Late Cretaceous/ early Cenozoic igneous intrusions
growth faulting
major margin uplift
faulting and canyoning along shelf edge
Atlantic fully open
thermal subsidence
regional drowning
flood basalts and seaward dipping reflectors
break-up unconformity
rift onset, dating uncertain
alluvial / conglomerate
deltaic / coastal plain
shelf / sandstone, siltstone
slope - shelf / clay, siltstone
deep marine / clay
igneous instrusions
carbonate
volcanics
non-deposition
erosional hiatus
organic-rich shale source rock
oil
gas

The thermal structure of the South Atlantic is comparatively uncharted. As the amount of volcanism and the relevant ages vary a lot between the South Atlantic and the North Atlantic, the findings from the more intensely studied North Atlantic offshore the US East Coast and the Thule province of Greenland (Lizarralde & Holbrook, 1997; Holbrook et al., 2001, respectively) can probably not be assumed to be true for the focus area of this thesis, the South Atlantic. However, the shallower volcanic extrusives (SDRs) seem comparable if not very similar. Episodicity has been suggested for their emplacement, based on these distinctive reflectors within the SDR units (Franke et al., 2007) and is also discussed for its southern African conjugate margin (Chapter 2). Based on the mapping of these volcanic units, the Argentinean margin has been divided into four larger segments (Fig. 8) between the Falkland Fracture Zone and the northern end of the dataset, namely called the Colorado Transfer, the Ventana Transfer and the Salado Transfer (Franke et al., 2007)

The studies on the Argentinean margin by Franke et al. (2007), Franke et al. (2010) show that the southernmost margin segment north of the Falkland-Agulhas Fracture Zone is magma-poor. Supporting the notion of an Atlantic opening starting in the south, Becker et al. (2012) suggest oceanic crust of pre-Barremian age in the vicinity of the Falkland-Agulhas Fracture Zone based on the extrapolation of North Falkland Basin seismic stratigraphy (Fig. 6). Further, it was also suggested by Franke et al. (2010) that the transition from the oldest, southernmost, magma-poor segment to the highly volcanic, SDRs dominated segment further north takes place within a matter of few kilometers at the Colorado Transfer Zone. Comparable margin segmentation has been reported previously for the Namibian margin (Clemson et al., 1997) and is the subject of Chapter 2 of this thesis. Segmentation is defined by multiply named segment boundaries (“transfer zones”, “accommodation zones” or “relay zones”). Structures like this have been reported elsewhere on the planet and in different rift systems (Fig. 9) and incorporated into analogue models (e.g. Corti et al., 2002; Corti et al., 2003) and the numerical models presented in Chapter 4 of this thesis. These segment boundaries are frequently described as reactivated inherited crustal structures, which in succession then might be the source for present day oceanic transform faults during the very beginning of oceanic crust formation (Olesen et al., 2007). Volcanic facies and structural differences along the margins can be used to determine the location of segment boundaries / transfer zones.

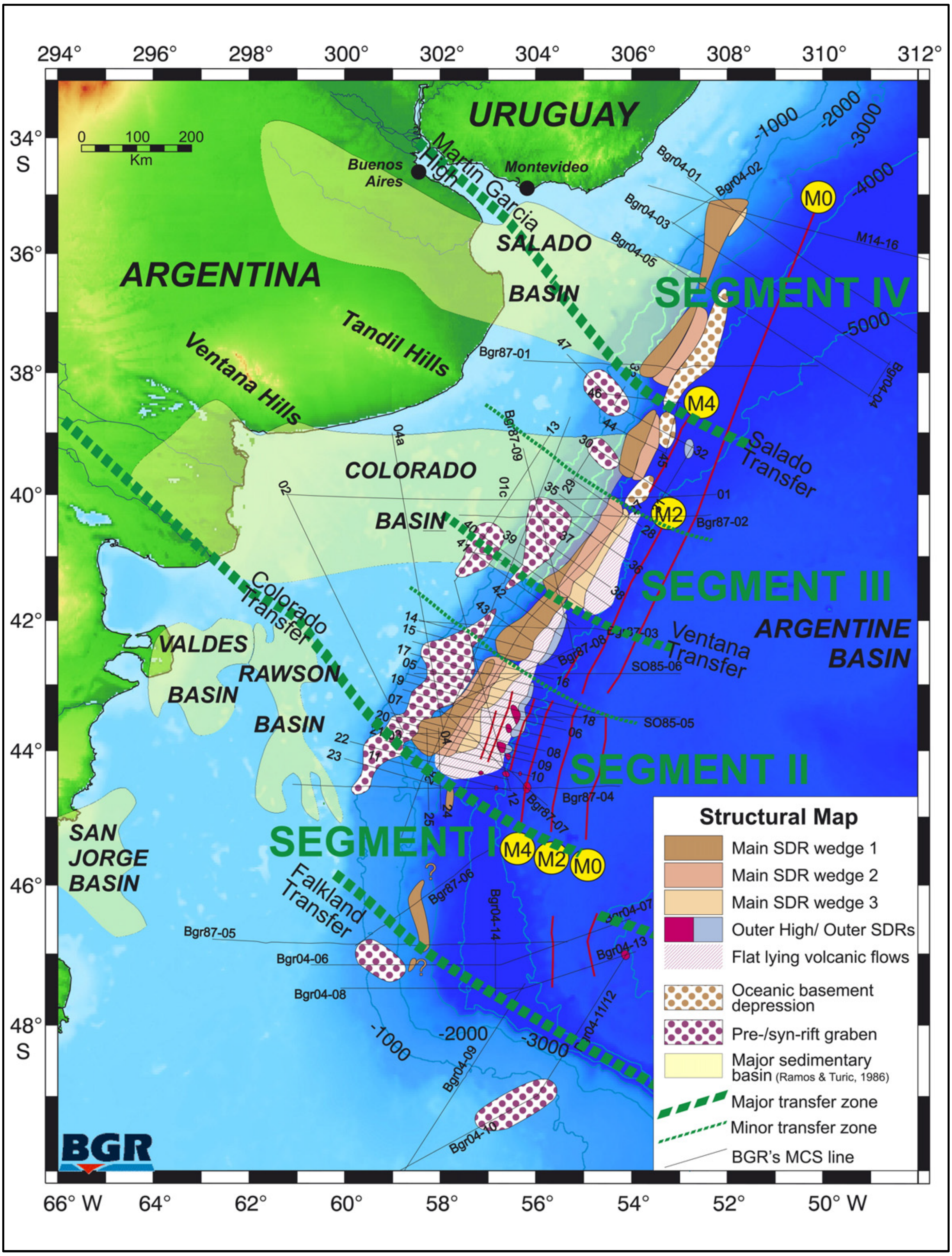


Fig. 1.8: Tectono-magmatic structures of the south American continental margin showing the distribution of offshore volcanic effusives (seaward dipping reflector sequences, SDRs) and the transfer zones derived from changes in their distribution (from: Franke et al., 2007; sedimentary basins therein from Ramos & Turic, 1996).

Implications on margin evolution and spreading history can of course also be made onshore, where for example Will & Frimmel (2013) present a multi-mode model for the direction of principal stress during extension in the Cretaceous (Fig. 10), indicating a change in direction of stress, which is also discussed in Chapter 2 and 3 of this thesis. The numerical model presented in Chapter 4 tests the hypothesis if adiabatic decompression and melt generation from shallow sources in combination with the supposed focusing effect of transfer zones on melt production location may explain some of the features found offshore South America and South Africa. For example, there is an apparent decrease within rift segments from one segment boundary to the next (Franke et al., 2007). The model results presented in Chapter 4 have also been published (Koopmann et al., 2014a).

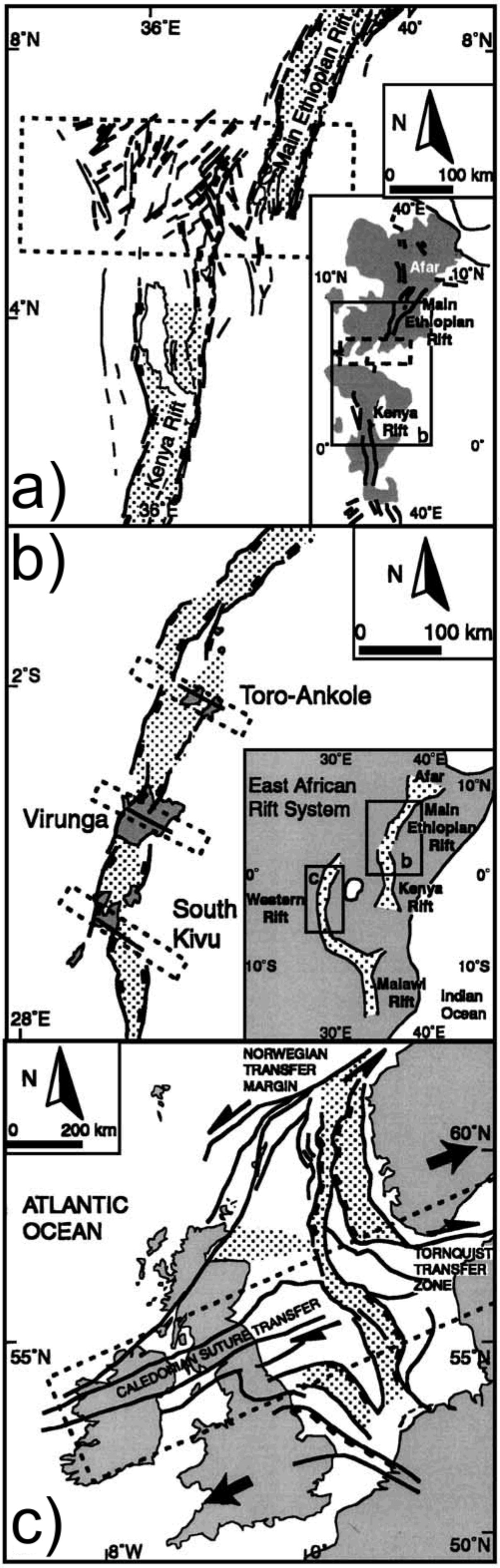


Fig. 1.9: Simplified sketch-maps of natural rift systems incorporating transfer zones (from: Corti et al., 2002; therein a) after Moore & Davidson, 1978; b) after Rosendahl, 1987 and Ebinger, 1989; c) after Gibbs, 1989): a) East African Rift System (Ethiopian and Kenyan part); b) western part of the East African Rift System; c) British Isles.

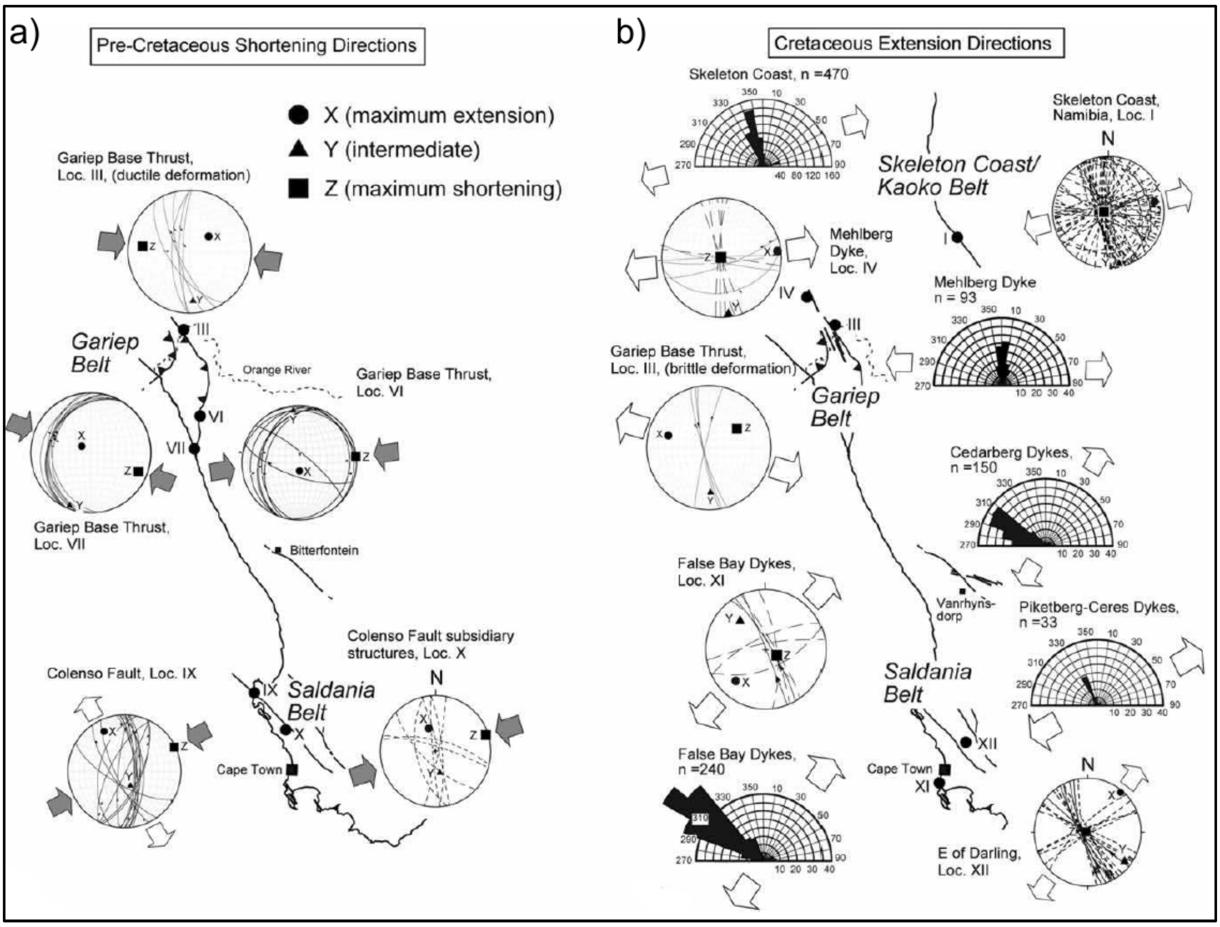


Fig. 1.10: Paleo-stress direction of South Africa and Namibia, as derived from onshore measurements (from: Will & Frimmel, 2013: a) Pre-cretaceous shortening directions; b) Cretaceous extensional directions: note the rotation of direction).

In their extensive plate reconstruction model, Heine et al. (2013) go back to Base Cretaceous plate positions by integrating structural information from basins along the conjugate continental margins, eliminating the need for major intracontinental shear zones. The model also includes a change a spreading direction during the early rift phase, potentially implying obliquity. Crustal-scale gravity modelling along the conjugate South Atlantic margins reveals the crustal architecture and the relationship of crustal features to variations in the potential field data (Blaich et al., 2009). One of the main issues dealt with in their study was the constraint of the continent-ocean boundary – Blaich et al. (2009) conclude that it is more likely to be a transition zone (see Chapter 5). In a recent review paper, lithospheric processes, including rift propagation and propagation barriers (see also Chapter 4) are proposed as major controlling factors for margin evolution (Franke, 2013). It is further suggested that a deep, mantle source for rift evolution and rift-related volcanic activity is not directly observable in the in the investigated areas within the Arctic Ocean, the South China Sea and the South Atlantic (Franke, 2013). The approach of showing conjugated margin sections in the South Atlantic (Chapter 3) is only possible because of the excellent dataset available for this thesis and is comparatively new, as most previous studies were either limited to one side or did show only approximately conjugate margin sections which were in part compiled from previous studies (e.g. Blaich et al., 2009; Jackson et al., 2000; Mohriak et al., 2002; Talwani & Abreu, 2000). The detailed mapping of the spatio-temporal emplacement and development of the extensive volcanic activity of the southern African continental margin was the necessary first step (Chapter 2) which was in turn then followed by the analysis of properly conjugated seismic margin transects. As described in Chapter 1.2, the location of the COT must be a major focus point alongside the general crustal structure of the conjugated South Atlantic continental margins. The use of conjugate sections provides an increased certainty regarding this important aspect of continental break-up.

1.4 Multi-channel seismic data: acquisition to interpretation

In the following, I describe the basics behind the geophysical method of reflection seismic data as relevant to this thesis. It also includes a description of my specific work on the seismic data acquired by the Federal Institute for Geosciences and Natural Resources (BGR) in 2003, which I then used for the geological models and concepts presented in Chapters 2 to 4.

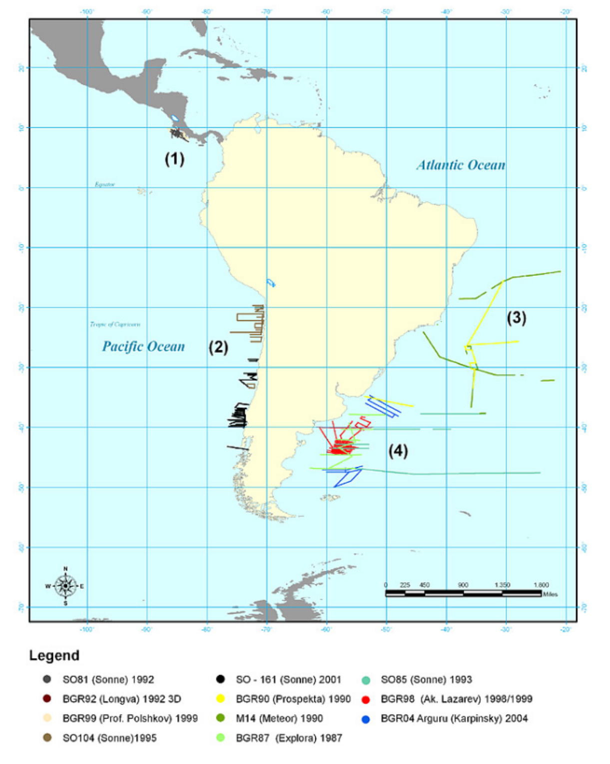
1.4.1 Introduction to multi-channel seismic data

Marine multi-channel seismic (MCS) data are acquired during logistically challenging marine expeditions and are the most important type of geophysical data used for this thesis. MCS data acquisition uses variations in the acoustic properties of different types of media, e.g. water, sand, carbonates etc. Acoustic waves pass through these media at varying speeds, for example ~1500 m/s for seawater, 1500-2500 m/s for clastic material and 3000-6000 m/s for carbonates (Yilmaz, 2001). At the contact interfaces between two acoustically different media, acoustic waves are reflected (or refracted, used in refraction seismic data acquisition). To receive MCS data, a controlled, artificial seismic energy sources is used (for example explosives or more commonly used in marine MCS data acquisition: air-pulse generators called air guns). The energy travels from this source through the strata and is reflected to be picked up by the receivers installed in what is called a streamer which is towed behind the research vessel and is essentially a long (several kilometers) cable with mounted hydrophones. As a wave travels from a given source to a boundary and after reflection back to a receiver, the recorded time between energy impulse and reception is called the two-way travel time (TWT) and is what is given on the vertical axes of the seismic sections shown in Chapters 2 and 3. After data registration, data are changed to electronic, digitally available data. The digitally available data have to be seismically processed before interpretation is possible, since the raw data are essentially not much more as seismic wavelets for each energy pulse, receiver and reflective surface.

1.4.2 Datasets used in this thesis

While the Federal Institute for Geosciences and Natural Resources (BGR) is active around the world conducting scientific research expeditions and marine geophysical cruises, relevant for this thesis are the datasets acquired in the South Atlantic. The BGR acquired a total of 39100 km of reflection seismic data between 1978 and 2004 offshore Argentina and Uruguay (Fig. 11; BGR78: 2900 km, BGR87: 3700 km, BGR91: 4500 km, SO85: 7000 km, BGR95: 5,100 km, BGR98: 12,100 km, BGR04: 3,800 km).Further, four research cruises were conducted by the BGR between 1991 and 2003 along the continental margin of western Africa and 12200 km of MCS data were gathered (Fig. 12; BGR91: 4200 km of MCS data; SO85: 1900 km; BGR95: 2800 km; BGR03: 3300 km). During the research cruises, eight seismic refraction traverses were acquired to further image the study area along the conjugate southern African and South American margins.

The datasets formed the basis for an impressive number of research papers (Gladczenko et al., 1997; Hinz et al., 1999; Bauer et al, 2000; Franke et al., 2006; Franke et al., 2007; Schnabel et al., 2008; Hirsch et al., 2009; Franke et al., 2010; Grassmann et al., 2011; Becker et al., 2012) and in addition for the results presented here and in the related research papers (Koopmann et al., 2014b; Koopmann et al., 2014c) forming chapters 2 and 3 of this thesis.



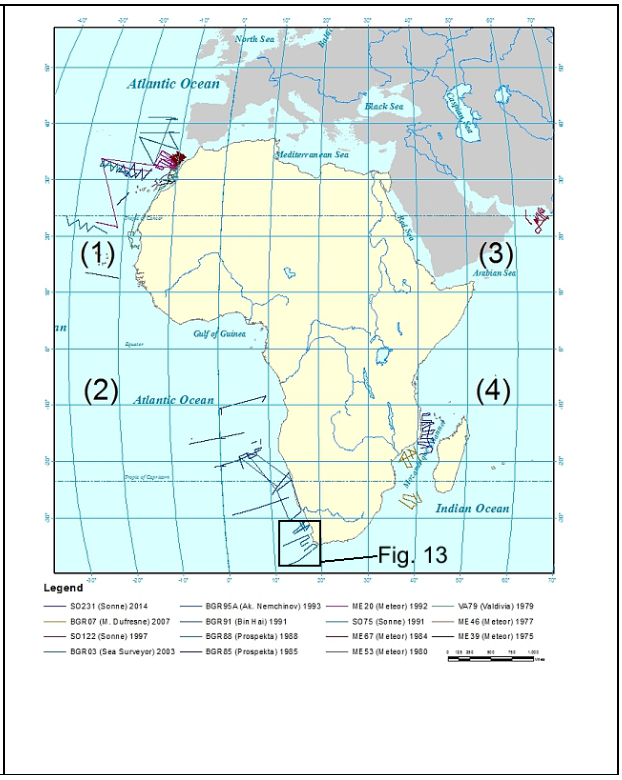


Fig. 1.11: Map illustrating the marine geophysical surveys conducted by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) offshore Middle- and South America (from: website of Bundesanstalt für Geowissenschaften und Rohstoffe. accessed 2014-May-25). Dataset 4 was used in this thesis (see Chapter 3).

Fig. 1.12: Map illustrating the marine geophysical surveys conducted by the Bundesanstalt für Geowissenschaften und Rohstoffe offshore Africa- and Pakistan (from: website of Bundesanstalt für Geowissenschaften und Rohstoffe. accessed 2014-May-25). Dataset 2 was used in this thesis (see Chapters 2 and 3). The box indicates the location of the 2003 BOSA cruise (Schreckenberger & Shipboard Scientific Party, 2003).

The 2003 Break-up Of the South Atlantic expedition (BOSA; Schreckenberger & Shipboard Scientific Party, 2003), gathered a unique geophysical dataset across the South African continental margin (Fig. 13). One of the main tasks behind this thesis was the seismic processing and interpretation of the gathered data to form a more conclusive picture of the southern African margin's architecture (Chapter 2 of this thesis) and the South Atlantic's continental break-up (Chapter 3 of this thesis). Besides the MCS data, gravity and magnetic geophysical datasets were also gathered (Schreckenberger & Shipboard Scientific Party, 2003). For acquisition of MCS data during the BOSA expedition, a then-new G-Gun twin sub-array system was employed. This system has a total volume of 50.8 l pressurized at 138 bar, was towed at a depth of 6 m and controlled by a Syntron GSC-90 system. The Syntron streamer used during the cruise consisted of 40 active seismic sections.

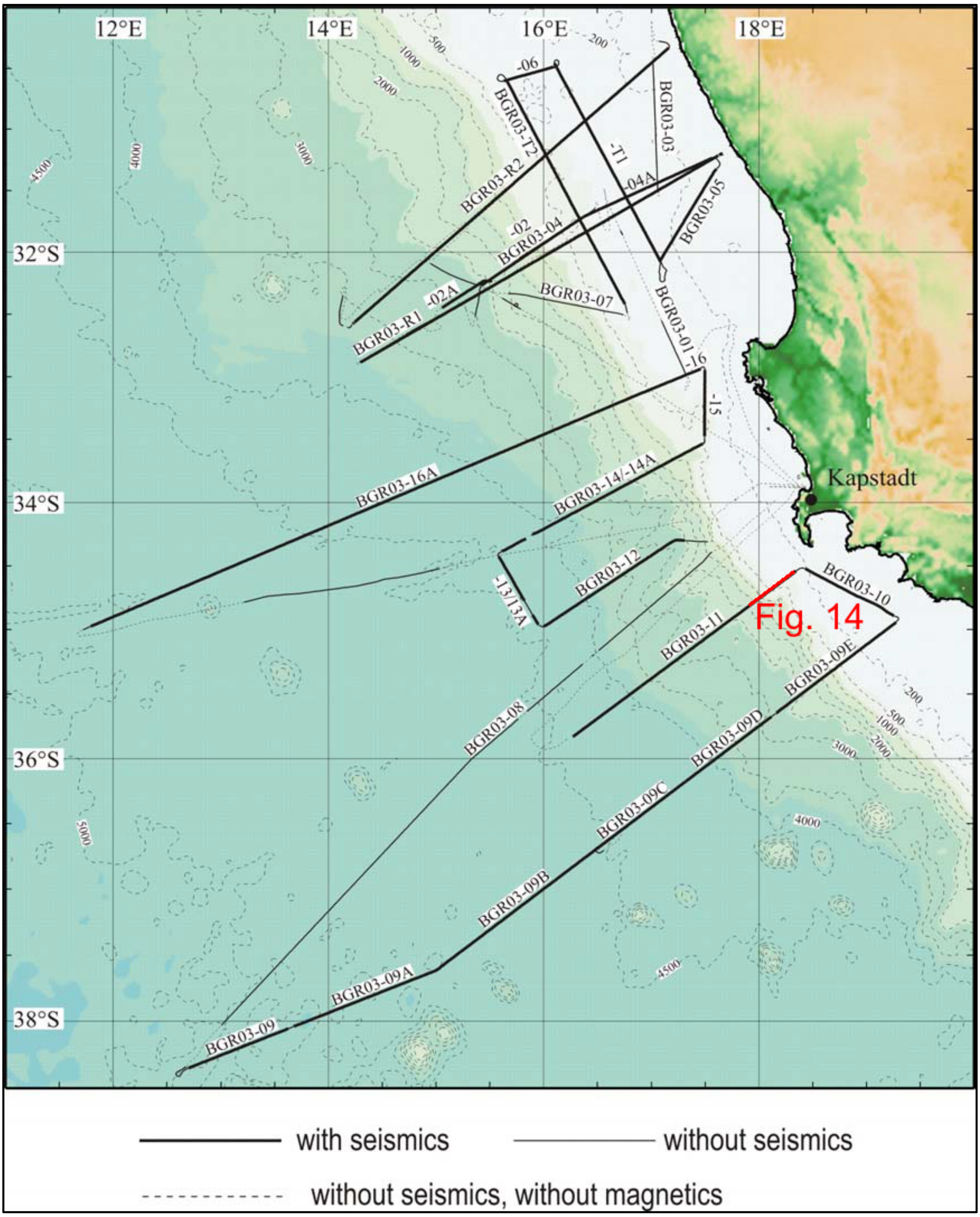


Fig. 1.13: Ship-track map of the 2003 BGR Break-up of the South Atlantic (BOSA) cruise (from: Schreckenberger & Shipboard Scientific Party, 2003). Geophysical data acquired during this cruise forms the basis of this thesis (see Chapters 2 and 3) and the multi-channel seismic (MCS) data was seismically processed by the author of this thesis (see also Fig. 14).

The signals were amplified, filtered, and analogue-digital converted by active electronic acquisition modules within the streamer before being recording by a Syntron 960 system. Depth and heading of the streamer was controlled by the Syntron Multitrak system which controlled the “birds”, winged units attached to the streamer to position the streamer at the desired depth. Towing depth varied between 9 m ± 1 m, 12 m ± 1 m and 14 m ± 1 m depending on weather conditions. Technical difficulties mandated the switch from 16 to 14 guns during the second leg of the cruise and the change in streamer geometry from 132 traces down to 120 traces from profile BGR03-12 onwards (Schreckenberger & Shipboard Scientific Party, 2003), also indicating the challenges faced by geophysical expedition crews. Data were sampled at a 4 ms rate and gathered using a shot point interval of 18 s ± 0.3 s (duration between energy pulses to achieve a shot distance of 50 m at a speed of 5.4 knots).

The magnetic data acquired during the BGR03 BOSA cruise cover almost 4800 kilometers, with 3700 km recorded using a magnetic gradiometer array and the rest recording using a single sensor setup. The gradiometer approach, using two sensor towed 150 meters apart behind the vessel results in results which are free from temporal variations and the integration of two sensors values results in total intensity or magnetic anomaly values.

1.4.3 Seismic processing of the BOSA MCS dataset

To be able to work with the seismic data, it has to go through the process of seismic processing to basically convert it from what are basically seismic wavelet log files (seismograms) for individual shots, receivers and reflective surfaces to the seismic sections shown for example in the chapters 2 and 3 of this thesis. There is an abundance of literature about the mathematics of and physics behind seismic processing (e.g. Claerbout, 1976; Yilmaz, 2001; Brown, 2004) as well as a number of software packages for computation of the algorithms. The software available to me at BGR was Landmark SeisSpace ProMAX. The basic goal of processing marine MCS data is to be able to successfully stack the acquired seismic data. Stacking is the addition of filtered seismograms to improve the signal to noise ratio. This improvement is achieved since after stacking multiple seismograms cover the same point at depth and random noise is eliminated in a robust manner (common-depth-point method).

To get there with the BOSA dataset, my commonly used processing flow typically included the following steps (among others):

1) Loading of the profiles geometry into the processing system, so every receiver and shot are located at the proper point in space and time and resampling of the data to a sampling rate of 4 ms.
2) Checking the geometry by applying a brute stack to the data with estimated stacking velocities (Fig. 14a)
3) Decrease of the noise-level in the data by applying an Ormsby band pass filter (Frequency polygon (Hz): 6-12-60-120) and a pre-stack spiking deconvolution algorithm to improve the resolution of the reflections by shortening the impulse length (Fig. 14b)
4) To be able to properly stack the data, estimated velocities for the reflectors are not sufficient, so stacking velocities were derived during velocity picking at regular intervals of 3 km along each line. As seismic waves need more time to be picked up by receivers at the far end of the streamer a horizontal reflector is displayed as hyperbola branch. During velocity analysis, the correct velocity for each reflector is determined to display horizontal reflectors as horizontal reflectors, correcting their normal moveout (NMO correction).
5) On the stacked data, a post-stack deconvolution to further improve the resolution of the reflections and more importantly a Kirchhoff time migration algorithm to account for display difficulties in areas of sharp acoustic contrast and high angles were applied (Fig. 14c).
6) As multiple reflections of prominent reflectors (especially the seafloor multiple) are often hindering interpretation, especially in shallow regions, multiple reduction techniques were employed. The most successful one was surface related multiple elimination (SRME), during which the algorithm estimates positions of multiple reflection based on reflector picks and the velocity field picked during Step 4. After estimation, the calculated multiples are subtracted from the pre-stack data. This results in a very crisp image and even better migration results (Fig. 14d)

Especially steps 4 to 6 took a lot of time in manually picking velocities and reflectors as well as in computation time, sometimes taking several days to compute even on the powerful server-based system I used.

After successful processing, the seismic data are loaded into interpretation software, where seismic reflectors are picked, faults are mapped and surfaces are calculated from reflectors. The results from interpretation of the seismic data are shown in Chapters 2 and 3, as well as the maps drawn based on the interpretation of these marine multi-channel seismic data.

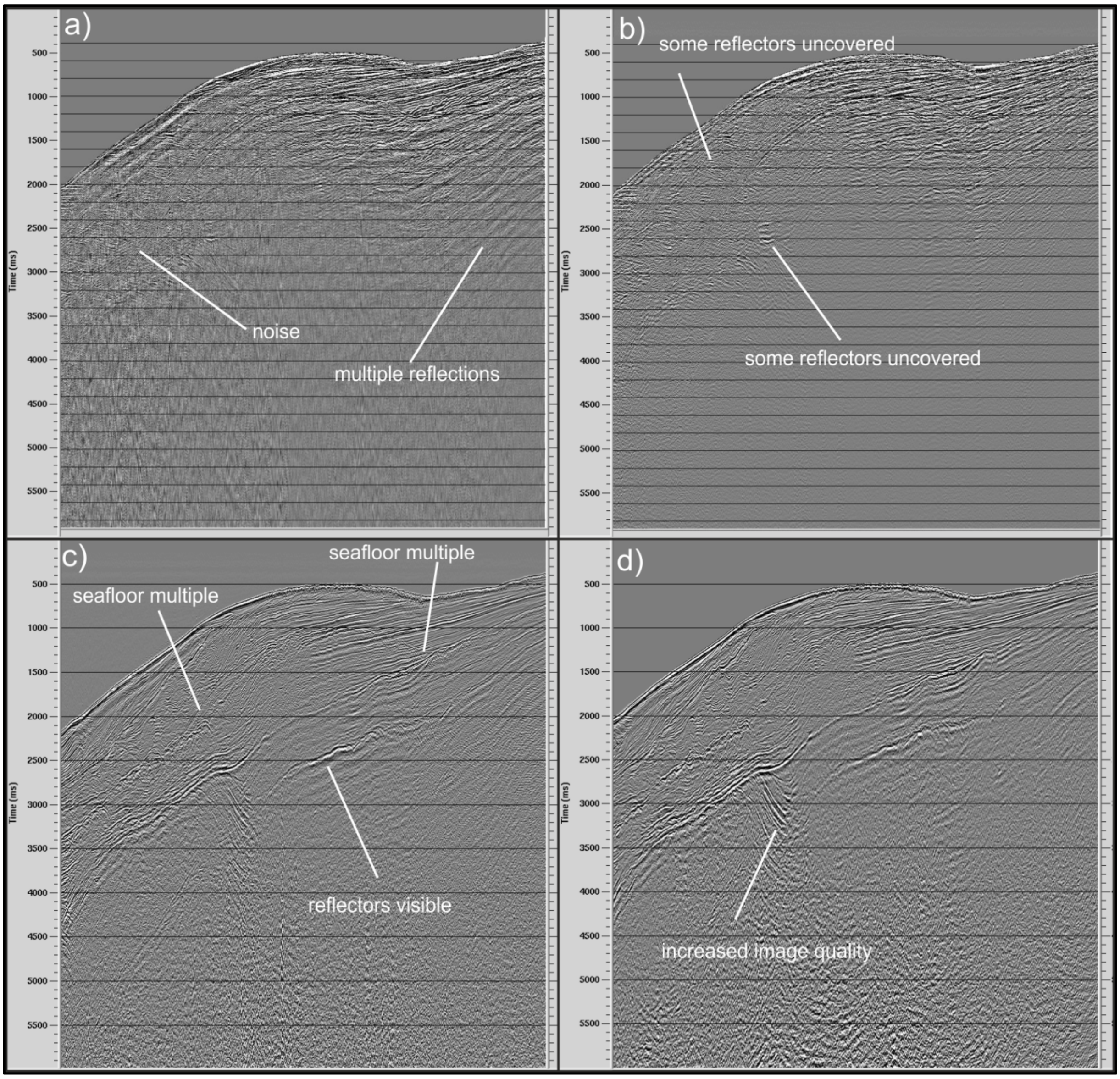


Fig. 1.14: 50 km section of MCS profile BGR03-11 to illustrate different stages of seismic processing. Note: to avoid confusion, data above the seafloor reflector (water!) has been cut off. a) Brute stack of unedited seismic data results in a very noisy, unclear image where not much more than the seafloor reflector can be seen; b) after band pass filtering, the worst of the noise is gone but signal quality is less than satisfactory and still hampered by massive multiple-reflections, especially in the shallower part of the section; c) after further filtering and migration of the seismic data, deeper reflectors can be seen more clearly and geometries within the sedimentary reflectors are more plausible; d) after applying multiple reduction algorithms on unmigrated data and migration of the data afterwards, image quality is crisp and the seafloor multiple has been successfully removed from the data, further increasing ease of Interpretation.

2. SEGMENTATION AND VOLCANO-TECTONIC CHARACTERISTICS ALONG THE SW AFRICAN CONTINENTAL MARGIN

Remarks

Contents of this chapter have been published with slight, largely editorial adaptations as a peer-reviewed research paper:

Koopmann, H., Franke, D., Schreckenberger, B., Schulz, H., Hartwig, A., Stollhofen, H., and di Primio, R., 2014, Segmentation and volcano-tectonic characteristics along the SW African continental margin, South Atlantic, as derived from multichannel seismic and potential field data: Marine and Petroleum Geology, v. 50, no. 2, p. 22–39. http://dx.doi.org/10.1016/j.marpetgeo.2013.10.016.

Abstract

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, the southernmost 460 km long margin segment was found 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 this 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.

Four distinct First-order Segments along the 2400 km section of the southwestern African margin covered by the seismic data are defined. 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), proposed to be is reflected in magnetic anomaly data as well. This variability along the margin is mainly due to a change in stretching / rifting character from oblique during the early stages of break-up to conventional seafloor spreading from Chron M4 (~130 Ma) onwards.

2.1 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; Blaich et al., 2009; Blaich et al., 2010; Brown et al., 1995; Corner et al., 2002; Eagles, 2007; Elliott et al., 2009; Geoffroy, 2005; Gladczenko et al., 1997; Gladczenko et al., 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 history. This study questions both assumptions to a certain degree, as evidence that the southwestern African passive continental margin is not continuously of the volcanic type is presented. Further, the change from non-volcanic to volcanic margin occurs abruptly. Based on 3300 kilometers of previously unpublished BGR multichannel seismic data off South Africa along with seismic data provided by industrial partners alongside with publically available geophysical data the margin architecture between the Agulhas Falkland Fracture Zone (AFFZ) is studied in detail, 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. Margin segmentation is a prime feature to allow insights into the early break-up histories of continents. The final extension that resulted in break-up 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 the term “segment boundary” is used 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. Previous investigations on SDRs (Gladczenko et al., 1997; Gladczenko et al., 1998) are incorporated and an update on an earlier segmentation model for the Namibian part of the study area (Clemson et al., 1997) is provided. This results in a consistent and conclusive description of margin segmentation along the entire eastern margin of the southern South Atlantic.

2.2 Regional geological setting

The South Atlantic continental margins (Fig. 2.1) 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 (Fig. 2.2) 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; Franke et al., 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).

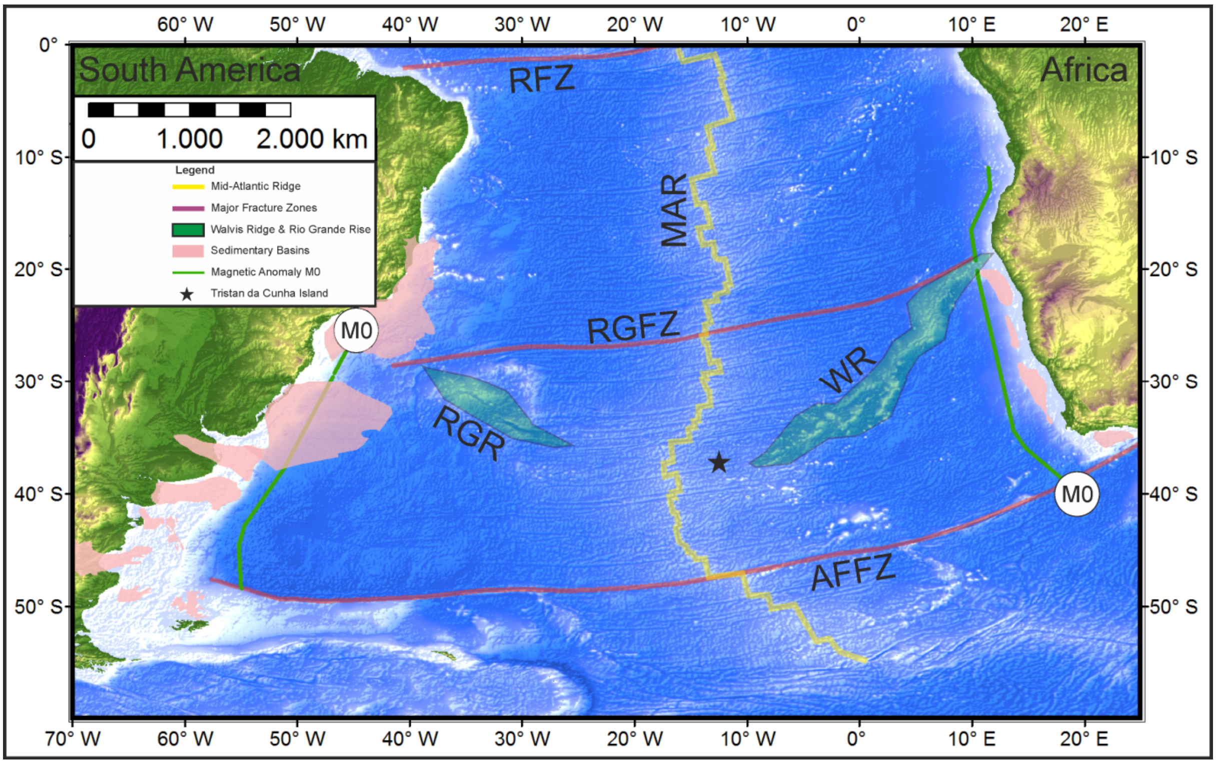


Fig. 2.1: Regional map of the South Atlantic. In this work, the volcano-tectonic characteristics along the Namibian and Southern African margin between the Agulhas Falkland Fracture Zone (AFFZ) and the Rio Grande Fracture Zone (RGFZ) are studied.

Fig. 2.1 continued: 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).

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 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 150-130 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.

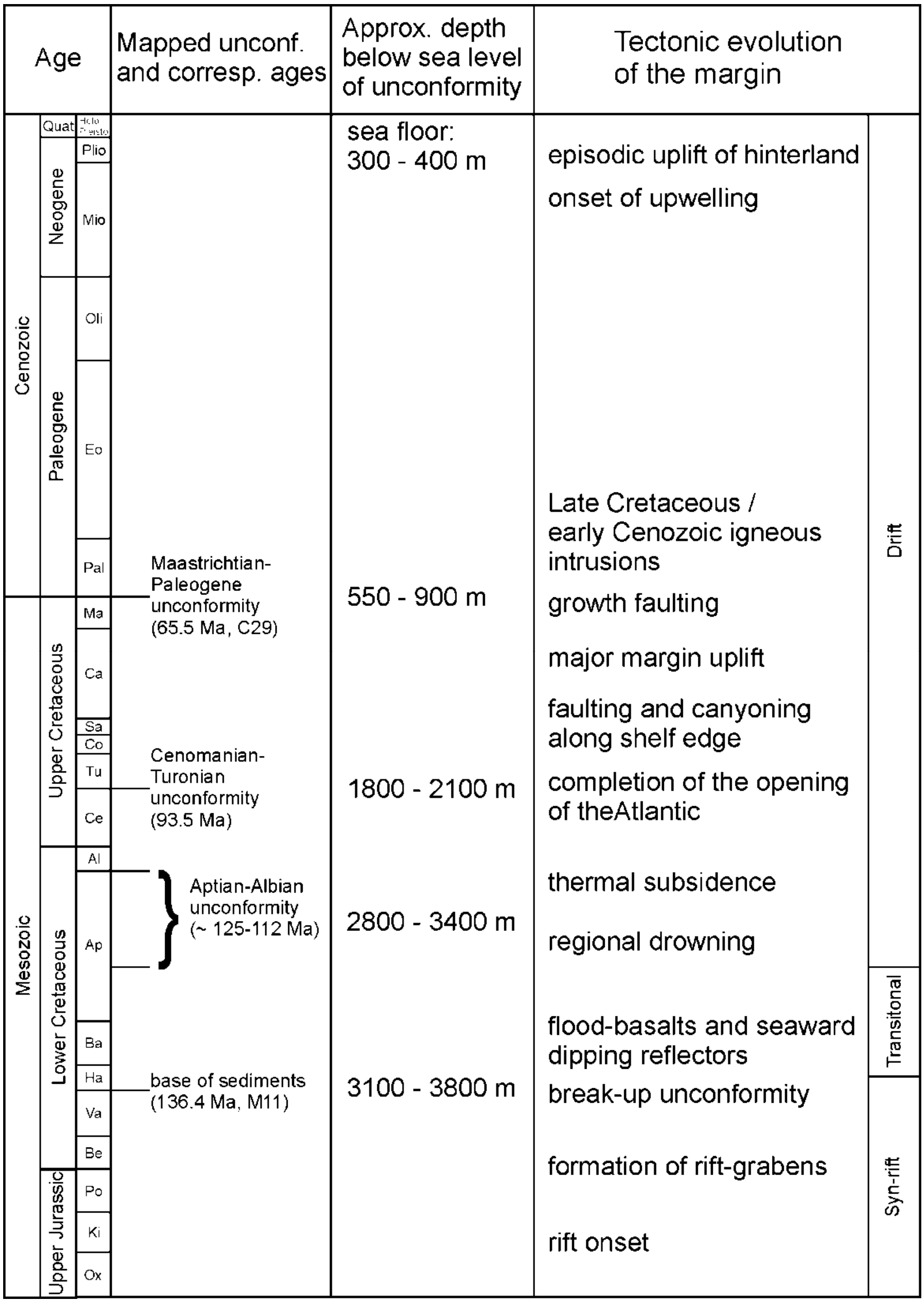


Fig. 2.2: Generalized tectonostratigraphic chart for the southern African margin. Ages according to Gradstein et al. (2004), regional events as suggested by Hartwig et al. (2012), depths from four distal wells (A-C1, A-C2, A-C3, A-N1) within the Orange Basin (Hirsch et al., 2010).

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 seperated 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.

2.3 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 12200 km of MCS data were acquired (Figs. 2.3 and 2.4; 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.

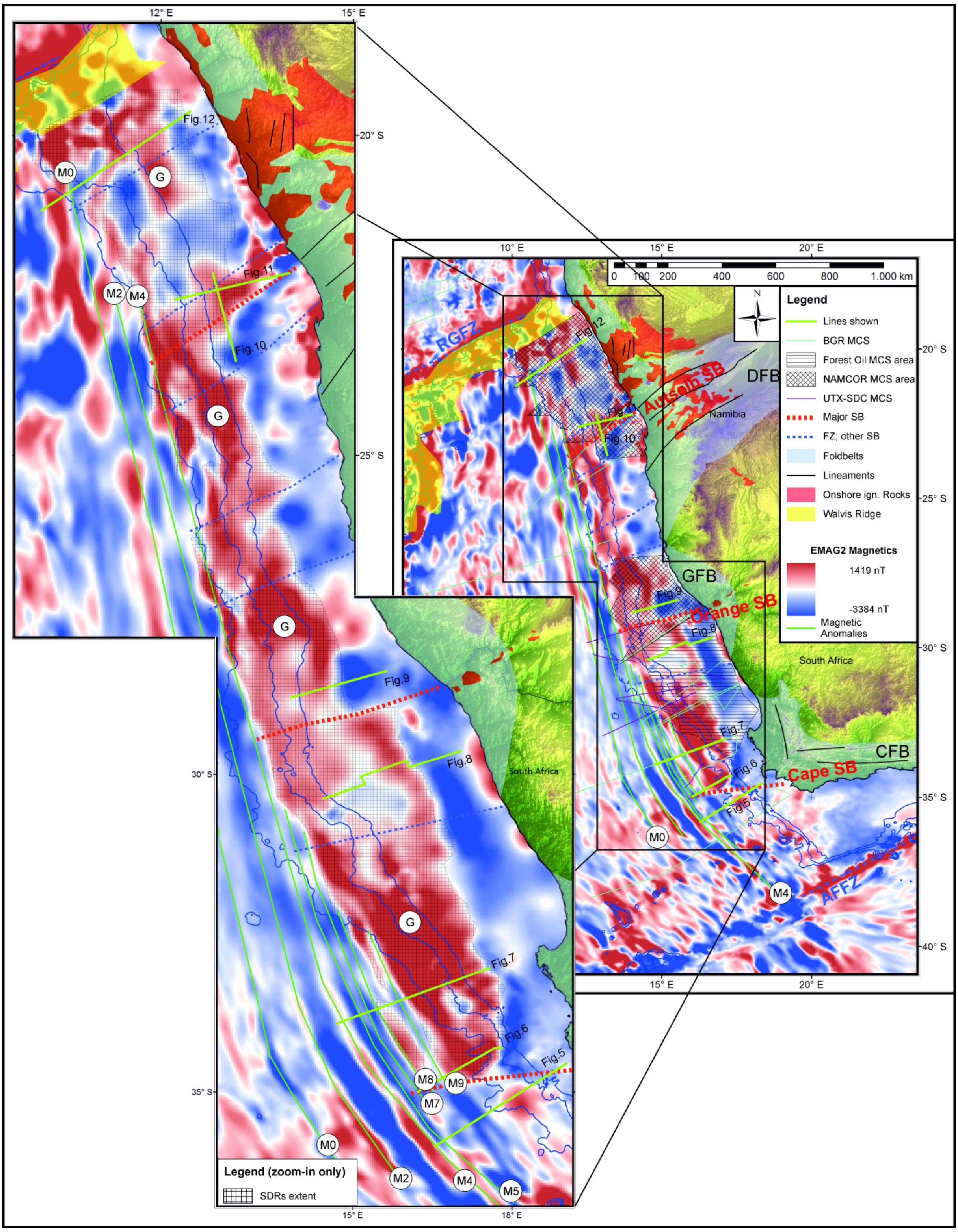


Fig. 2.3: EMAG2 Earth Magnetic Anomaly Grid (Maus et al., 2009) at the southwestern African margin. The large margin parallel positive anomaly correlates well with the extent of Seaward Dipping Reflector Sequences (SDRs), especially in the southern part of the study area. It also reflects the sudden 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.

Fig. 2.3 continued: 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.

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.

2.4 Interpretation

2.4.1 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. 2.4) 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.

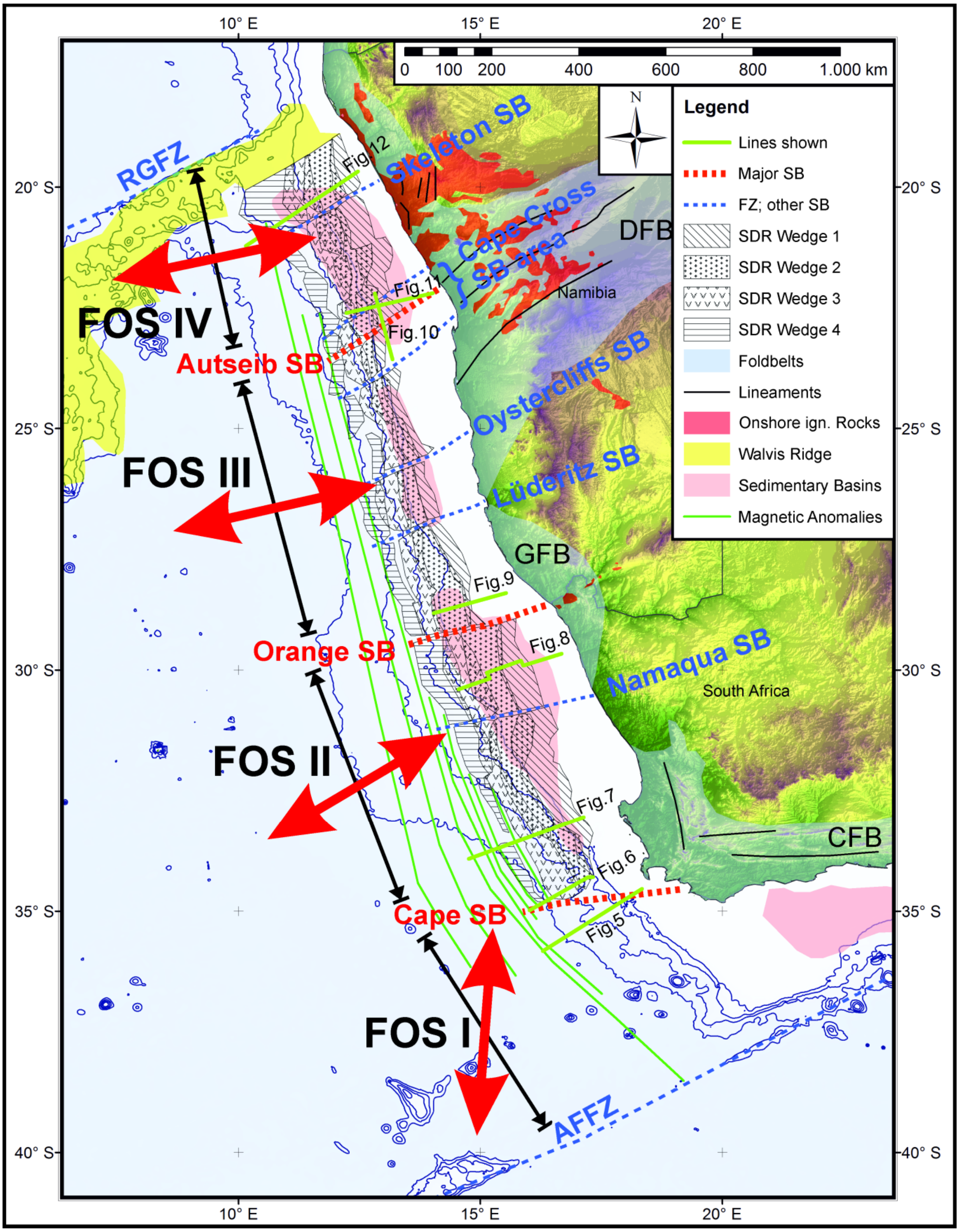


Fig. 2.4: Structural Map of the South Western African passive continental margin between the AFFZ and the RGFZ. Along this section of margin, four First-order Segments (FOS) were identified. Shown are the SDR wedges mapped as seen of the seismic data along the margin, with the three major segment boundaries (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.

Fig. 2.4 continued: 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 Fig. 2.3; further shown: the four main sedimentary basins on the southwestern African margin; from south to north: Outeniqua Basin; Orange Basin, Lüderitz Basin, Walvis Basin.

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. 2.2). These are an unconformity within Aptian to 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. 2.3). 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. 2.3). 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.

2.4.2 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. 2.3). 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 Fig. 2.5. The architecture of this margin segment is different from the volcanic rifted type further north along the margin and elsewhere. Thus the margin segment is interpreted as not volcanic rifted (Fig. 2.5).

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.

As there are only 80 km between the two MCS lines shown in Fig. 2.5 and Fig. 2.6, 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. 2.3, 2.5 and 2.6 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.

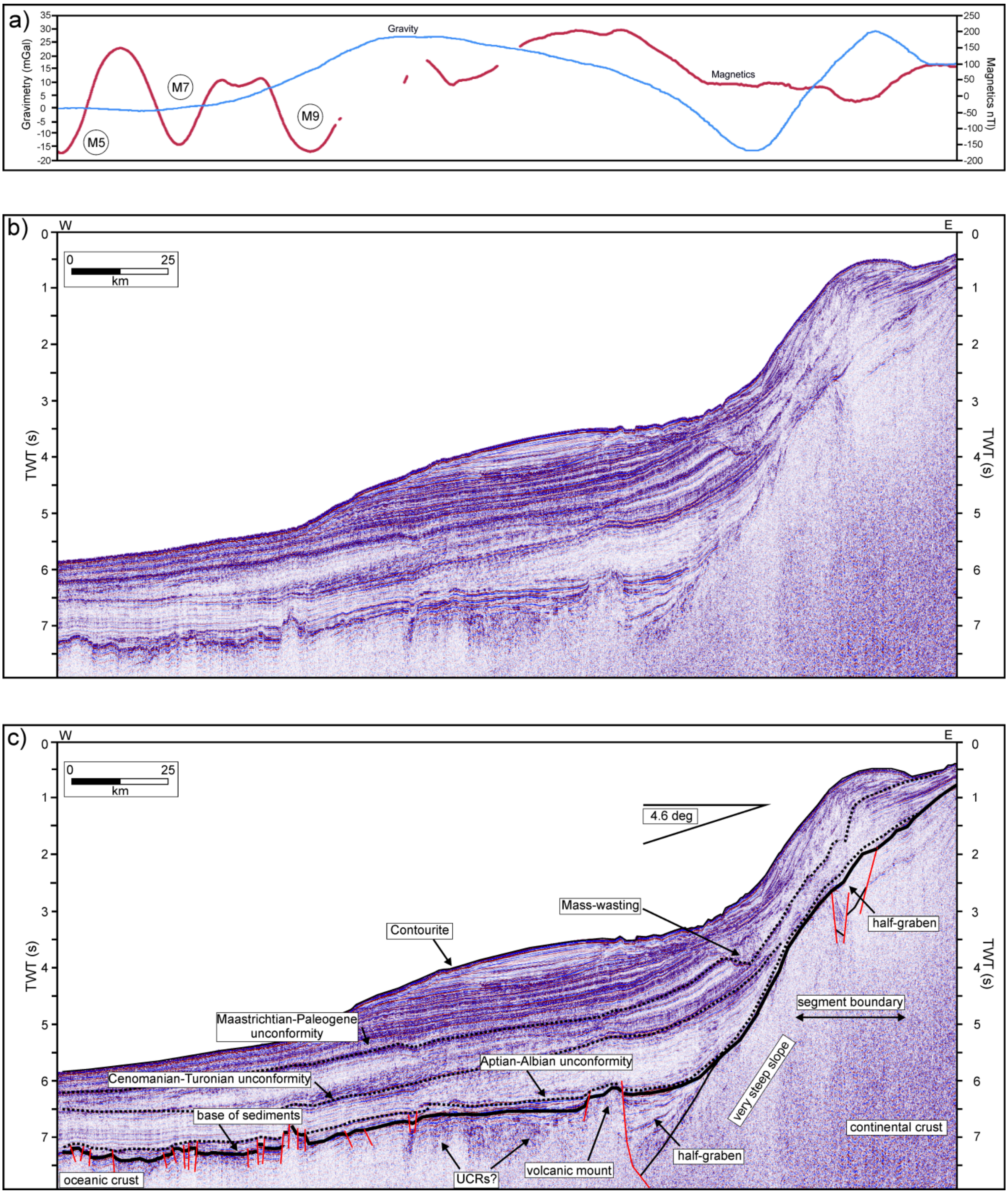


Fig. 2.5: 235 km section of BGR migrated MCS line BGR03_11 (see Figs. 2.3 and 2.4 for location); a) cross-plot of ship-track potential field data; b) uninterpreted, c) interpreted. Located in the North of First-order Segment I. An example of the Magma-poor segment of the Southern African continental 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. 2.3).

2.4.3 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. 2.3) is characterized by widespread volcanic effusives, reflected on seismic images as SDRs and correlating to the large positive margin-parallel magnetic anomaly (compare Figs. 2.3, 2.5, 2.6, 2.7 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. 2.6). 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. 2.7). 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. 2.6). Northwards, SDR reflections show a more continuous pattern (Fig. 2.7). The basement slope angle is much less steep than in First-order Segment I (< 1 °) and further decreases towards the north (compare Figs. 2.5, 2.7 and 2.8). Outer highs and outer SDRs sensu Planke et al. (2000) as a integral part of the succession of inner SDRs (e.g. Fig. 2.7) 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; Franke et al., 2007). On the profiles that show outer highs in this sense, the outer SDR sequence is also less prominent than on the conjugate margin.

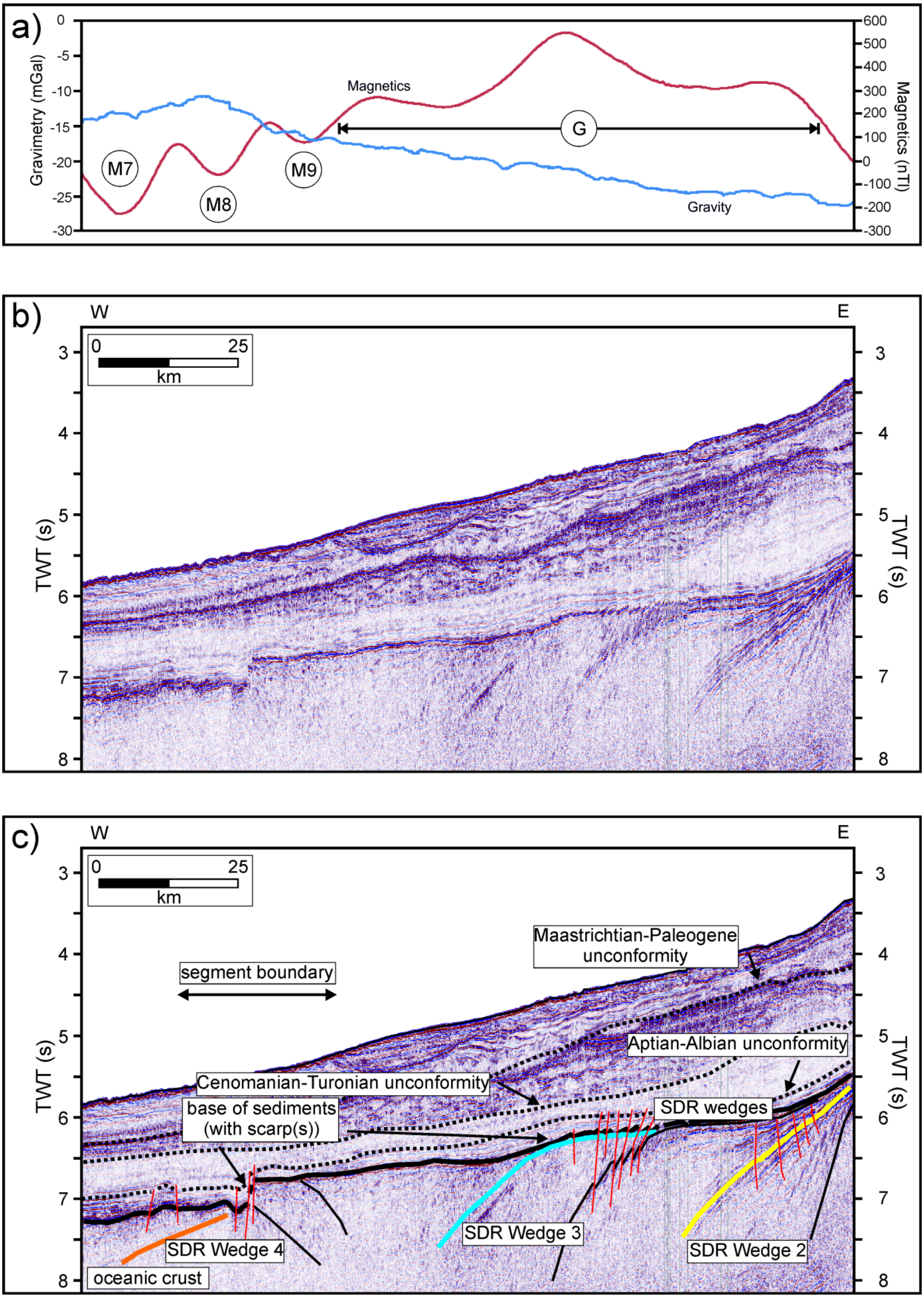


Fig. 2.6: 140 km section of BGR migrated MCS line BGR03_12 (see Figs. 2.3 and 2.4 for location); a) cross-plot of ship-track potential field data; b) uninterpreted, c) interpreted. Southernmost section within First-order Segment II. Note the strong Seaward Dipping Reflectors, separating individual wedges.

Fig. 2.6 continued: 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 & 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.

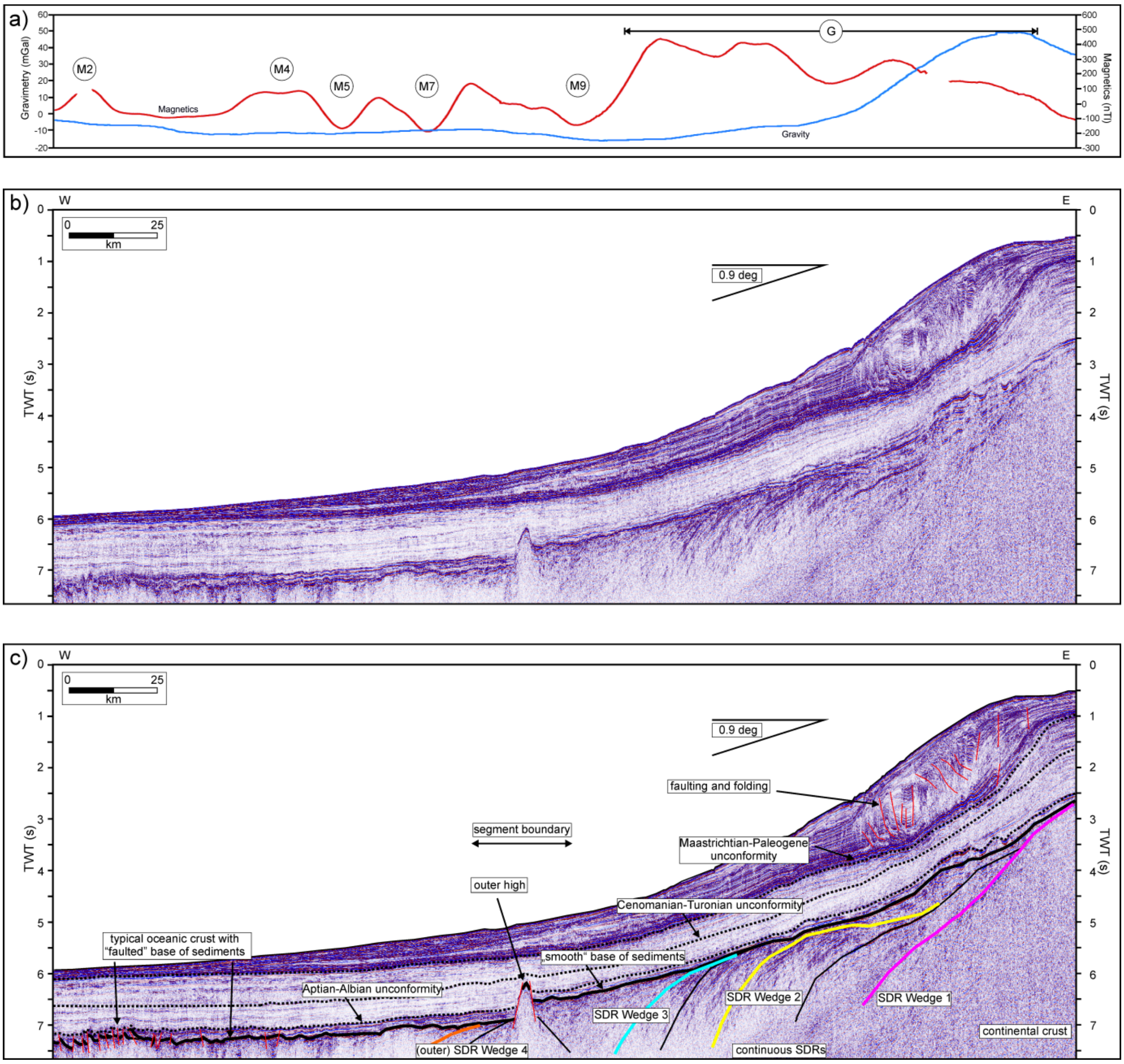


Fig. 2.7: 290 km section of BGR migrated MCS line BGR03_16A (see Figs. 2.3 and 2.4 for location); a) cross-plot of ship-track potential field data; b) uninterpreted, c) interpreted. Note that the SDR wedges are less characterized by strong reflectors separating individual wedges instead showing a more continuous reflection character, without the intense deformation of the more southerly profile in Fig. 2.6. 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 & 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.

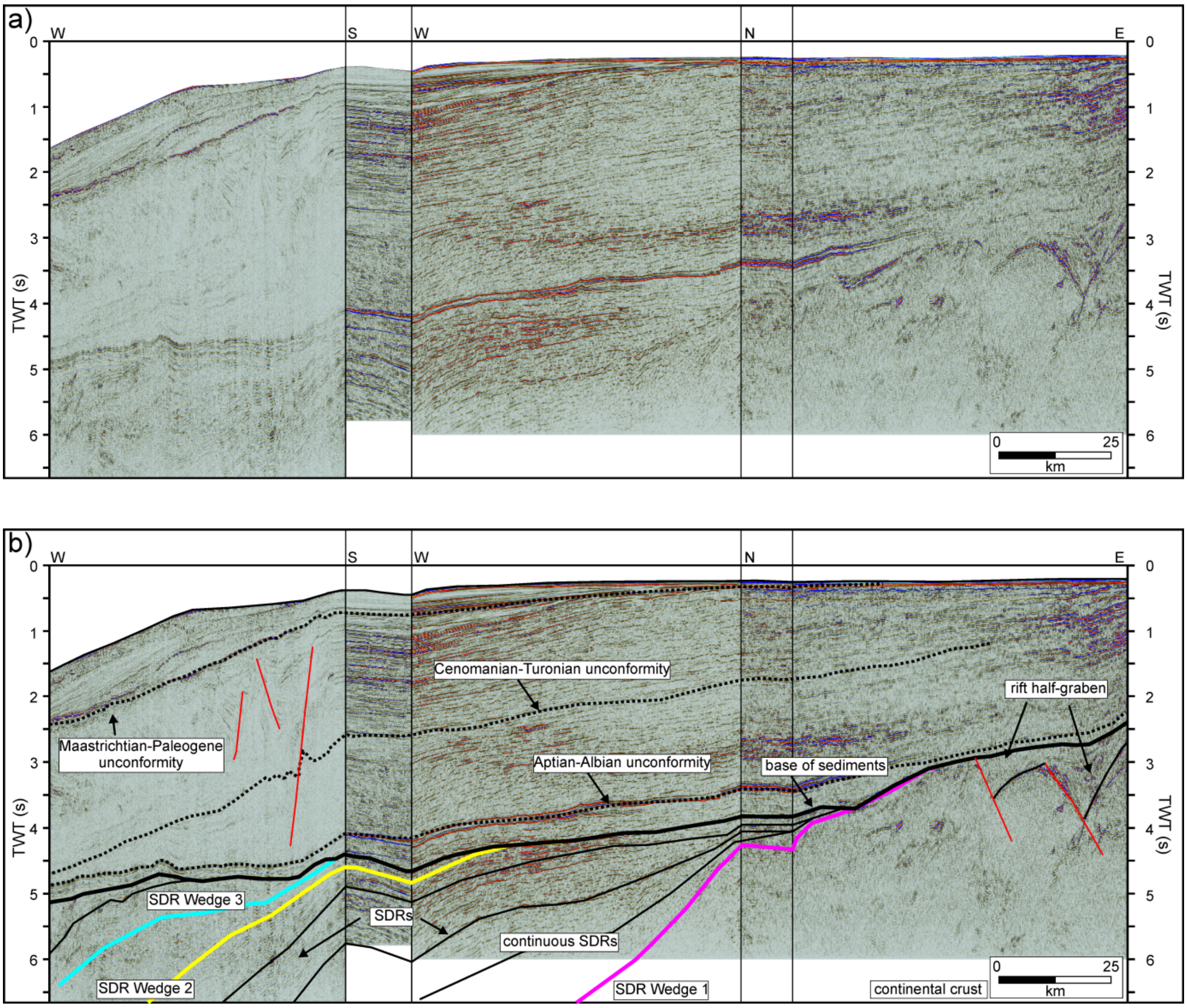


Fig. 2.8: 240 km composite section (directional changes!) of migrated MCS lines provided by Forest Oil (see Figs. 2.3 and 2.4 for location); a) uninterpreted, b) interpreted. This profile shows an almost ideal succession of SDR wedges with the typical (Hinz, 1981; Mutter et al., 1982; Franke et al., 2010) convex-up, arcuate reflection pattern.Basement dip is very shallow. The half-grabens are interpreted as results of crustal stretching during break-up, as opposed to the half-grabens shown in Fig. 2.5, which are suggested to result from oblique extension.

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. 2.4). Within the Orange Basin two distinct left-lateral offsets within the lateral extent of the SDRs are observed (Namaqua SB and Orange SB; Fig. 2.4). Furthermore, a remarkable feature within this margin segment and exclusive to this segment is the (across margin) dissection of the SDRs (Fig. 2.6). The dissecting faults partly affect also overlying Aptian sediments, providing an age estimate for the timing of deformation. From margin-parallel data, the general continuity of SDR reflectors along the margin is confirmed, 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 northern part of the study area (see 4.5 Margin Segment IV) is confirmed here to be limited to that area.

2.4.4 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. 2.4). 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. 2.9), which may have forced the rift to a westerly position resulting in the corresponding offset of the volcanic flow units. At this position a change in the strike of the transfer zones from W-E to SW-NE from here on northwards is observed.

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 one major right lateral offset in the distribution of the SDRs, the Autseib Segment Boundary was found (Fig. 2.4). This comes along with a significant vertical offset along faults affecting the SDR sequences, which is best imaged on margin-parallel MCS lines (Fig. 2.10). 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. 2.11), it becomes apparent that what might resemble sedimentary sequences below 3.5s TWT in Fig. 2.10 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. 2.11). Across the Autseib SB a considerable increase in the width of the SDRs is observed (Fig. 2.4).

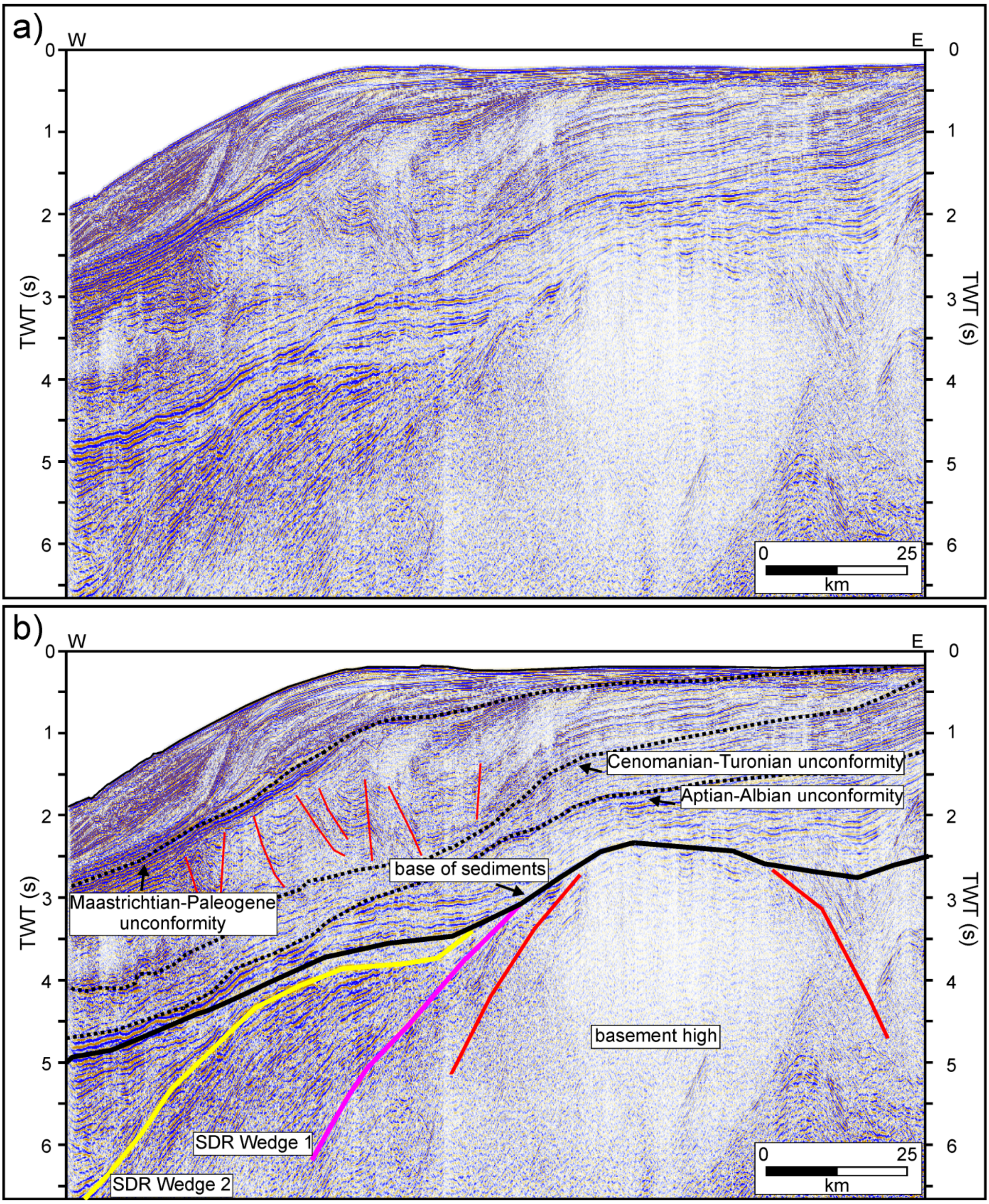


Fig. 2.9: 155 km section of migrated MCS line provided by NAMCOR (see Figs. 2.3 and 2.4 for location); a) uninterpreted, b) interpreted. The decrease in width of magnetic anomaly G is reflected in the decrease of the width of the SDRs north of Orange SB. Note the structural high, proposed to be the reason for inhibited rift propagation and subsequent change from predominantly left- to right-stepping offsets in the SDRs extent at segment boundaries. Note that Fig. 2.3 shows the basement high corresponding to a negative magnetic signal.

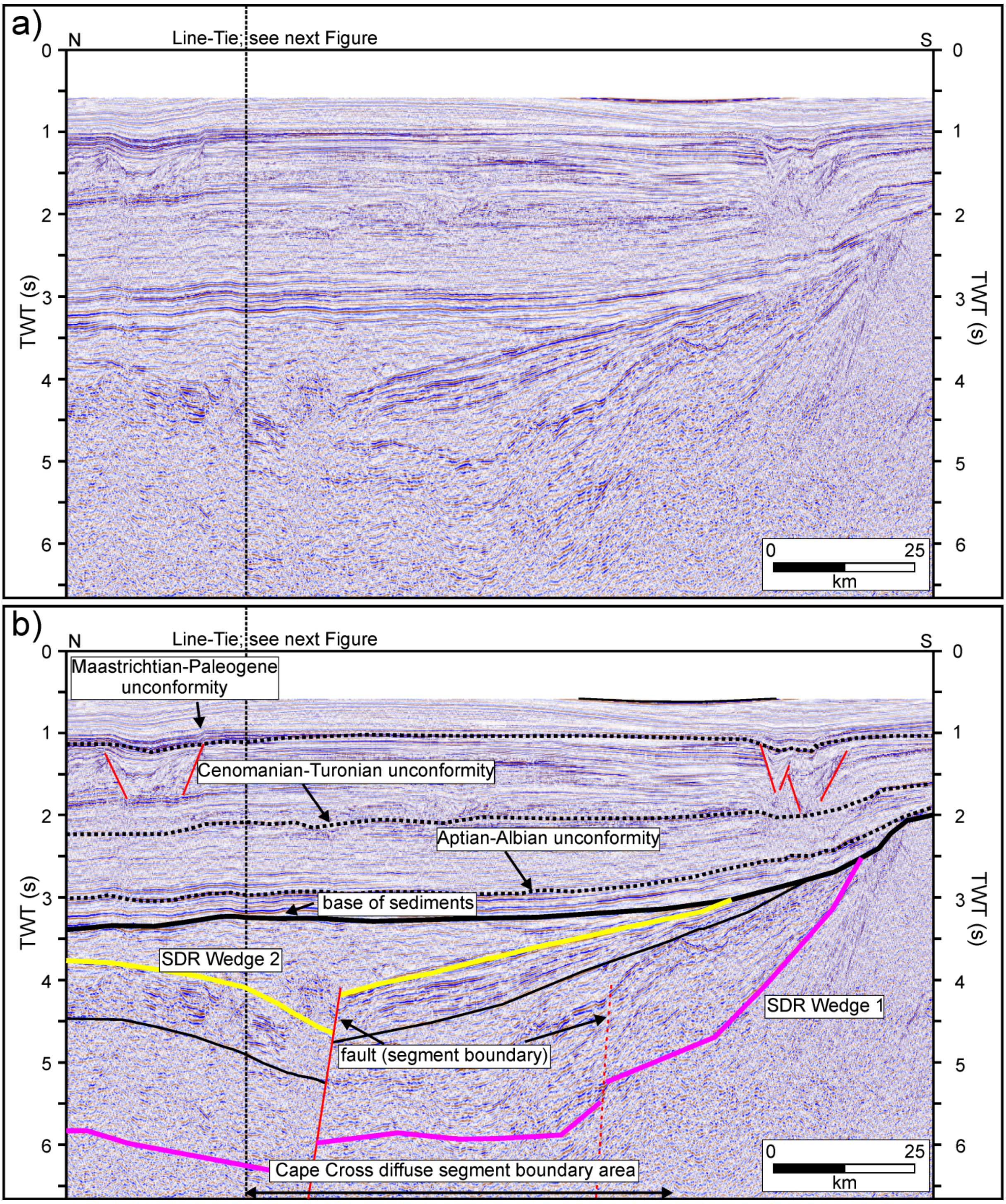


Fig. 2.10: 155 km composite section of migrated MCS lines provided by NAMCOR (see Figs. 2.3 and 2.4 for location); a) uninterpreted, b) interpreted. This margin parallel profile shows evidence that movement along segment boundaries in this area was at least partly after the emplacement of Seaward Dipping Reflector sequences but before extensive sedimentation commenced, as only the SDRS are affected by movement along the transfer zone faults. It does not seem useful, however, that this finding should lead to expecting geologically sharp contact all along the margin.

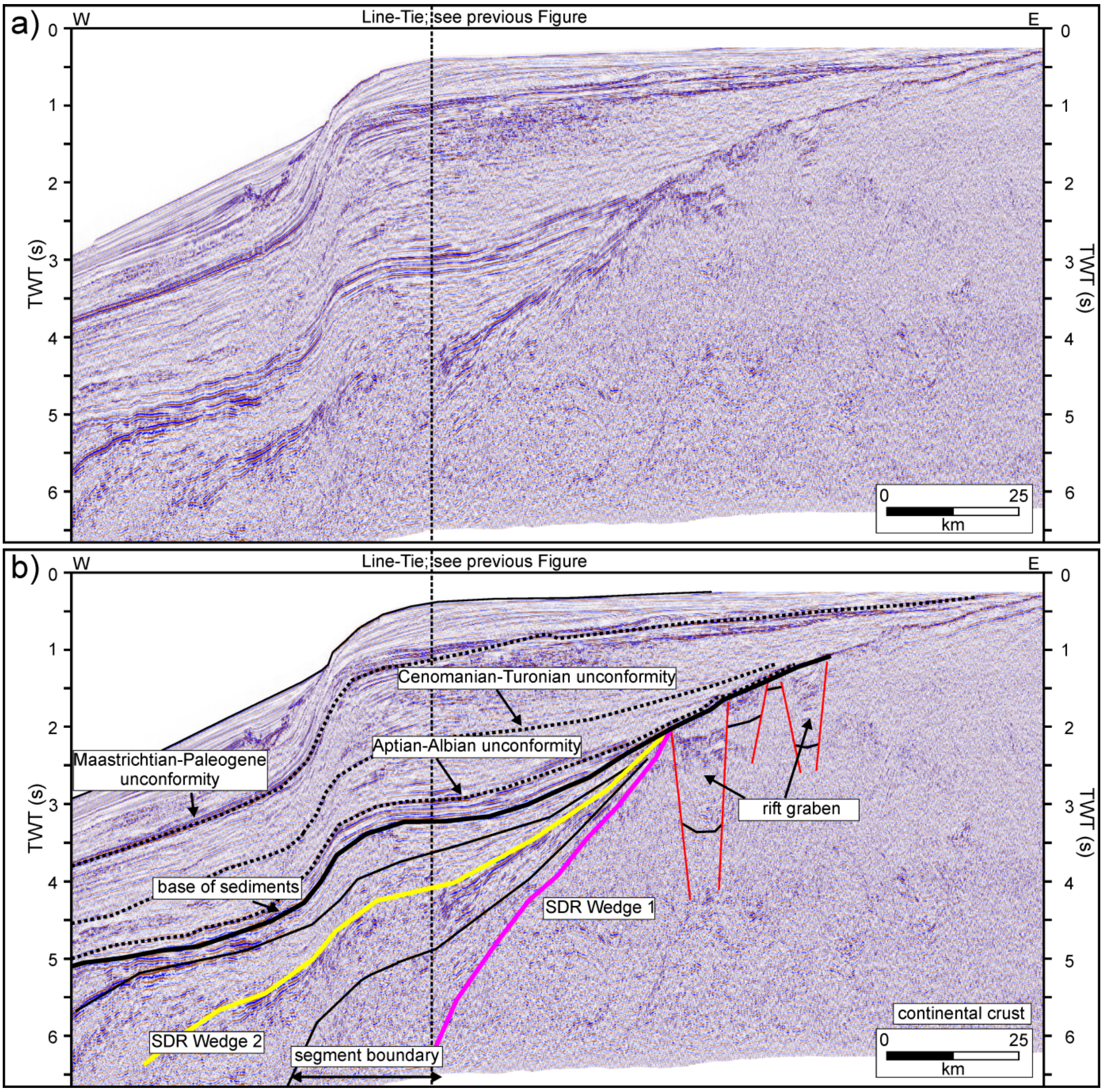


Fig. 2.11: 185 km composite section of migrated MCS lines provided by NAMCOR (see Figs. 2.3 and 2.4 for location); a) uninterpreted, b) interpreted. Autseib SB, northernmost of the segment boundaries defined in the intensely segmented area due west of Cape Cross, is identified on this cross-section by the abrupt change in basement convexity, which can be presumed to mark the transfer zone in which the segments moved relative to the other.

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 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.

2.4.5 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. 2.4) 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. 2.3). When approaching the Walvis Ridge, from about 400 km away (Skeleton SB; Fig. 2.4), 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. 2.12).

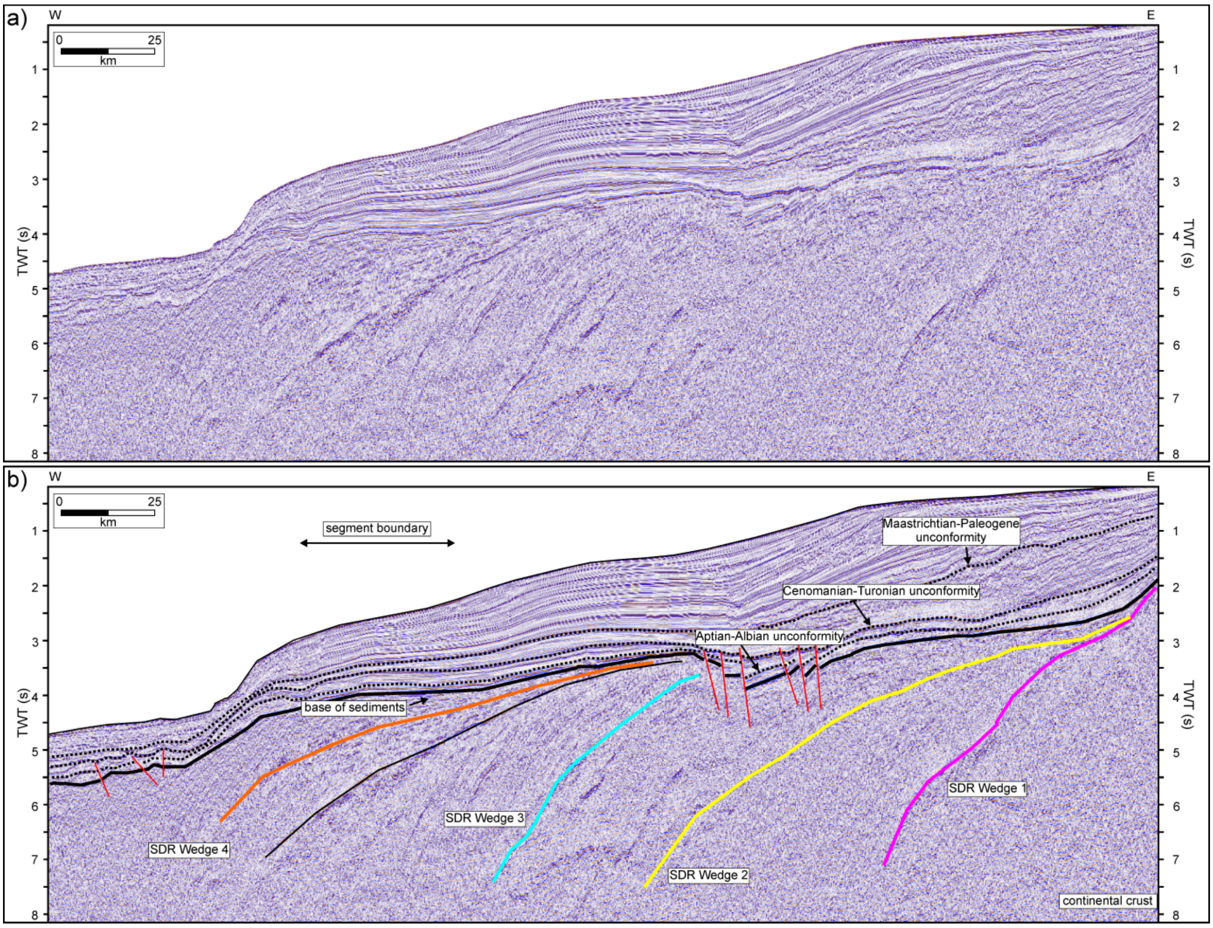


Fig. 2.12: 300 km section of migrated MCS line provided by NAMCOR (see Figs. 2.3 and 2.4 for location); a) uninterpreted, b) interpreted. On the northernmost profile shown in this study, the influence of Walvis Ridge volcanism is reflected in the tremendous width of the SDRs which cannot be followed to their seaward termination on the data used.

North of the Skeleton SB, the seaward end of volcanics was not reached by the 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.

2.5 Discussion

2.5.1 SDRs

Along the margin, distinct variations in volcanic output rates and volumes were found, imaged by varying thicknesses (compare Fig. 2.6 and Fig. 2.8), overall SDR wedge widths (compare Fig. 2.8 and Fig. 2.12) 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’ 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, it can be concluded 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; Franke et al., 2007; Hinz et al., 1999). However, the 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; Franke et al., 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. The presence of both northerly and southerly undulations of SDR packages not only close to, but also far away from the Walvis Ridge are confirmed. 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.

2.5.2 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 drastic changes in the volume of volcanic effusives were found.

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 a good fit with the trend of the proposed segment boundaries can be achieved. Clemson et al. (1997) suggested that the Autseib SB represents the offshore continuation of the Autseib Lineament within the Damara Fold Belt. It is further suggested 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. 2.9) 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.

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, it is suggested 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 & LaBrecque, 1979) and accordingly implemented in plate reconstruction models (e.g. Moulin et al., 2010; Nürnberg & 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.

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

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). It can be concluded 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) it is suggested 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 this 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; Franke et al., 2007; Hinz et al., 1999) offshore South America SDR wedges were emplaced ~380 km north of the AFFZ. In contrast, the results presented here 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. It is suggested 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. 2.13). 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 & 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 & Müller, 1991). The steep slope angle on both sides of this southern segment is an indication for margin-parallel shear movements during opening. It is suggested 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 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).

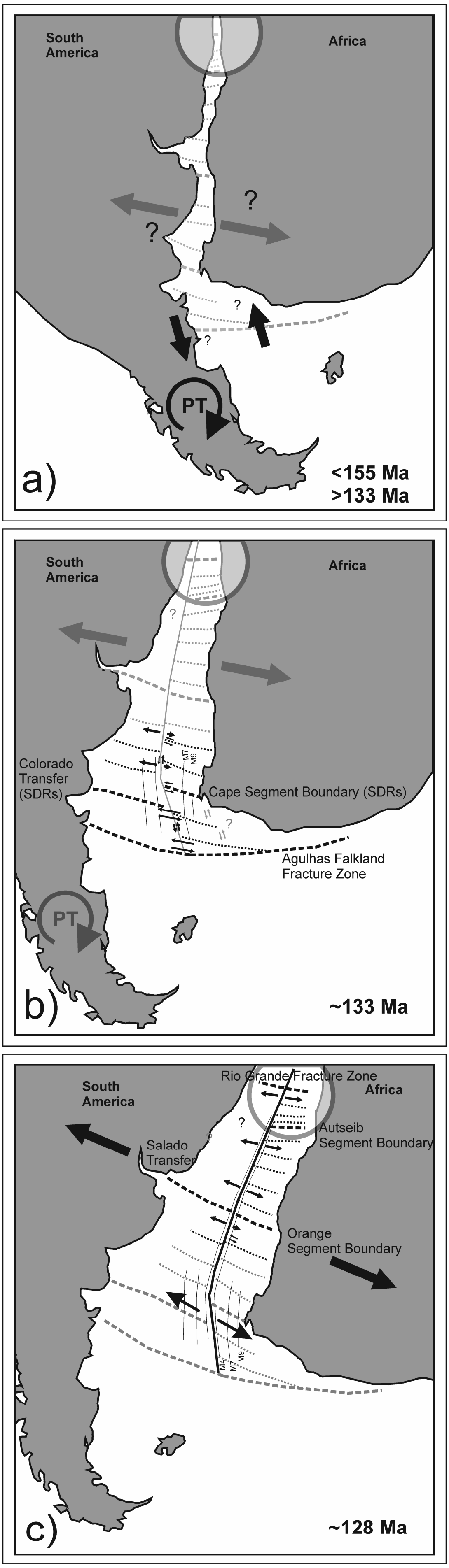


Fig. 2.13: Plate reconstruction of the South Atlantic at <155 Ma >133 Ma (a), ~133 Ma (b) and ~128 Ma (c) (modified from Jokat et al., 2003 and Macdonald et al., 2003). Segment boundary locations and names of the South American margin as interpreted by Franke et al. (2007). Semitransparent circles mark the proposed extent (diameter: 800 km) of Tristan da Cunha hot-spot related volcanism. Fracture zones, segment boundaries and movement directions are drawn in more pronounced gray shades up-to black with increasing certainty and impact.

Fig. 2.13 continued: Starting with Fig. 2.13a, 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. 2.13b. Magnetic Anomaly M4 is assumed to be equivalent to the onset of conventional seafloor spreading as indicated in Fig. 2.13c.

As suggested in the 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).

2.6 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. It is proposed 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, it is suggested 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.

Chapter-specific acknowledgments

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3. THE LATE RIFTING PHASE AND CONTINENTAL BREAK-UP OF THE SOUTHERN SOUTH ATLANTIC

Remarks

Contents of this chapter have been published with slight, largely editorial adaptations as a peer-reviewed research paper:

Koopmann, H., Schreckenberger, B., Franke, D., Becker, K. and Schnabel, M., 2014. 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. Geological Society, London, Special Publications, Magmatic Rifting and Active Volcanism, in press.

Abstract

Multichannel seismic and potential field data shed light on the final rifting stage in the South Atlantic. This was associated with major episodes of magmatism during the Early Cretaceous continental break-up. An asymmetric simple shear-dominated variable strain rifting model is proposed with 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 rifting-direction from N-S to W-E is 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 (~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 (SDRs) point 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 seafloor-spreading magnetic anomaly is M9 (~135 Ma). Older anomalies (e.g. M11 (~137 Ma)) are related to structural or magnetization variations within SDRs.

3.1 Introduction

The South Atlantic continental margins (Fig. 3.1) 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 in the range between 126 and 137 Ma (Rabinowitz and LaBrecque, 1979; Unternehr et al,. 1988; Nürnberg and Müller, 1991; Gladczenko et al., 1997; Jokat et al., 2003) and it is commonly proposed that this process progressed from south to north (Rabinowitz and LaBrecque, 1979; Austin and 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 and Duncan, 1990; Hinz et al., 1999; Jerram et al., 1999a; 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 and Eldholm (1973), Larson and 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 and 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 and Müller (1991) using the older anomaly identifications by Rabinowitz and LaBrecque (1979) in the area of interest of this study.

Rabinowitz and LaBrecque (1979) identified lineations back to M11 off Cape Town but they were only able to recognize M3 or M4 off Argentina. Larson and Ladd (1973) and more complete Rabinowitz and 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 is not considered a simple seafloor-spreading anomaly but was interpreted as an edge anomaly at the boundary between oceanic and continental crust (Rabinowitz, 1976; Rabinowitz and LaBrecque, 1979). A recent study by Moulin et al.

(2010) also propose the presence of M7 magnetic anomalies in the southern part of the South Atlantic but infer that most of the movement of the Austral and Nubian African blocks for the first opening stage occurred between chrons M4 and M2.

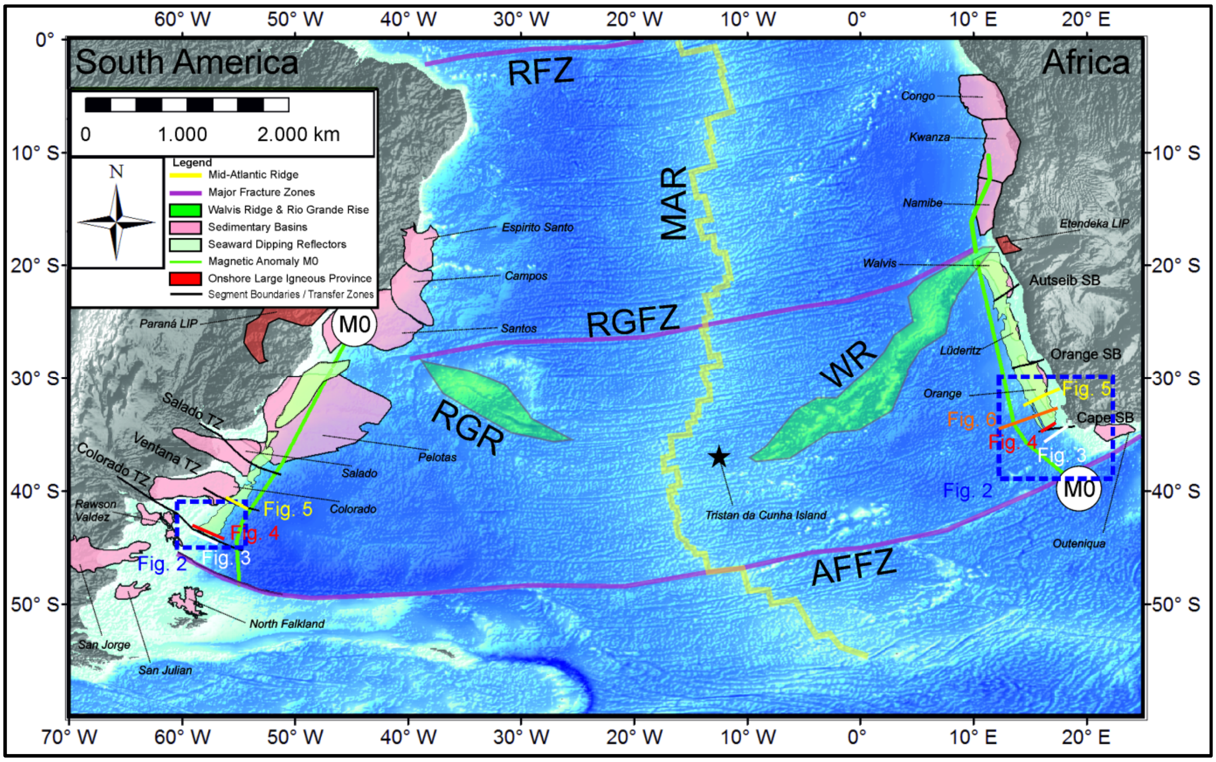

Fig. 3.1: Regional map of the South Atlantic. Shown are the topography and bathymetry as well as important regional features. These features include sedimentary basins of the southernmost South Atlantic (Africa: south to north: Outeniqua Basin, Orange Basin; Lüderitz Basin; Walvis Basin; Namibe Basin; 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 reflectors sequences (SDRs) along the passive continental margins and the segment boundaries separating structurally distinct margin segments on either margin. The segment boundaries separating the magma-starved from the volcanic margin segments have been named Colorado Transfer Zone (Colorado TZ) (Franke et al., 2007), respectively Cape Segment Boundary (Cape SB) (Koopmann et al., 2014b). Note the almost margin-perpendicular basin axes of the Argentinean South American basins in contrast to the margin-parallel basins on 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, alongside 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 Fig. 3.2. Also shown are the locations of the profiles presented in Figs. 3.3 to 3.6. Note the difference in distance from the southernmost SDRs to the AFFZ.

Reflection seismic investigations revealed that the volcanic margin type is widespread in the South Atlantic (Hinz, 1981; Austin and Uchupi, 1982; Gerrard and Smith, 1982; Gladczenko et al., 1997; Gladczenko et al., 1998; Hinz et al., 1999; Bauer et al., 2000; Talwani and 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 SDRs, Koopmann et al. (2014b) 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., 2014b) showed a sudden onset of volcanism as revealed by the presence of SDRs. 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 and LaBrecque (1979) are not available or rather cover more northerly South Atlantic margin segments (e.g. Brazil-Namibia (Talwani and Abreu, 2000) or Brazil-Gabon/Angola (Mohriak et al., 2002)) in a broader overview.

Here a combination of a structural investigation of rift-related margin structures is presented, 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. 3.2). 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.

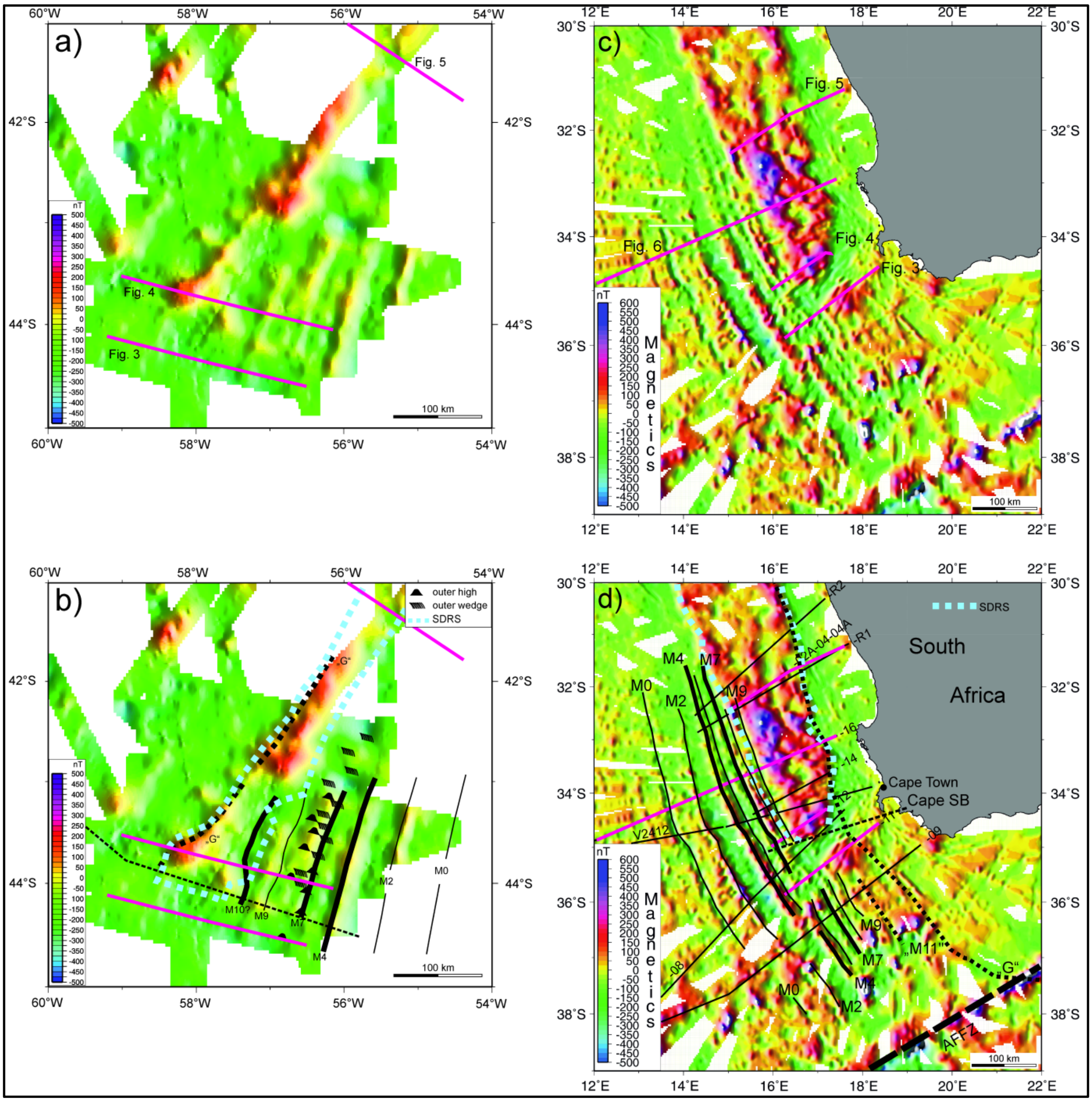

Fig. 3.2: Gridded magnetic anomaly maps offshore South America (Fig. 3.2a,b) and South Africa (Fig. 3.2c,d), respectively. Note the different scales! Marked in pink are the profiles from surveys BGR98 (South America) and BGR03 (Africa) shown in Fig. 3.3 (BGR98-11 and BGR03-11), Fig. 3.4 (BGR98-20 and BGR03-12), Fig. 3.5 (BGR98-39 and BGR03 02A-04-04A) and Fig. 3.6 (BGR03-16A). On the magnetic anomaly maps, important features and structures are visible. The mapped area of 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 allows 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. Further note 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 (circa 175 km on the South American compared to circa 150 km on the African margin). Shown as well for reference as a bold dotted line marked "G" is the "G-anomaly" and "M11" offshore South Africa from Rabinowitz and LaBrecque (1979) (Fig. 3.2d).

3.2 Dataset

3.2.1 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 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 open file data set GEODAS published of 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 were already used by Rabinowitz and LaBrecque (1979) to identify magnetic lineations and the G-anomaly. Here, the data were used to compile a magnetic map (Fig. 3.2c, 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 IGRF fields. Gridding and contouring were performed using GMT routines. Illumination is set from an approximate location at the mid-oceanic ridge (from east for the Argentine map, from west for the African map). There are still some remnants of mis-leveled lines in the database but the map gives a valuable overview about the general features of the anomalous magnetic field in the area.

3.2.2 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: 3.700 km, SO85: 4.300 km, BGR98: 12.000 km, BGR04: 3.800 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 set-ups. These cruises provided the MCS dataset used for previous BGR investigations of different aspects of the margin (Franke et al., 2006; Franke et al., 2007; Schnabel et al., 2008; Franke et al., 2010; Grassmann et al., 2011; Becker et al., 2012; Franke, 2013).The magnetic map in Fig 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 Fig. 3.2c,d for the African data.

3.3 Interpretation

3.3.1 Magma-poor vs. volcanic rifted margin type on MCS data

For interpretation, conjugated profiles on the South Atlantic margins were investigated. Stratigraphically, four main reflectors shown in Franke et al. (2010) and Becker et al. (2012) for the Argentine margin respectively 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 and the Maastrichtian-Palaeocene unconformity.

On the southern-most conjugated profiles (BGR98-11 and BGR03-11) shown here (Fig. 3.3), approximately 40 km south of the Colorado Transfer Zone (Colorado TZ) (Franke et al., 2007) respectively the Cape Segment Boundary (Cape SB) from Koopmann et al. (2014b), the margins are remarkably different to 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 and Manatschal, 2006; Péron-Pinvidic and 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 shiptrack magnetic data for the African profile, seafloor spreading anomalies can be correlated to as old as M9, whereas the American side, due in part of much lower amplitudes does not allow a satisfying correlation to seafloor spreading anomalies older than M4 in this segment (Becker et al. 2012). The gravity data, (Fig. 3.3a) likely reflect sedimentary structures (contourites, mass wasting events; Grützner et al., 2011). The base of (post-rift) sediments reflector is located about 2 s (TWT) deeper on the Argentine profile than on the conjugate African section.

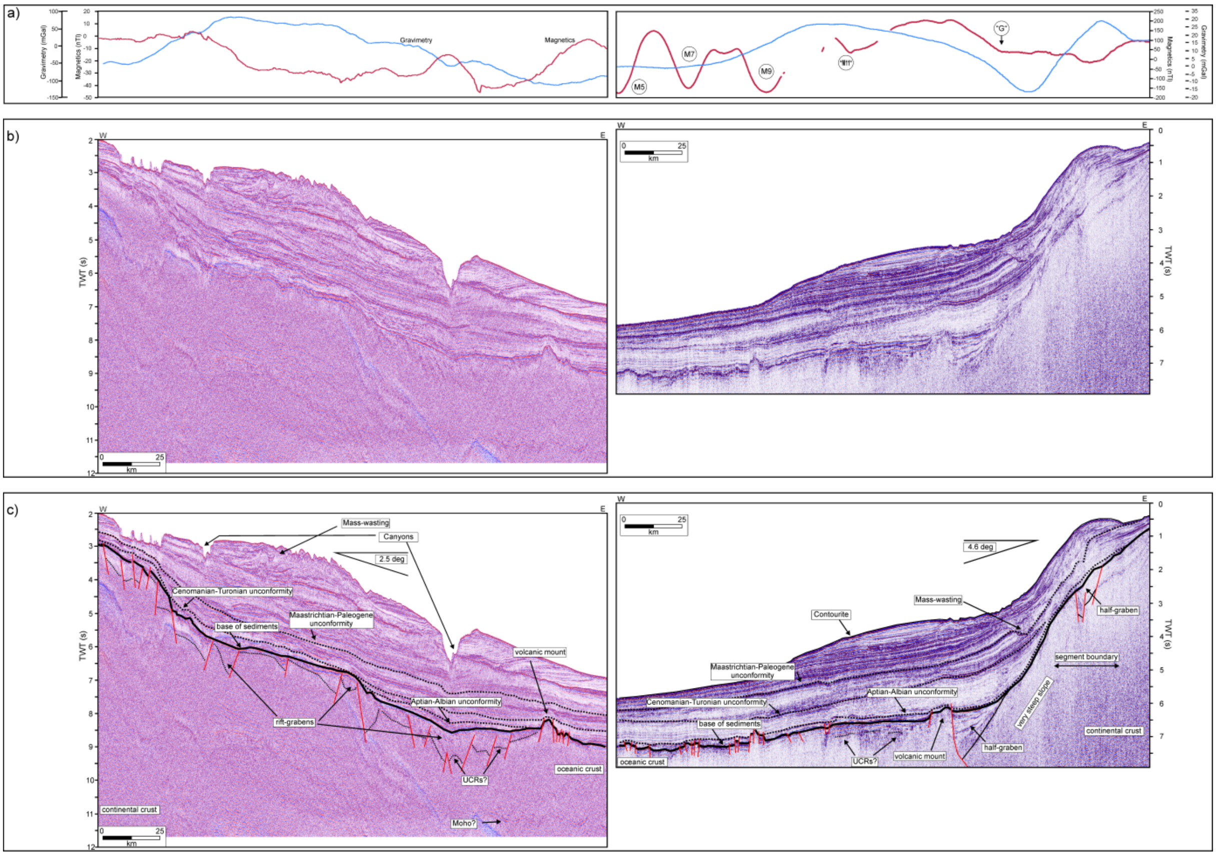

Fig. 3.3: Approximately conjugated sections of BGR marine geophysical data profiles BGR98-11 (left, South America) and BGR03-11 (right, South Africa) (see Figs. 3.1 and 3.2 for location); a) ship-track potential field data, b) uninterpreted multichannel seismic profile, c) interpreted multichannel seismic profile. The African profile features a comparably steep continental basement slope, few rift grabens and a volcanic mount.

Fig. 3.3 continued: Seafloor spreading anomalies can be correlated to as old as M9r on the African side. The base of sediments reflector is meant represent the onset of post-rift sedimentation but due to lack of well-control and margin parallel seismic data 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 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”, the linear “G-anomaly” from Rabinowitz and LaBrecque (1979) is indicated at the landward end of that zone.

80 km north of the southernmost MCS lines shown in Fig. 3.3, just north of the Colorado TZ respectively the Cape SB, the conjugated profiles (BGR98-20 & BGR03-12) (Fig. 3.4) show what the southern profiles were distinctively missing: sets of arcuate reflectors, commonly referred to as seaward-dipping reflectors sequences (SDRs) and 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 SDRs and related volcanics (outer wedges, upper crustal reflectors (UCR)) extend over a width of up to 200 km on the African (the maximum described for this “First-order Segment II”, Koopmann et al., 2014b), and 180 km on the South American profile and extend to up to 3.5 s two-way travel time (TWT) equivalent to 9 km thickness assuming a 5.5 km/s 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 to 3 (seaward of the “G-anomaly” of Rabinowitz and 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 SDRs 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 (post-rift) sediments reflector on the American side is again located about 2 s (TWT) deeper than the reflector on the conjugated African margin.

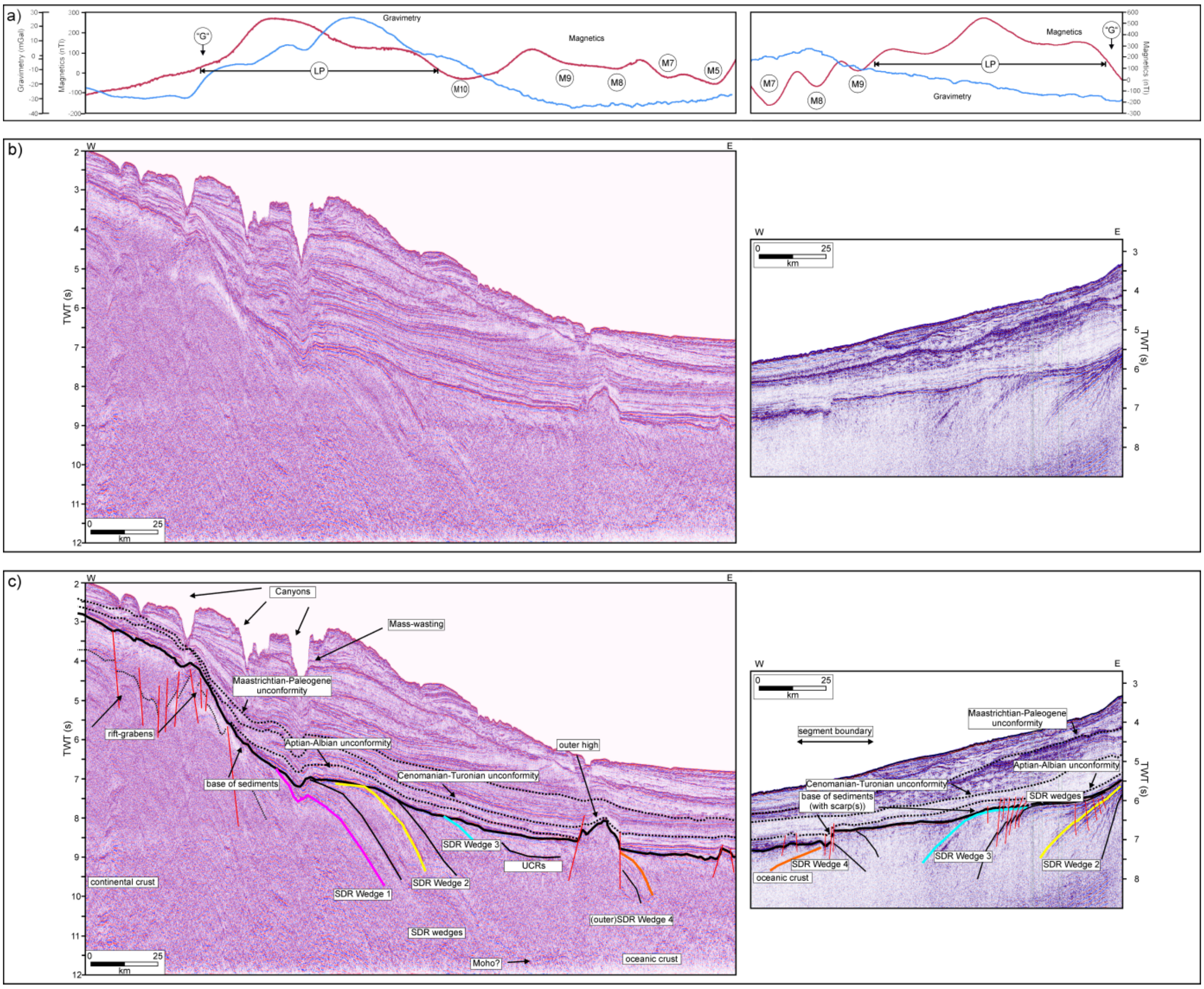

Fig. 3.4: Approximately conjugated sections of BGR marine geophysical data profiles BGR98-20 (left, South America) and BGR03-12 (right, South Africa) (see Figs. 3.1 and 3.2 for location); a) ship-track potential field data, b) uninterpreted multichannel seismic profile, c) interpreted multichannel seismic profile. These conjugated profiles (~ 80 km north of the profiles shown in Fig. 3.3) are remarkably different towards the more southern profiles regardless the spatial proximity. On both margins, huge wedges of arcuate, seaward-dipping reflector sequences (SDRs) are easily recognizable. The more landward SDR wedges 1 to 3 show a good fit to a positive magnetic anomaly (LP) next to the "G-anomaly" of Rabinowitz and 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 and LaBrecque (1979) is indicated at the landward end of that zone.

The third MCS transect shown here (BGR98-39 and BGR03-02A-04-04A), 300 km further north along the margins (Fig. 3.5) 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., 2014b). The basement slope angle side is now shallower than 1° on either margin, suggesting more pronounced crustal thinning due to 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 symmetric than those shown in Figs. 3.3 and 3.4. The arcuate SDRs 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 at a 150 km (and still close to the of 200 km seen on Fig. 3.4, the maximum described for “First-order Segment II”, Koopmann et al., 2014b) 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 margins base of sediment reflector is about 2 s (TWT) lower than its African counterpart.

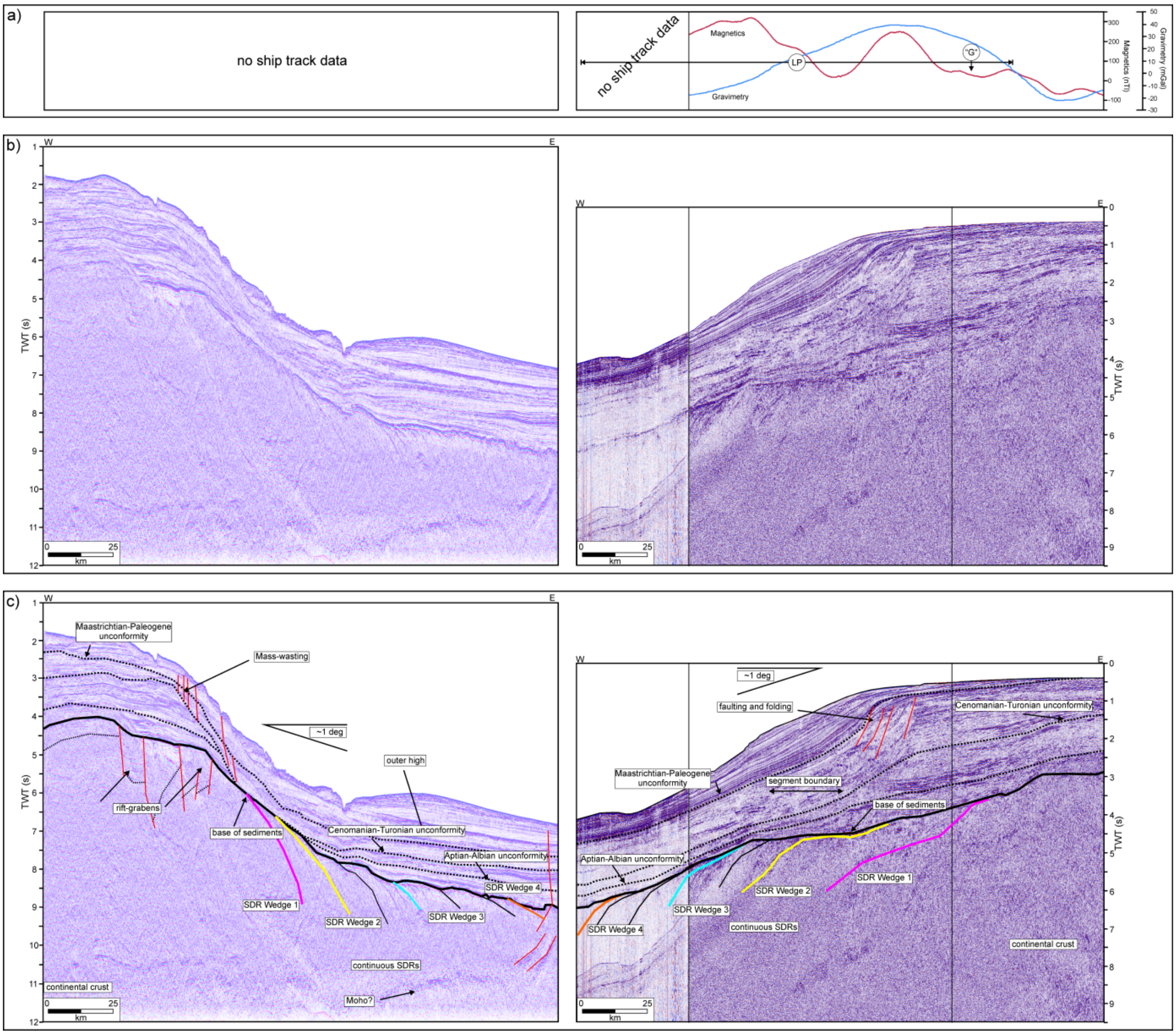

Fig. 3.5: Approximately conjugated sections of BGR marine geophysical data profiles BGR98-39 (left, South America) and BGR03-02A-04-04A (right, South Africa) (see Figs. 3.1 and 3.2 for location); a) ship-track potential field data (no data were recorded for the Argentinean profile and BGR03-02A), b) uninterpreted multichannel seismic profile, c) interpreted multichannel seismic profile. Compared to the more southerly profiles showing volcanics, the conjugated sections shown here (~ 300 km north of the ones shown in Fig. 3.4) show less distinct SDRs reflectors and definition of individual wedges is more difficult.

Fig. 3.5 continued: 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 1°. The profiles appear more symmetric 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 2 s (TWT) lower than its African counterpart. The large positive magnetic anomaly is marked "LP", the linear "G-anomaly" from Rabinowitz and LaBrecque (1979) is indicated at the landward end of that zone.

3.3.2 Conjugated magnetic features

The magnetic maps in Fig. 3.2 show two conjugated segments of the Argentine and South African margins as indicated in Fig. 3.1. Both maps have the same scale and 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 and 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 to 36°S but that the amplitude becomes continuously reduced to the north until the they are virtually absent from about 32°S.

Landward of M9 and north of 35°S a broad mostly positive magnetic anomaly over the continental margin is visible 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 G-anomaly (Larson and Ladd, 1973). It is a linear feature and marked "G" in the figures, 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.

3.3.3 Seafloor-spreading lineations

Rabinowitz and LaBrecque (1979) interpreted Chron M11 (~136 Ma (Gradstein and Ogg, 2004)) as the earliest spreading anomaly along the African margin from off Cape Town to the Orange Basin. Elsewhere (Nürnberg and 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 (~ 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 Figs. 3.2a,b and 3.2c,d it is obvious why the magnetic lineations on the African side were the first to be detected (Talwani and Eldholm, 1973; Larson and Ladd, 1973), as they have much higher amplitudes and are easier to correlate. Rabinowitz and LaBrecque (1979) identified anomalies M0 to M9 as shown in Fig. 3.2c,d as well anomalies back to M11. However, the location of pre-M7 / pre-M9 anomalies in the shelf region and the appearance of the anomalies does not suggest a typical seafloor-spreading origin (see Discussion). Rabinowitz and LaBrecque (1979) suggested a correlation with oceanic crust back to M11 but the more landward anomalies require a different explanation. Voluminous volcanic extrusives of the seaward-dipping reflector sequence (SDRs) type provide an explanation more suitable to account for the shape and the enlarged amplitudes of the margin parallel earliest magnetic anomalies at this margin. This proposal is derived from comparison with the extent of SDRs as mapped with the help of reflection seismic data (Franke et al., 2007;

Koopmann et al., 2014b). 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 and 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 offshore South Africa. These weaker anomalies however are predicted by the magnetic source model calculations. 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 identifications M2 and M4 are distinctively recognizable and serve, together with some indications for M0 as fix points from where the identifications 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 -09 where a distinct similarity between anomalies M4 to M10 with the model can be recognized. From here, correlations were continued to the more northern profiles along some prominent anomalies. These are the negative part of M7 which can be followed until 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 no more 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 -18. This is also visible in the magnetic map (Fig. 3.2a,b). Although there are some uncertainties, this 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 -09) (Figs. 3.2a,b and 3.4) turns into a wide negative anomaly on the adjacent lines to the north, interfering with the area of 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 Argentine side. The striking positive anomalies landward of these lineations (Fig. 3.2) seem to include normal intervals M10 and M11. These intervals are possibly identifiable within the large margin parallel positive magnetic anomaly

(Fig. 3.4a) 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 Agulhas Falkland Fracture Zone 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.

3.4 Discussion

3.4.1 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 and 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° and 33°S.

Magnetic lineations are an important proxy used to deduce spreading rates and infer opening ages for a given study area and comparing plate motions on a global scale (Gradstein and 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 margin-parallel large positive magnetic anomaly northward on both conjugate margins (i.e. in the N-S 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 (~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.

3.4.2 The G-anomalies

Rabinowitz and 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. Fig. 3.2 now shows that denoting this large positive margin parallel anomaly has very distinct meaning along the margins and was in the past also defined at places where no prominence in the magnetic anomalies can be detected from the new data as south of 44°S off Argentina and everywhere south of Cape Town. For the margin-parallel positive “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 massive SDRs. The re-interpretation of the large positive anomaly (LP) proposed here, is rather similar with the difference that additional volcanic material was emplaced. These effusives explain most of the large positive margin parallel anomaly’s extent. Further, Bridges et al. (2012) propose that the concept of using the first linear magnetic feature to date the onset of oceanic seafloor spreading possibly 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. The interpretation is another example for this problem. SDRs in the data can be viewed as equivalents of the axial rift volcanics basalts of Bridges et al. (2012). Reflection and refraction seismic data allow a more detailed model of the magnetic anomalies (Fig. 3.6).

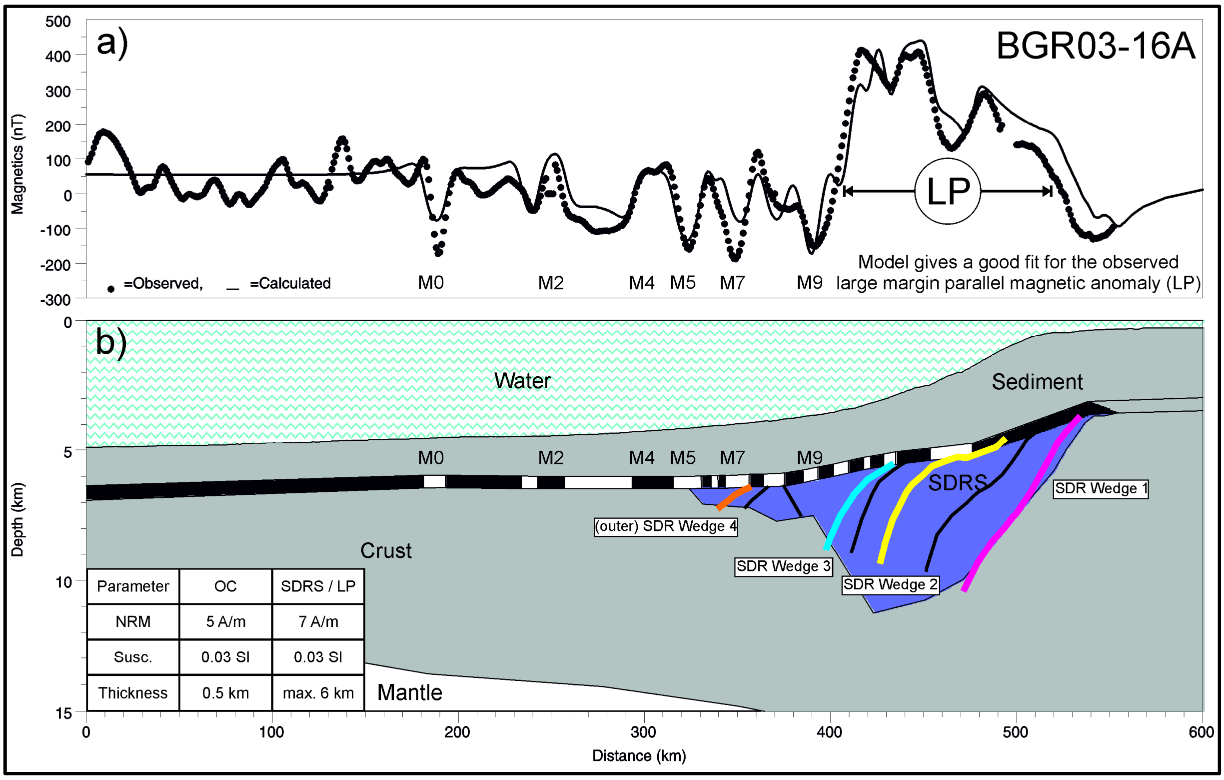

Fig. 3.6: Magnetic model for profile BGR03-16A (see Figs. 3.1 and 3.2 for location); a) observed ship-track magnetic data and modelling results with the extent of the large margin parallel magnetic anomaly (LP) marked by arrows, b) Magnetic model bodies with magnetic polarity intervals of the oceanic crust indicated in black (normal) and white (reversed). The model shows the feasibility to explain the long-wavelength character of the distinct, margin-parallel positive magnetic anomaly with a magnetic source body (blue) with a natural remnant magnetization (NRM) intensity of 7 A/m, susceptibility (Susc.) of 0.03 SI and a triangular cross-sectional area of about 600 km². Oceanic crust (OC) was modelled with an NRM value of 5 A/m 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 to be plausible. Also plotted are the results of SDRs mapping in seismic data, showing that the calculated size of the magnetic body fits to the dimensions of the observed SDRs wedges. Similar investigations on profiles on the Argentine margin revealed comparable results (Schreckenberger, 1997; Hinz et al., 1999).

Therefore, a new definition of the G-anomaly as a (mostly positive) large margin anomaly which 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 it can be seen in Fig. 3.2 it is not feasible to define it by a simple, single line in 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 in (e.g. north of Cape Town) and where it is not distinct or 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.

3.4.3 Emplacement of seaward-dipping reflectors sequences (SDRs)

It is widely accepted that seaward-dipping reflector sequences (SDRs) as interpreted in seismic reflection data are resulting from the impedance contrast (Planke and 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 and Keir, 2011) suggest 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 SDRs would overlie continental crust of varying thickness that thins quite dramatically towards the “seawardmost” SDRs.

Bauer et al. (2001) show for the northern Namibian margin landwardmost SDRs to overlie continental crust of about 30 km thickness, and seaward SDRs to overlie a high velocity lower crustal body (HVLC) of 15 to 20 km thickness with seismic velocities exceeding 7.0 km/s. Outer SDRs are described by these authors above slightly thickened oceanic crust of 15 km thickness and velocities of up to 7.0 km/s. On the conjugate South American margin, Schnabel et al. (2008) propose values of 25 to 20 km (partly thinned) continental crust underlain by a first high velocity lower crustal body of up to 7.3 km/s 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 SDRs derived from refraction seismic data is potentially not a clear indicator for COB / 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 less good and might indicate that the landwardmost SDRs in this area were not deposited during the same time span/magnetic polarity, respectively.

The data presented in this study support the general concept of subaerial, axial-parallel emplacement of volcanic effusives following adiabatic decompressional melting. However, the variable widths of the SDRs on either margin and also across the oceanic basin, questions the idea of symmetrical emplacement and/or symmetrical subsidence of SDRs 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 and 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 and 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-grabens 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 asymmetric 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). Asymmetric 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 SDRs to the COB is not homogenous along the South Atlantic margins and most likely variable on either conjugate section. The proposition here is accordingly not to define a continent-ocean boundary (COB) but rather a zone of continent-ocean transition (COT), which deems most reasonable 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 by Smythe (1983).

The origin of SDRs as extrusive basalt flows makes it likely that they have a strong magnetization. Fig. 3.6 shows that a magnetic source body with magnetization intensity of 7 A/m is capable to cause the long-wavelength character of the anomaly. The modelled magnetic body is only reasonably larger than the interpretation from MCS data suggest, further supporting the concept of magnetized basalt flows to be 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 (namely the magma-poor Iberian margin) 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.

3.4.4 SDRs and the Paraná-Etendeka LIP and Tristan hot-spot

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 Mkm²) mapped as SDRs in the South Atlantic is on-par with other large igneous provinces (LIPs) around the globe, such as the 2 Mkm² of the Paraná-Etendeka (Peate, 1997; see Fig. 3.1 for approximate extent), 0.75-1.75 Mkm² of the Deccan Traps and Seychelles province (Mahoney, 1988; Devey and Stephens, 1992; Verma and Banerjee, 1992), 2.5 Mkm² of the Siberian Traps (Fedorenko et al., 1996; Reichow et al., 2009) or the > 0.2 Mkm² 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 10s of km shown in this study appears difficult to be explained by a distant hot-spot. Rather this argues for local variations in melt supply. Further, the Tristan hot-spot 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 SDRs 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 a link to localized melting that may be related to segment boundaries is suggested. For mid-ocean ridge basalts, varying compositions across segment boundaries (Salters, 2012) have previously been shown and also support the notion of elongated, but bound to margin segments, feeder magma chambers.

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

Depending on which current geologic / geomagnetic time scale is used (Fig. 3.7), the period of maximum emplacement of the Parana Etendeka LIPs (Hawkesworth et al., 2000) and thus the peak activity of the hot-spot turns out have 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 to 131 Ma for Paraná activity from Hawkesworth et al. (2000). The only timing information on the SDRs 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 ~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 few (means about 3) million years are supposed for the formation of these features, resulting in an initial emplacement at about middle Valanginian times. 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 hot-spot 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 to 131 Ma for Paraná activity from Hawkesworth et al. (2000). The observed influence of the hot-spot renders GTS 2012 more plausible for the study area. With the MHTC12 timescale, magmatic activity in the north postdates the peak activity of the Paraná volcanic province. However, within 200 km diameter of the hot-spot, the architecture and style of the SDRs implies a direct influence of the hot-spot. This period of increased melt production is better covered using GTS 2012. However, the duration of elevated temperature after arrival of the hot-spot is unknown and might also increase melt-production once rift has reached this limited area of elevated temperature.

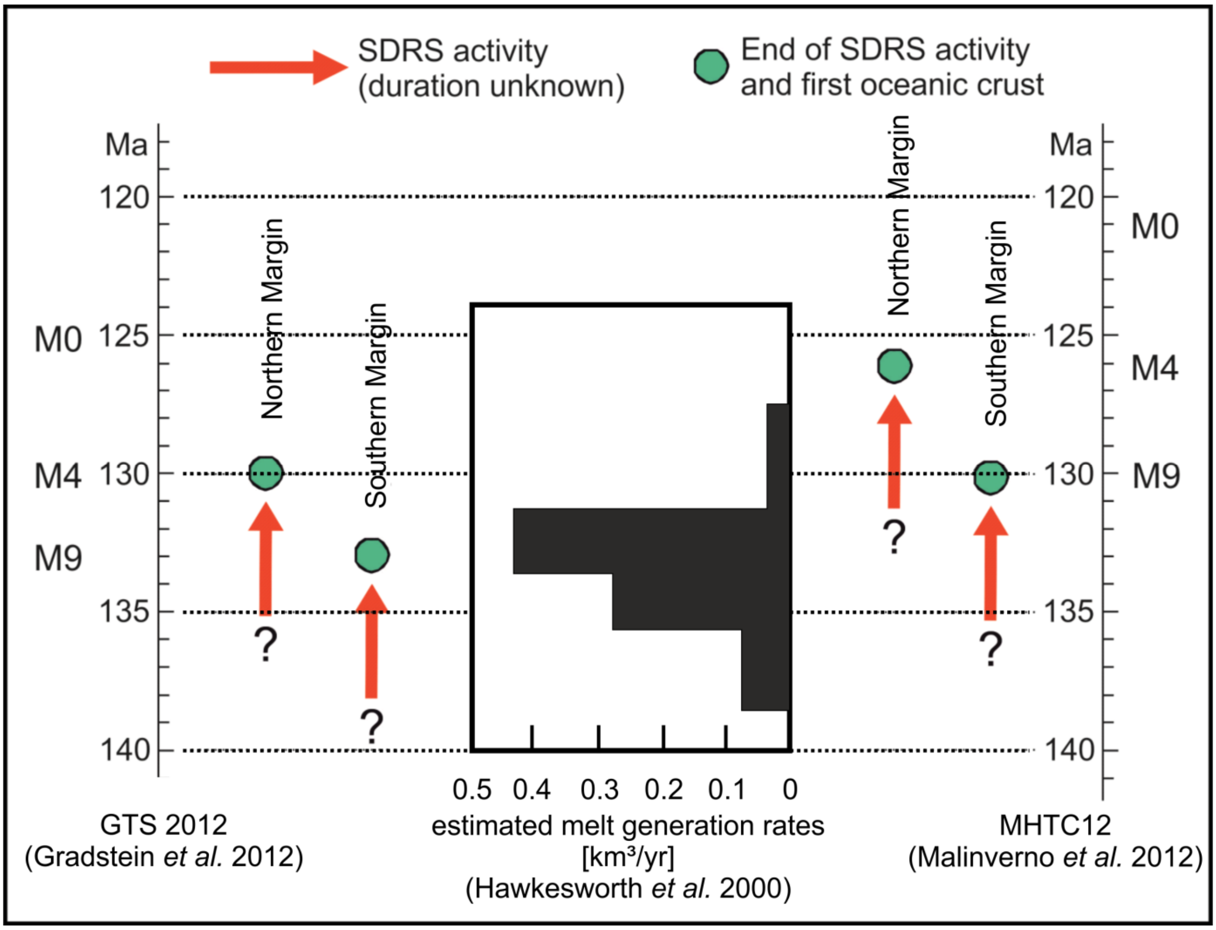

Fig. 3.7: Comparison of the effect of uncertainties in global time scales for the temporal relationship of SDRs emplacement and peak activity of the Paraná LIP. Depending if the Global Time Scale 2012 (GTS12) (Gradstein et al., 2012) or the M-sequence geomagnetic polarity time (MHTC12) (Malinverno et 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). Southern margin indicates a location approximately offshore Cape Town; 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.

3.4.5 Geometrical difficulties of uni-directional opening of the South Atlantic

A simple reconstruction of rigid African and American plates causes geometrical problems. If axial-parallel (although asymmetric in volume) emplacement of SDRs is assumed, SDRs in the South Atlantic should align without N-S “offset” on both margins once reconstructed (Fig. 3.8). However, a uni-directional E-W reconstruction leads to a significant N-S “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 Agulhas-Falkland Fracture Zone and the Colorado Transfer Zone / Cape Segment Boundary on side of the South Atlantic (Fig. 3.1). 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 Agulhas-Falkland Fracture Zone 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.g. Torsvik et al., 2009; Moulin et al., 2010; Heine et al., 2013) for reconstruction models that include the South Atlantic. For the modest scale and comparably small study area of this research, the existing rotation pole sets all show different problems for the earliest phase of southern South Atlantic opening (Fig. 3.9). 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 sub-plates. In contrast, the Heine et al. (2013) poles do not produce onshore overlap, but the offshore fit is less good. The different extensional domains from south to north (Fig. 3.10) are also reflected in margin-parallel basin axes on the South African in contrast to margin-perpendicular basin axes on the southern South American basins. For example, Pángaro and 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 W-E striking basin axis. The Colorado Basin has been argued to represent a failed rift system (Franke et al., 2006; Pángaro and Ramos, 2012) instead of a sag basin. This notion is supported from the data presented here, according to which the Colorado Basin and similar oriented sedimentary basins on the southern South American margin may have formed in the earliest stage of crustal thinning and rifting which favored N-S extension, prior to the succeeding of the W-E extension direction still observed today.

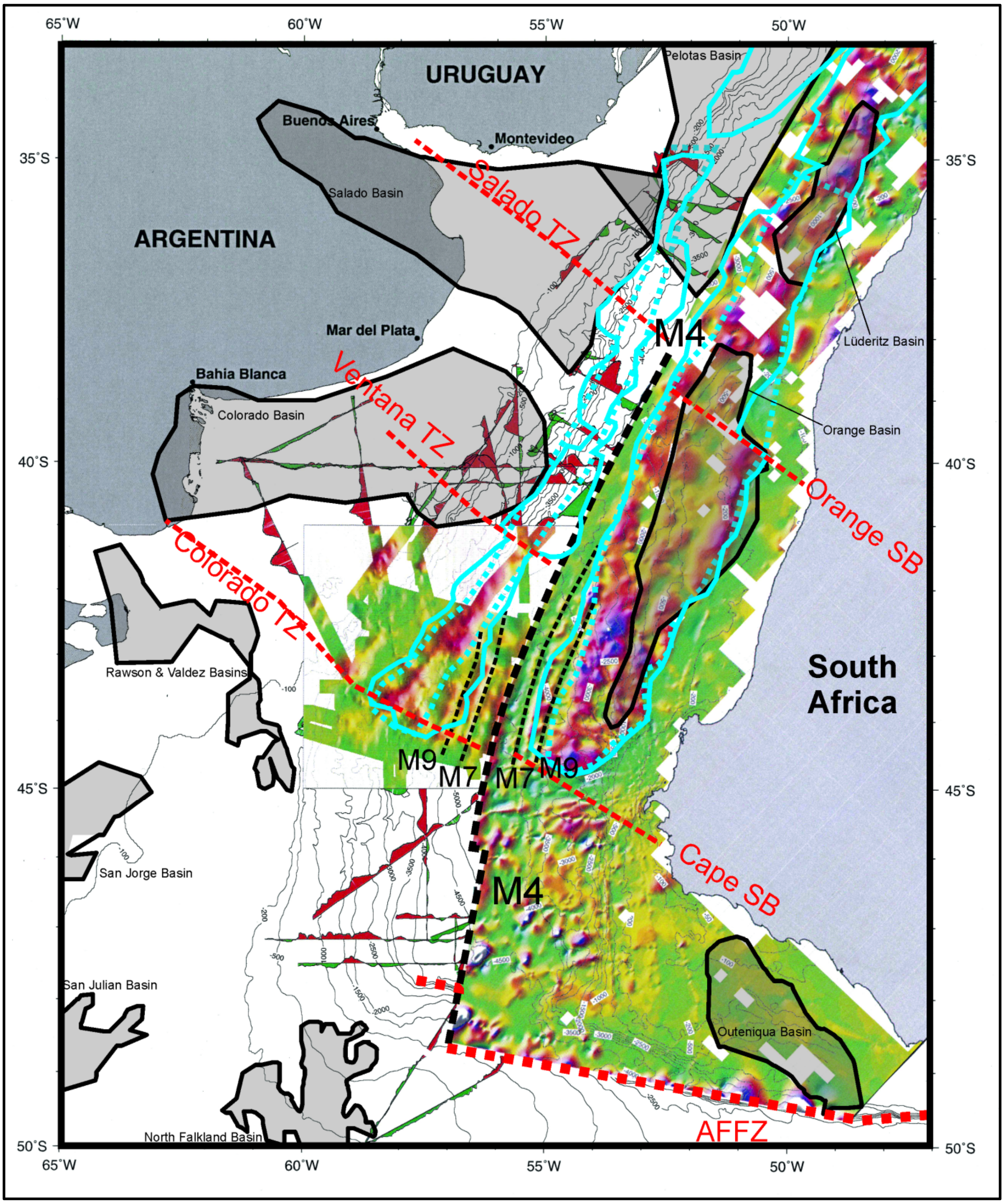

Fig. 3.8: Manual reconstruction to seafloor spreading anomaly M4 of the southernmost South Atlantic. Detailed SDRs extent: thick blue line; conservative SDRs extent (not including outer highs, flat lying flows or outer wedges): thick blue dots; Magnetic anomalies are named and drawn in black dashes. 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-symmetric emplacement of volcanics along the spreading axis is the most likely scenario for the SDRs formation, there should be no N-S offset between SDRs on either margin after full reconstruction.

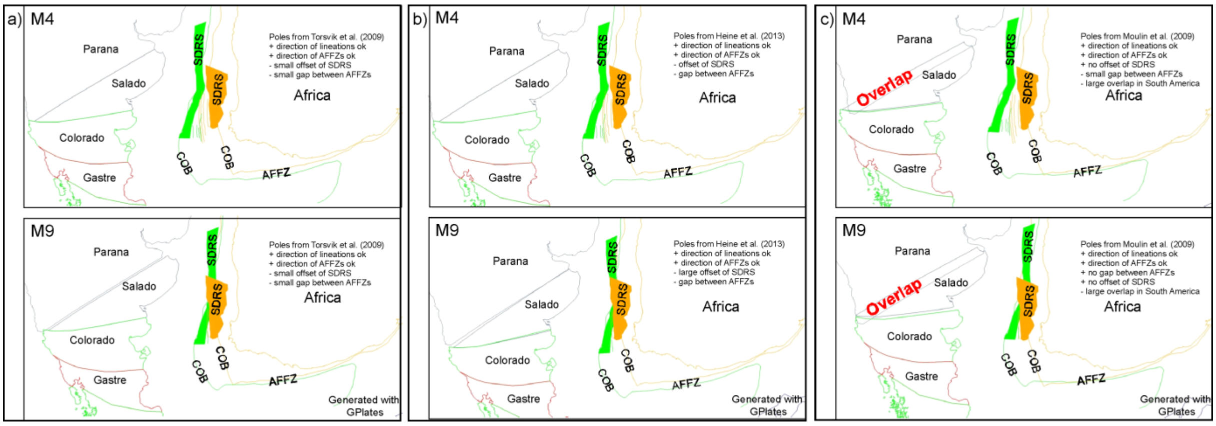

Fig. 3.9: Comparison of three recently published rotation pole sets in the study area. a) Reconstruction of the study area in the South Atlantic at M4 (126 Ma) and M9 (129 Ma) according to the rotation poles proposed by Torsvik et al. (2009); b) Reconstruction of the study area in the South Atlantic 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 this 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.

It is proposed that this extensional regime caused movements within the South American plate assembly, allowing for the W-E oriented sedimentary basins to form. On the South African margin, the sedimentary basins opened the way expected from a W-E extending rift, i.e. their basin axis is sub-parallel (N-S) to the main rift axis, indicating W-E extension for these basins. This indicates that the main recipient of the N-S extension was the South American plate (rotational intra-plate deformation) and the rift basins on the African margin developed subsequently 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). Intra-plate deformation of the South American plate along major sutures of limited extent (versus diffuse distribution) within the Brazilian Craton and / or between the Brazilian and Guyana Craton has previously been suggested (Unternehr et al., 1988). Following Eagles (2007), Moulin et al. (2010) also propose intra-plate deformation of South America as the main actor within 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. 3.10) in extensional direction fits onshore findings from South Africa and Namibia describing rotations of the main extensional domain from NNE-SSW extension documented in the Saldania Belt near Cape Town to W-E extension from the Gariep Fold Belt on northwards up to the end of their study area in northern Namibia (Will and Frimmel, 2013). 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 syn- 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 an ENE-WSW directed extension (Will and Frimmel, 2013) and ESE-WNW directed extension (Salomon et al.; pers. comm.; E. Salomon, July 2013), respectively, is derived from onshore measurements. The margin-perpendicular basins on the South American side shown in Fig. 3.10 also reflect the South American plate assembly as the main recipient of N-S extension and accordingly intra-plate 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 which was approximately perpendicular to the present-day continental margin.

It is thus proposed 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 Colorado Transfer Zone / Cape Segment Boundary 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.

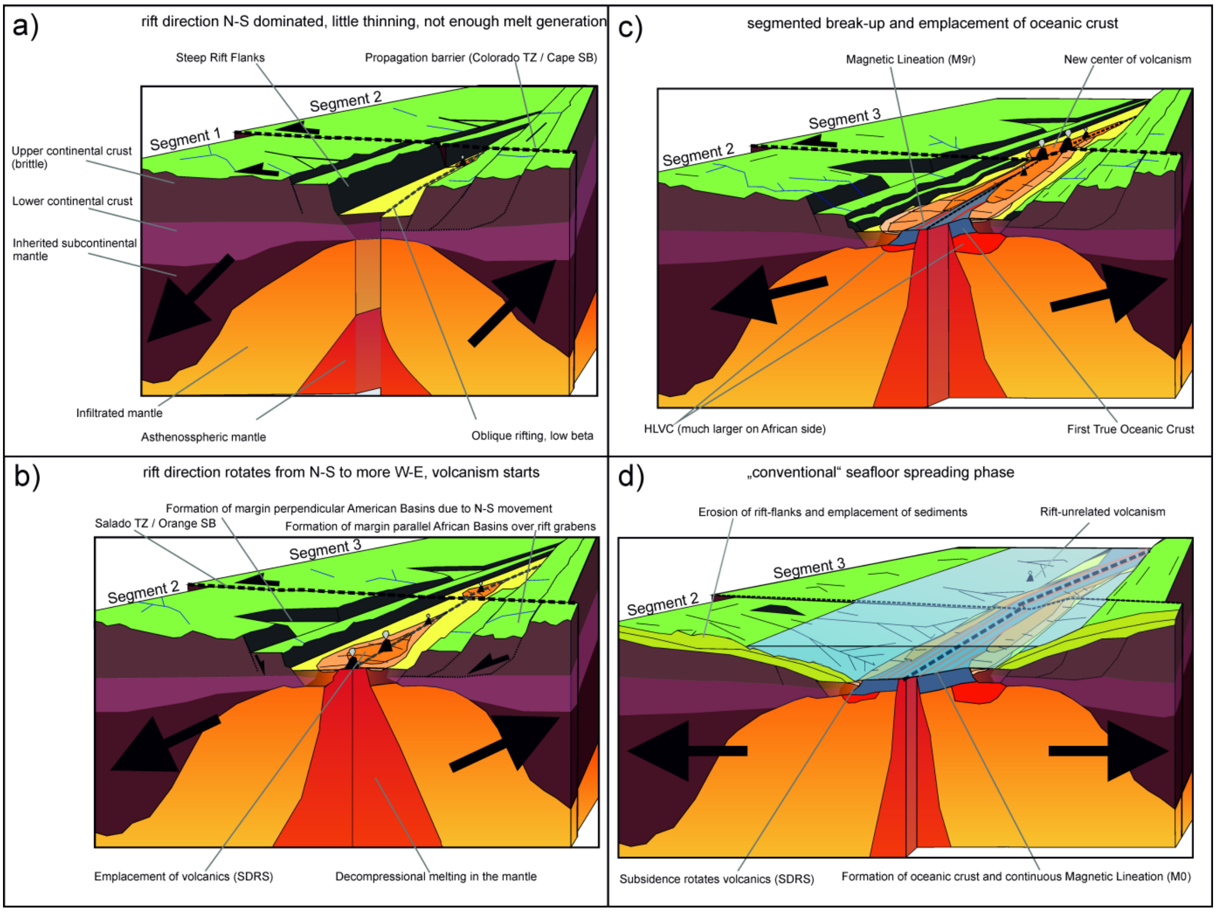

Fig. 3.10: 4D Conceptual Sketch Model for the opening of the southernmost South Atlantic. a) View of the southernmost, magma-poor Segment 1 of the South Atlantic. Opening of this segment occurred in an dominatingly oblique manner, with the American plate moving mostly southwards relative to the African 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 N-S 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 (W-E extension) of volcanics on both margins combined was possible due to the more extensively thinned crust; 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. (2001) and Schnabel et al. (2008) to be thickened (15 to 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 center of volcanism along the Segment Boundary. Asymmetric (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.

3.5 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 for 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 at 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 SDRs 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 a southward movement relative to the African plate. This is reflected today in an N-S “offset” in the SDRs 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 a 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 hot-spot 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 10s of km. This is more plausibly explained by a local change in spreading regime than sudden impact of a hot-spot centered 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 timescale used the emplacement of the Parana Etendeka LIPs and peak activity of the hot-spot post-date the emplacement of first oceanic crust and thus the emplacement of SDRs.

Only within 200 km from the proposed hot-spot location a consistent relationship between the hot-spot and increase in magma production can be deduced. Volcanic material is proposed to have flown from the break-up center towards the margin, imaged today as SDRs. In closer proximity to the hot-spot (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 hot-spot is consequently interpreted as limited to about 200 km.

Chapter-specific acknowledgments

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4. LINKING TRANSFORM FAULT ZONES TO VOLCANIC MAXIMA AT VOLCANIC PASSIVE MARGINS

Remarks

Contents of this chapter have been published with adaptations as a peer-reviewed research paper:

Koopmann, H., Brune, S., Franke, D., Breuer, S., 2014. Linking rift propagation barriers to excess magmatism at volcanic rifted margins. Geology, Advance online publication. http://dx.doi.org/10.1130/G36085.1

Abstract

Break-up-related extrusive magmatism, imaged in reflection seismic data as seaward dipping reflectors (SDRs), extends symmetrically along the volcanic margins of the Atlantic Ocean. Recent research found distinct along-margin variations in the distribution of SDRs and abundance of volcanic material was found to be spatially linked to transfer fault systems. These segmented the propagating rift that later developed into the ocean and are interpreted as rift propagation barriers. Based on these observations, we develop a numerical model, which shows that rift parallel mantle flow and locally enhanced rates of volcanism are the result of delays in rift propagation and segmented opening. Our model suggests that segmentation is one of the major factors in the distribution and localization of rift-related extrusive magmatism. We conclude that in addition to mantle temperature and inherited crustal structures (e.g. weaknesses from previous rift episodes), rift propagation delay plays an important role in the distribution of extrusive volcanism at volcanic passive margins by controlling the mantle flow beneath rift axis.

4.1 Introduction

Continental break-up is frequently accompanied by extensive intrusive and extrusive magmatism (Fig. 4.1). The volcanic rifted character of large portions of the Atlantic Ocean is known since decades (e.g. Hinz, 1981; Mutter et al., 1982; Roberts et al., 1984; Eldholm et al., 1986; White et al., 1987; Holbrook et al., 1994; Clemson et al., 1997). In the following the focus is on the southern South Atlantic and the northern North Atlantic, both the result of a preceding propagating rift. Volcanic rifted margins in these portions of the Atlantic have been shown to be segmented, with segments separated by transfer zones (e.g. Planke et al., 1991; Tsikalas et al., 2001; Eldholm et al., 2002; Tsikalas et al., 2005; Franke et al., 2007; Soto et al., 2011; Koopmann et al., 2014b; Stica et al., 2014), although parts of the segment boundaries in the North Atlantic have been questioned (Olesen et al., 2007).

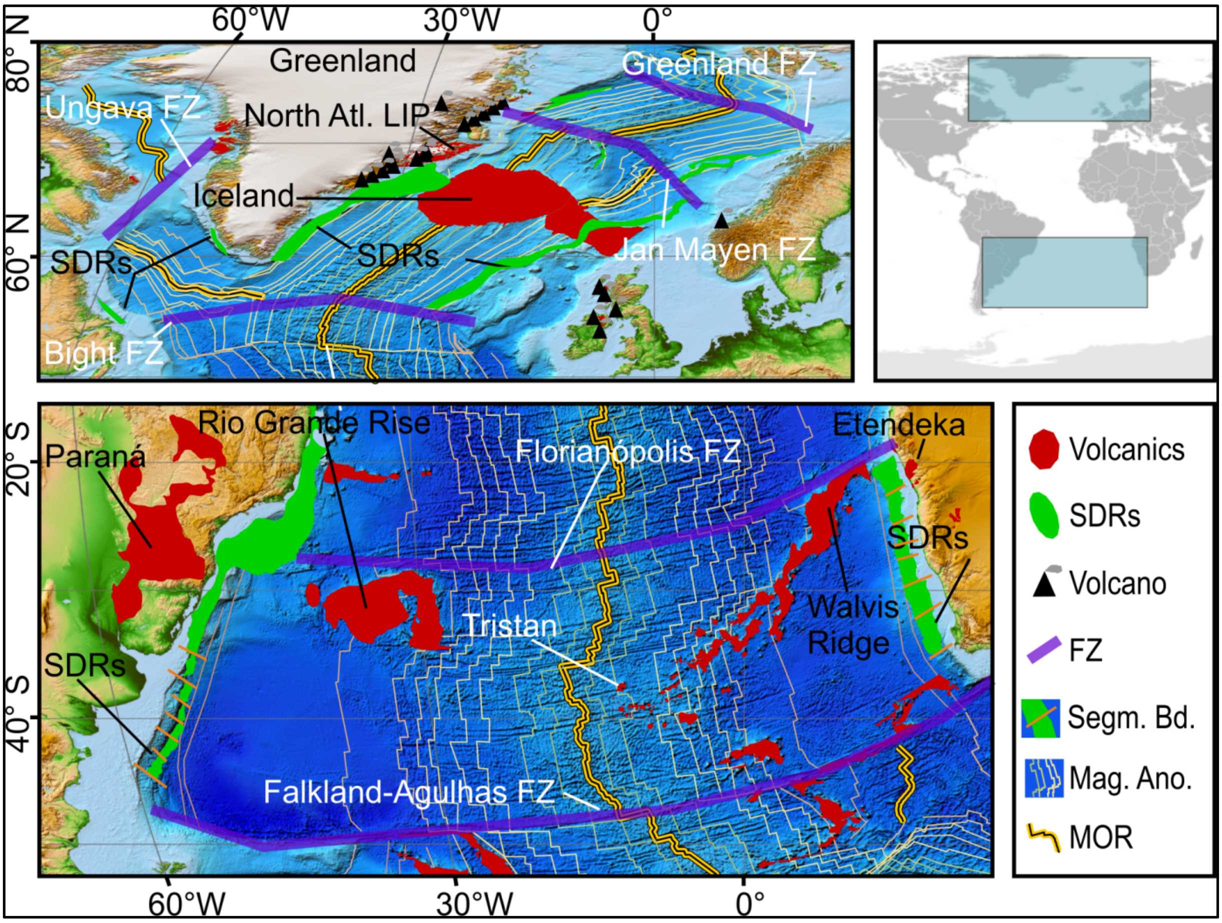

Fig. 4.1: Topobathymetric (ETOPO1) map of the study areas. Indicated on the map are the locations of relevant off- and onshore Large Igneous Provinces (LIPs), Marine Magnetic Anomalies and other structural elements of the South and North Atlantic. Note the apparent spatial correlation between fracture zones (FZ) and areas of volcanic activity. Structural information compiled from Bryan et al. (2010), Courtillot et al. (2003), Franke et al. (2007) and Koopmann et al. (2014b).

Segmentation of continental margins dates back to the early rifting stage where a propagating rift has been compartmentalized at high angles. This may either result from the structural grain of the rifted area, where previous zones of stiffness or weakness may guide the rift, or by the mode of rifting, where accommodation zones are interpreted that transfer displacement or strain from one rift-graben segment to another with opposite sense via oblique shear (e.g. Rosendahl, 1987). Morley et al. (1990) developed a classification of extensional fault displacement zones and introduced the term “transfer zones”.

Offshore volcanics, known as seaward dipping reflectors (SDRs; e.g. Hinz 1981; Mutter et al., 1982; Planke and Eldholm, 1994) are offset or dissected along such transfer zones (Fig. 4.2). In the South Atlantic an intrinsic relationship between the volumes of SDRs and the presence of segment boundaries has been proposed (Franke et al., 2007). It might be speculated that variations in the volumes of the extrusive magmas are the result of varying accommodation space within the rift, potentially resulting from the presence of segment boundaries but also that rift propagation barriers by themselves cause variations in the volumes of melts. Analogue models by Bonini et al. (2001) indicate that lateral flow of viscous material play a role in rift-flanking volcanism as found in the East African Rift system. While variations in mantle temperature are considered to have primary control on melt generation (Pérez-Gussinyé et al. 2006), they cannot account for small-scale variations in melt supply.

Here it is proposed that the stresses related to plate separation create shallow, pressure-driven flow across segment boundaries thereby generating along-strike variations in melt volumes without additional deep mantle upwelling.

4.2 Volcanism and break-up in the South and North Atlantic

4.2.1 The South Atlantic

There was significant extension at least from the Late Triassic (about 210 Ma; e.g. Stollhofen et al., 2000; McDonald et al., 2003) until the South Atlantic opened in the Early Cretaceous at about 134 Ma. Almost all of south and west Gondwana was affected by magmatism in the Late Triassic (McDonald et al., 2003) before volcanic activity related to break-up of the South Atlantic and leading to emplacement of the Paraná-Etendeka large igneous province (LIP) in Brazil and Namibia and northern South Africa peaked in late Hauterivian–early Barremian (134-129 Ma; Peate, 1997).

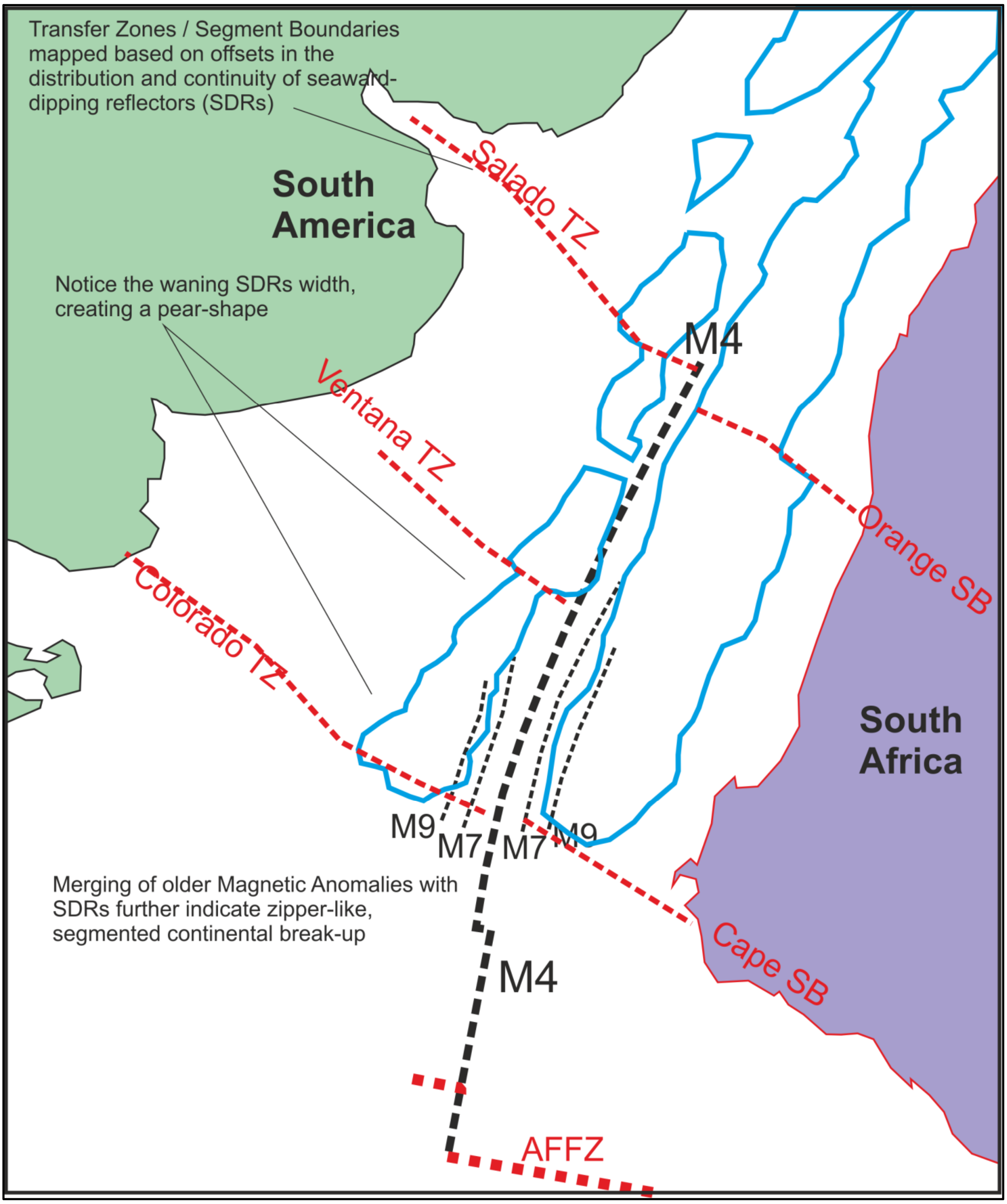

Fig. 4.2: Simplified plate reconstruction of the South Atlantic margins to Magnetic Anomaly M4. The term margin segmentation as used in this research is derived from detailed mapping of South American (e.g. Franke et al., 2007) and South African (e.g. Koopmann et al., 2014b) margin structures. Most importantly, the onset of and offsets within offshore volcanic units, reflected in seismic data as seaward dipping reflectors (SDRs) allow the definition of segment boundaries or transfer zones along the margin. Further, magnetic anomalies merge with the mapped area of SDRs occurrence, underlining the idea of a segmented continental break-up from south to north.

There is consensus in the literature that the opening of the southern segment of the South Atlantic occurred diachronously, rejuvenating from South to North (e.g. Rabinowitz and Labrecque, 1979; Austin and Uchupi, 1982; Sibuet et al., 1984) and may be described as a successive northward unzipping of rift zones (e.g. Jackson et al., 2000; Franke et al., 2007).

The onset of seafloor spreading in the central segment of the South Atlantic, to the north of the Florianópolis Fracture Zone (Florianópolis FZ), initiated much later, during the Aptian–Albian boundary, at about 112 Ma (e.g. Torsvik et al., 2009; Moulin et al., 2010). Thus, there is an interval of approximately 20 Ma between the break-up age of the segment south of the Florianópolis Fracture Zone (132-130 Ma) and the break-up of the segment north of the fracture zone (112 Ma). In contrary to the widespread supposition that the opening of the South Atlantic was triggered by the Tristan plume, continental break-up was considerably delayed at the proposed pre-break-up position of the Tristan hot-spot (Franke, 2013). The hot-spot was likely located at the tip of an aborted rift and an intrabasinal ridge jump to the final break-up position resulted in the opening of the central segment of the South Atlantic (Moulin et al., 2010). Mohriak (2001) suggests that an oceanic propagator advanced from the Pelotas Basin, south of the Florianópolis FZ towards the Brazilian Santos Basin, but was aborted and deflected in an en-echelon pattern towards the east, as the break-up progressed across the fracture zone (Mohriak et al., 2008).

For the offshore volcanics, an age progression from South to North is distinct from the relation of the most seaward SDRs and the oldest magnetic seafloor spreading anomaly, adjacent to the SDRs. In the southernmost volcanic segment, Koopmann et al. (2014c) found conclusively M9 as the oldest anomaly seaward of the SDRs and 2000 km further north the corresponding magnetic anomaly is M0, marking a difference of approximately 10 Ma.

4.2.2 The North Atlantic

Continental break-up in the North Atlantic culminates a ~350-Ma-long period of predominately extensional deformation in the northern North Atlantic subsequent to the Caledonian orogeny (e.g. Ziegler, 1988; Mosar et al., 2002).

During break-up two sublinear rift segments in the south and north were connected by a winding segment in the middle (Larsen et al., 1994). This winding segment is the center of the North Atlantic LIP. The main flood basalt succession in East Greenland is traditionally thought to have been erupted at 56–55 Ma (e.g. Eldholm et al., 1989; Storey et al., 2007). However, plateau basalts in Scoresby Sund (East Greenland) in the center of the North Atlantic LIP were emplaced during three separate volcanic episodes (Larsen and Watt, 1985) and are interpreted to represent repeated unsuccessful attempts uniting the southern and northern spreading axis segments into one linear feature (Larsen and Watt, 1985). The first and second episodes failed, but the third episode at around 55 Ma is correlated with formation of the now extinct seafloor spreading axis at C24.

Thus, rifting and seafloor spreading was not continuous between Greenland (including the associated proto-Jan Mayen microcontinent) and Eurasia (Gaina et al., 2009). Complex rifting including formation of a highly extended or even fragmented Jan Mayen microcontinent (Gaina et al., 2009) is indicated by geometrical difficulties in reconstruction of conjugate SW Vøring and NE Greenland margins (Olesen et al., 2007). Assuming continent-ocean transition at the SDRs province along the shelf break (Hinz et al., 1991), oceanic spreading anomalies terminate against the NE Greenland continental slope. Break-up started at C24B in the north with an oblique angle of the anomalies C24A, C23 and C22 along the margin between Shannon Island and the Jan Mayen FZ. If this is correct, spreading propagated southward towards the proposed hot-spot location, starting at the Greenland FZ at 54.2 Ma and ending at 50 Ma near the proto-Jan Mayen FZ, as has been proposed by Lundin (2002) and Voss et al. (2009). Simultaneously, the Atlantic spreading system propagated northwards along the proto-Reykjanes and proto-Kolbeinsey ridges (Lundin, 2002), creating overlapping spreading centers on the Greenland–Iceland Rise that persisted to C6 (20 Ma). The Jan Mayen FZ was an active, complex oceanic transform zone between the two spreading ridges until progressive abortion of Aegir Ridge between C13n and C6B (Gaina et al., 2009; Gernigon et al., 2012). A major delay in break-up at the position of the proposed plume is also derived from subsidence modeling. Clift (1997) argued from subsidence data from ODP Site 918 and from the structure of the Greenland-Iceland Ridge that the Iceland Plume did provide significant thermal input into the region only from 44 Ma.

Such delay in thermal input is supported by East Jan Mayen FZ feature Vøring Spur's structure, which is interpreted as an atypical oceanic feature (Gernigon et al., 2009). The 16-to 17-km-thick oceanic crust of the structure is surprising, as average oceanic crust is only 7 km thick. Thickened crust of ~25 km thickness is also reported for the Baffin Bay in the western branch of the North Atlantic system (Funck et al., 2012). The thickening of the crust is comparable in size to a lower crustal body modeled beneath the Vøring Marginal High (Mjelde et al., 2007). Existence of thick oceanic crust below Vøring Spur provides evidence that anomalous melt production still persisted (or started only) after break-up of the Mid-Norwegian volcanic margin.

4.2.3 Margin segmentation

A frequently described feature of continental margins is segmentation along transfer zones or segment boundaries. For example, Soto et al. (2011), derive a system of transfer faults along the Uruguayan margin which divide the margin into two major segments. These authors define these transfer faults in the Rio de la Plata region based on SDRs, magnetic anomalies and depot center properties. The transfer faults divide the Uruguayan margin in two segments. Clemson et al. (1997) reported along margin segmentation on the conjugate African margin.

Franke et al., 2007 for the Argentinean margin and Koopmann et al., 2014b for the southern African margin derive margin segmentation from the onset, lateral offsets and varying sizes of SDRs in a similar manner (Fig. 4.2). Based on magnetic anomalies it is further underlined in Koopmann et al. (2014c) that opening of the South Atlantic happened successively in a segmented style, as older magnetic anomalies are only reported for the southernmost segments. Segments opened with 10-15 Ma time difference. Franke et al. (2007) also suggest a mechanism for the distinct pear-shape of SDR units along the South American margin, suggesting that the initial opening of segments occurs in triangular way and the tip of the triangle might be starved of melt by the emplacement of larger volumes near the initiation of rifting in each rift segment.

Elliott and Parson (2008) suggest strong along-axis segmentation for the northeast Atlantic between Norway and Greenland. Their model incorporates three major segments based on variations in SDRs distribution and the presence of the Hatton Bank Block and Endymion Spur. The authors also point at the strong influence segmentation has on break-up style and post break-up volcanism.

4.2.4 Condensend structural findings

Both the North and the South Atlantic share a couple of common characteristics:

Both oceans are the final result of long-lasting extensional phases and of propagating rifts. Break-up took place in individual segments bounded by transfer zones.

Besides the segmentation, rift delay at the transfer zones coincides with the rift-parallel emplacement of abundant volcanics both off- (South Atlantic SDRs, North Atlantic SDRs) and onshore (Paraná-Etendeka LIP, Jan Mayen LIP, Vøring Plateau).

Initiation of rifting occurred distal from the proposed hot-spot location with a rift migration towards the hot-spot position and there is consistently delay in rifting at the proposed location of hot-spots.

This questions the earlier proposition that continental rifting commonly follows flood basalt volcanism (Richards et al., 1989) and it appears unlikely that hot-spots triggered and initiated the opening of the North and South Atlantic Ocean.

Rather, abundant volcanism is found at the location of large-scale transfer zones and fracture zones. The most prominent examples are the Jan Mayen Fracture Zone system in the North Atlantic and the Florianópolis Fracture Zone in the South Atlantic. Variations in extent of volcanism (SDRs) are also observed on a smaller scale.

These findings were used to establish a conceptual model without a deep mantle thermal upwelling to set up the numerical model (Figs. 4.3-4.5).

4.3 Methods

Numerical modelling tests the concepts presented in this paper. Using the three-dimensional, implicit, finite element code SLIM3D (Semi-Lagrangian Implicit Model for 3 Dimensions, (Popov and Sobolev, 2008) the thermo-mechanically coupled conservation equations of momentum, energy and mass are solved. The code has been successfully applied in a number of 3D rift experiments (Brune et al. 2012, Brune et al. 2013, Brune & Autin 2013, Heine & Brune 2014). The model consists of a 1500 km long domain that is 250 km wide and 150 km deep (Fig. 4.3a). It comprises laterally homogeneous felsic and mafic crustal layers, a strong mantle that is dominated by dry olivine rheology and a weak mantle layer that is governed by a wet olivine flow law (Fig. 4.3b). In order to localize deformation to the center of the model, an elongate weak zone is introduced in the middle of the prospective rift zone by means of a small temperature anomaly (Fig. 4.3a,b) which effectively mimics a small amount of lithospheric thinning. An extension velocity of 10 mm/yr is applied at both boundaries in x-direction resulting in a full rift velocity of 20 mm/yr. This velocity is comparable to the extension rate of the southern South Atlantic rift system (Heine et al., 2013). In order to test the effect of sequential segment activation, rifting for the first 500 km long segment is imposed from the beginning while the remaining 1000 km of the model experience zero extension. After 5 My, the second rift segment (between y=500km and y=1000 km) is activated with the same extension velocity and only the third segment remains inactive. From 10 My on, all segments extend with 20 mm/yr. Transfer faults between the segments are introduced by reducing the friction coefficient from 0.5 to 0.05. The top boundary has a free surface, the boundaries facing in y-direction feature a free slip condition, while the bottom boundary allows for in- and outflow of material through a dynamically tracked Winkler boundary condition (Popov & Sobolev, 2008). Decompression melting of mantle material is incorporated in a post-processing step. A Peridotite batch melting model using the formulation of Katz et al. (2003) is applied, taking into account the consumption of lattice energy (Brune et al. 2014). For simplicity, vertical and total melt extraction is assumed.

4.4 Model results

Fig. 4.3c shows the sequential segment activation both in terms of strain rate and velocity vectors. The velocity vectors shown in the figures indicate the direction of material flow in each element. Continental break-up is accomplished upon break-up of the entire lithosphere when the initially lowermost layer reaches the surface. As expected, break-up occurs via rift propagation from low y-values to high y-values, corresponding to the segmented break-up observed in the South and North Atlantic. Simultaneously, decompression melting occurs in a ~ 40 km thick region that progresses along-strike (Fig. 4.3d). The segment boundaries feature distinctly increased along-strike velocities of the material flow (Fig. 4.4a, vectors therein) upon segment activation. Note that flow directions perpendicular to the rift axis (i.e., positive y-values) at segment boundaries coincide with the arrival of the 2% melt contour. Material flow directions are massively influenced by the rift delay. While the free-slip boundary condition at the y-facing model sides allows only vertical velocities, the transfer fault system in the model interior shows distinct rift-parallel components of material flow.

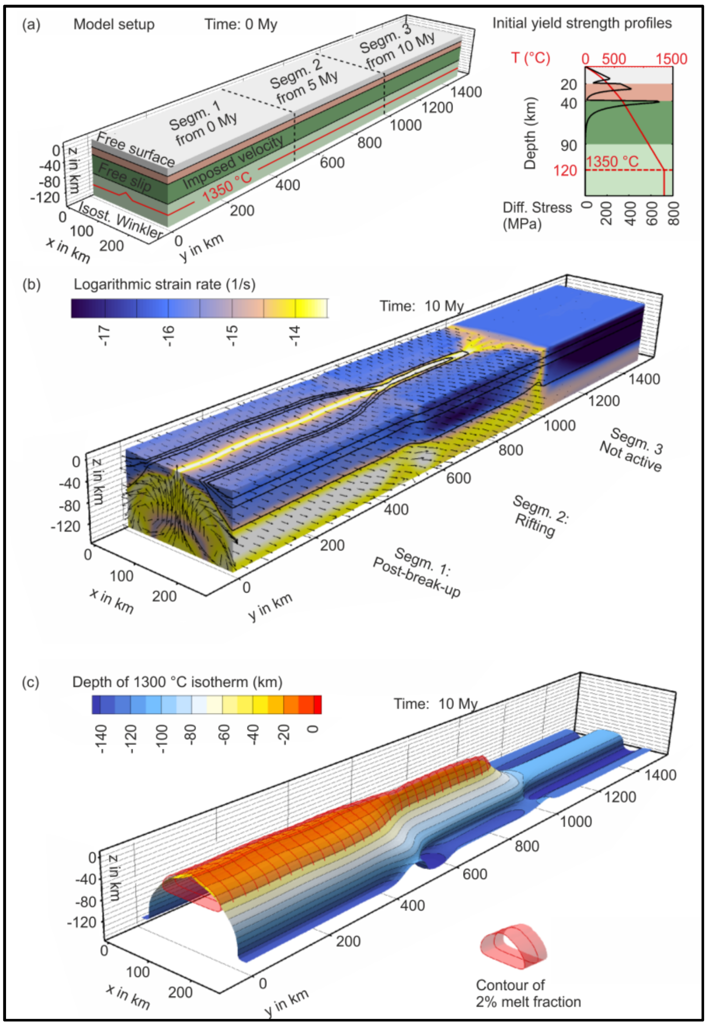

Fig. 4.3: a) Model setup: A 1500 km by 250 km rectangular rift zone is modeled, divided into three segments of 500 km length, activated at 0, 5 and 10 My model runtime, respectively, b) The logarithmic strain rate plot shows the sequential segment activation both in terms of strain rate and boundary velocity vectors at 10 My. Black lines designate material boundaries. Break-up is accomplished when the initially lowermost layer reaches the surface. Segment 1 is already in regular seafloor spreading mode, Segment 2 is almost completely in the rifting stage while Segment 3 is not active yet; c) Depth of the 1300 °C isotherm and the generation of a melt domain at 10 My.

Velocities in the central plane are shown in the diagrams in Fig. 4.4b, depicting the importance of rift delay regarding the material flow direction: At 6 My, the already opened Segment 1 constitutes a large reservoir of hot, low-viscosity mantle material. Hence, upon activation of Segment 2, a horizontal pressure gradient induces lateral material flow across the first segment boundary. This repeats at 11 My, when the opening of Segment 3 increases rift-parallel flow across the second segment boundary. Note that in nature, melting could lead to a strong local viscosity reduction (Bürgmann & Dresen, 2008), a process that is not contained in the batch melting model. Since a lower viscosity in the melt region adjacent to the segment boundary will generate even more lateral flow, the experiments provide a lower limit on the along-strike velocity component.

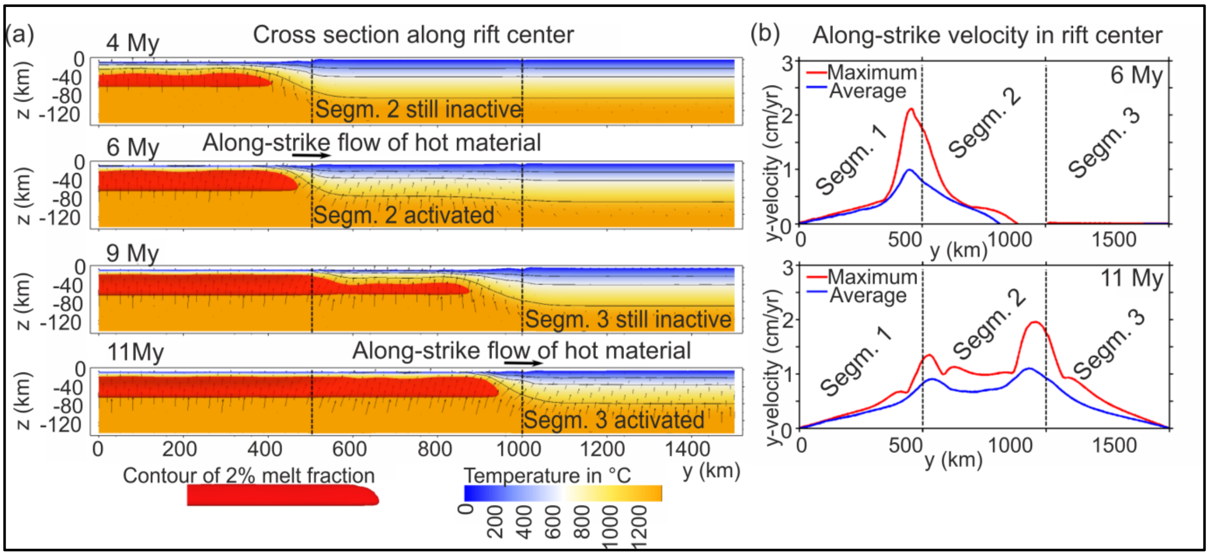

Fig. 4.4: a) Cross section along rift center (x=125 km), with the temperature distribution shown at different runtimes: At 4 My, before Segment 2 becomes active, the dominant directions are upwards; At 6 My, after the activation of segment 2, along strike-flow emerges at the segment boundary, in addition to upward flow; At 9 My, Segment 2 has almost fully opened and Segment 3 is not yet activated while Segment 2 shows dominantly upwards flow; At 11 My, lateral flow towards the now active Segment 3 becomes apparent. Note that at 6 and 11 My, the along-strike flow at the segment boundaries coincides with the arrival of the 2% melt fraction contour; b) Velocity in rift center: At 6 My, after activation of Segment 2, the rift-parallel flow component shows a distinct peak near the activated segment boundary; At 11 My, along-strike flow occurs at the now newly established second segment boundary between Segment 2 and Segment 3.

Fig. 4.5 shows two time-slices (at 6 My, 11) of the production of igneous crustal thickness assuming vertical (and total) melt extraction. The production of magmatic material is evaluated for each model slice with constant y-coordinate, by integrating along x whereas only pre-break-up melts are considered. A remarkable feature is that on opening of a delayed segment, (Fig. 4.5a and Fig. 4.5b, red colors in the upper panel and peaks in the lower panel), the highest productivity occurs at the triple-point, i.e. the location of rift delay / segment boundary. The along-strike directed material flow shown in Fig. 4.4 is also highly linked to segment boundaries and the timing of activation of rift segments. So, delaying a rift in the modelled manner significantly increases material flow, thus biasing the locus of melt production and eventually the emplacement of volcanic material.

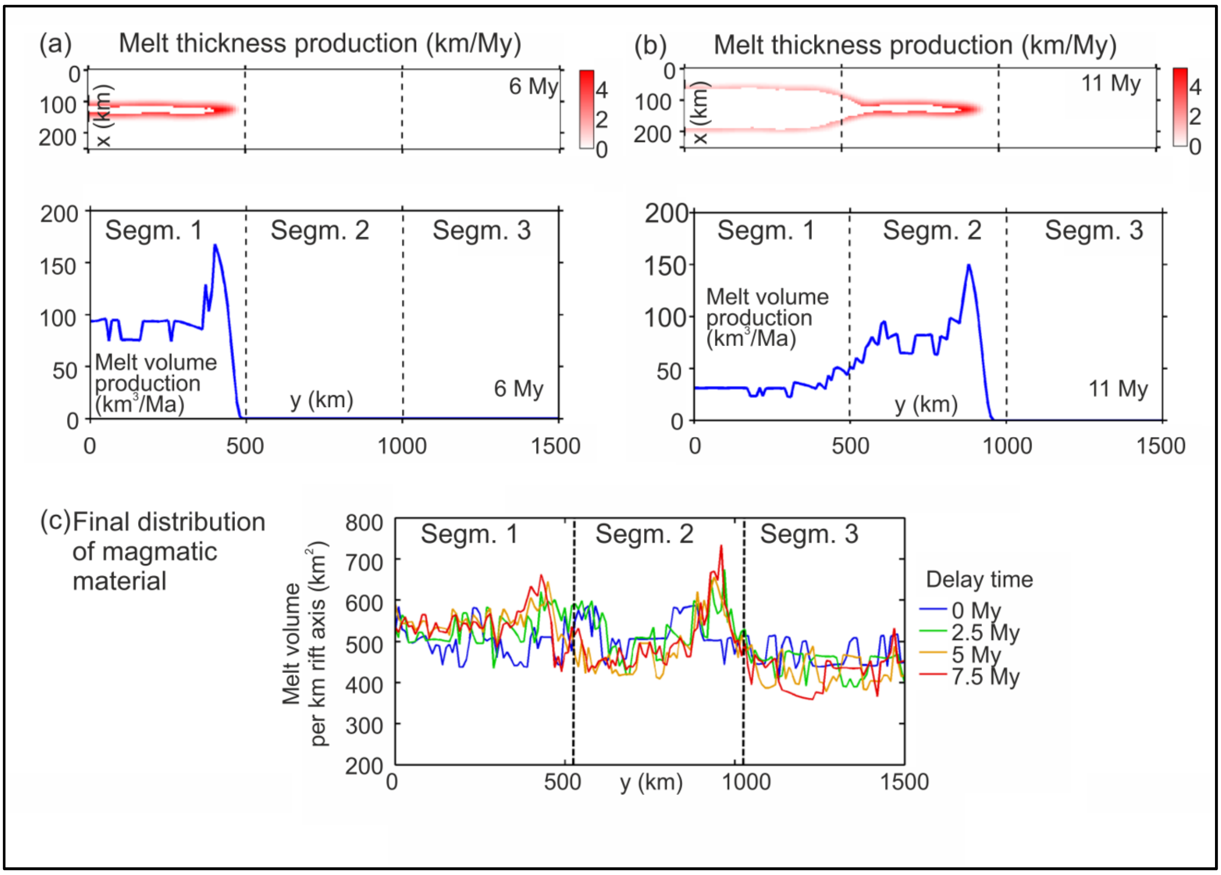

Fig. 4.5: a; b): Upper: Production of igneous crustal thickness over time at 6 My and 11 My. Lower: Igneous crust production integrated along the x-axis comparable to total melt emplacement at continental margins at 6 My and 11 My. Melt production peaks after activation of Segment 2 at 6 My. Viscous coupling forces peak production off imposed segment boundary at 500 km. Melt production peaks a second time at newly formed segment boundary at 11 My; c) Melt production indicates the importance of rift-delay duration.

4.5 Discussion

Assembled observations and modeling results indicate a close relationship between transfer zones and excess volcanism during break-up. This relates to previous analog modeling by Corti et al. (2002) who suggested that magma distribution at depth controls strain localization during transfer zone formation and that vice versa magma migrates towards imposed transfer zones (Corti et al., 2004). While these studies focused on magma migration, our study in contrast, provides an explanation for enhanced magma generation near transfer zones. Note that both the previous analog experiments and our numerical models consistently feature rift-parallel flow of either melt, or mantle, respectively.

The exclusive role of elevated temperatures has been questioned previously by Armitage et al. (2009) who found strong evidence that inherited structures from previous extensional periods were needed to explain volcanic rifting in the North Atlantic and that the mantle thermal structure alone was unable to do so. Here we provide additional evidence that geological structures and dynamic rift evolution can control locally enhanced magmatism.

Moreover, rift parallel flow of mantle material has the potential to elucidate the increase in along-strike magmatic volumes and the localization of melt at segment boundaries (Franke, 2013), creating a distinctive triangle-shape for mapped SDRs (see Fig. 4.2). Most material migration occurs during or right after incipient break-up at the proto-transform fault (the larger part of the triangle), whereas rift parallel material flow may be responsible for the thinning of the triangle.

If rift segmentation affects offshore volcanism, to what extent could this process have contributed to the emplacement of huge onshore volcanic provinces? Interestingly, the Atlantic Ocean LIPs are spatially linked to the transform fault systems with largest delay in rift propagation. During uni-directional rift propagation in the South Atlantic (Figure 1), the most prominent propagation barrier was the proto Florianópolis FZ with remarkable offset (150 km; Elliott et al., 2009) and delayed break-up of 5 – 20 My with respect to the oceanic crust further south. At the complex Jan Mayen FZ system (Figure 1), an even longer period of rift delay between C25 up to C5 can be derived from magnetic anomalies (e.g. Gernigon et al., 2012) and an offset of up to 320 km. This allows the speculation that rift delay and the along-strike flow at segment boundaries drive portions of off- and onshore volcanic provinces to their location.

4.6 Conclusions

Volumes of offshore magmatic material vary along the volcanic margins of the North and South Atlantic. These margins are segmented, with transfer zones between rift segments indicating rift propagation delay. Numerical modeling suggests a causal link between segment boundaries and magmatic volume variations. Our results explain observations made in natural systems by significant rift-parallel mantle flow across segment boundaries and subsequent melt generation at the tip of each opening rift segment. For specific rift configurations, delay at inherited structures can play an important part in enhancing and localizing volcanic activity.

Chapter-specific acknowledgments

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5. SYNTHESIS: WHAT WAS LEARNED FROM THE SOUTH ATLANTIC

Remarks

The following chapter synthesizes the findings presented in the previous chapters to directly address the issues raised by the title of this thesis: the break-up of the South Atlantic, the continent-ocean transition zone and implications on lithospheric controls and mantle dynamics. It concludes with an outlook on future tasks, questions and ideas for further understanding of the South Atlantic in particular and continental-break-up related processes in general. 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.

5.1 Break-up of the South Atlantic

The geophysical dataset available for this study allowed for confirmation of the south to north break-up direction of the South Atlantic. It could further be used to significantly improve the understanding of margin segmentation on the southern African margin. The main proxies for this understanding were distribution of offshore volcanics (seaward dipping reflector sequences, SDRs) and magnetic lineations. This combination showed emplacement of oceanic crust in the south to have happened synchronously with emplacement of pre-break SDRs further north. The area of SDRs distribution has magnetic anomalies older than M4 merge it. While this also gives a minimum age for the seaward most SDR sequence in the corresponding margin segment, it also underlines that the South Atlantic opened from south, propagating northwards. The most significant change along the margins is the switch from the volcanic-poor, southernmost margin segment to classically volcanic rifted margin northwards, where large volumes of volcanic effusives were emplaced prior to and during break-up. Segment boundaries along the segmented margins of the South Atlantic are interpreted as rift propagation barriers, responsible for rift propagation delay from south to north (see also 5.3). Based on geometrical difficulties if a simple east-west movement pattern is applied to the plates, a southward movement of the South American plate assemblage relative to the African plate is derived. The N-S “offset” of SDRs on either margin reflects this notion, which thus occurred in the very early crustal thinning phase, after emplacement of the southernmost SDRs. Sedimentary basins on both margins also show curiously different basin axes which fit the differing dominant extensional stress domains during break-up. The basin axes on the two margins are at an almost right angle and only the dominant W-E directions on the South African correspond to a simple W-E opening of the ocean basin. The concept of rotating directions is further mirrored in onshore findings from both margins.

5.2 Continent-ocean transition zone

Defining the position of continent-ocean boundary (COB) is important for both understanding the continental break-up as well as the sedimentary basin evolution (heat flow). The findings presented in this study, however, point at the importance of considering asymmetric rifting (see also 5.5) at possibly oblique angles and the influence of ductile, rather than brittle behavior during break-up. It can be implied that these factors do not allow the definition of a constant and homogenous relationship between SDRs and COB. The resolution found here is to define a broader zone of continent-ocean transition (COT). Seaward of this COT, there is no doubt about mafic oceanic crust proper based on magnetic lineations and the seismic properties of the crust. Landward of the COT, thinned continental crust underlies the feather edge of the SDRs. Asymmetric rifts also agree with break-up of continental plates happening on Earth, itself an anisotropic natural body, and direction of strain changing through time. In the past, it has been suggested that the landward side of the large-margin parallel magnetic anomaly can represent the COB and also the onset of SDRs emplacement. This correlation fades towards Walvis Ridge, indicating a delayed emplacement of volcanic effusives, giving some SDRs a negative magnetic signal. The inhomogeneous character of the continent-ocean transition is also reflected in the position of magnetic anomaly M0 relative to the SDRs along the margin. It is closed to the volcanics in the north of the study area, reflecting the south to north continental break-up and emplacement of the SDRs corresponding to this succession of rift-segment unzipping. Offshore Argentina, previously unknown pre-M5 magnetic lineations complete the lineation pattern in the South Atlantic, especially during the complicated phase of incomplete continental break-up in the Atlantic.

5.3 Implications on lithospheric controls

The data used for this study describes the final rifting stage of the South Atlantic in the Early Cretaceous, which was associated with major episodes of magmatism As discussed in 5.1, one of the major findings herein is the abrupt (10s of km) switch from magma-poor to volcanic rifted margin in the south of the study area. Further, the segmentation defined along the southern African margin, resulting in four First-order Segments can be considered another major finding of this thesis. The variability along the margin can attributed in large parts to a switch in spreading domain from an oblique angle during the early stages of break-up to conventional, east-west directed seafloor spreading from M4 onwards. A rifting model that is predominantly asymmetric simple shear and incorporates variations in strain through time is suggested here for the South Atlantic. Structures, margin architecture and variations in either can be addressed by along-margin rotation in spreading- and rifting-direction from N-S to W-E. A shallow source influencing break-up processes is implied by the abrupt switch from magma-poor to volcanic margin, the variability of the volcanic features within the segments and along the margins. Regarding the location of segment boundaries, there is a considerable spatial coincidence of offshore structures with onshore structures that likely represent preexisting crustal structures. This spatial coincidence implies that segment boundaries might form in zones of inherited lithospheric structures. From the numerical models presented in Chapter 4, it can further be said that rift propagation delay in a propagating rift setting is also responsible for excess melt accumulation and the rift-parallel flow of melt and subsequent emplacement of excess melt adjacent to segment boundaries.

5.4 Implications on mantle dynamics

From the condensed findings from this thesis, it can be concluded that the impact of the Tristan da Cunha hot-spot on volcanic activity and break-up processes in the South Atlantic was less direct than often implied. This might also apply to comparable systems across the globe. Emplacement of Paraná Etendeka large igneous provinces and thus the peak activity of hot-spot volcanism post-dates the emplacement of first oceanic crust and accordingly by quite a margin also the emplacement of SDRs, depending on the time scale used. From the southernmost margin segment that does not have much to offer volcanic activity wise the change to volcanic rifted margin is abrupt. This is more plausibly addressed by local or regional changes in spreading direction or speed rather than a sudden arrival of the impact of a hot-spot centered 2000 km away then. The change in spreading regime is quite well demonstrated in the South Atlantic both on- and offshore (see also 5.1). There further is no demonstrable increase in volcanic volume towards the Tristan da Cunha hot-spot and instead there is an alternating pattern in the effusive volume and width of the SDRs. Only, closer to Walvis Ridge, within an influence radius of about 200 km, the impact of the increased hot-spot related volcanism is visible in increased volume, length and widths of SDRs. Around Walvis Ridge, the usually assumed spreading-axis related formation of SDRs does not work conclusively anymore and 3D dipping SDRs were formed. This can be taken as a sign of a radial melt source than the assumed elongated source along most of the margin. As the numerical modelling showed production of localized excess melt just by lithospheric processes, the importance of a deep, mantle heat source for break-up related volcanism might be less direct than often suggested.

5.5 Margin (A)symmetry

As already suggested in 5.1, break-up of the South Atlantic occurred asymmetrical. This asymmetry is not only reflected in basin axes and the suggestion of a rotational component in plate motion of the South American plate assemblage. The asymmetry is also quite simply described by the sheer volume of volcanic material deposited on either conjugate margin, reflected in both SDRs and high velocity lower crustal bodies (HVLC). Volumes are considerably higher on the African side. The margin development of the South Atlantic continental margins can accordingly be better described with a dominatingly simple shear rifting model. Curiously, the distribution of volcanic material emplaced onshore is the opposite of what can be seen offshore, with the Paraná volcanic province in South America being a lot bigger than the Etendeka province. Asymmetry is also reflected by the strength of the magnetic anomalies. However, the new magnetic data that allow interpretation of magnetic anomalies as old as M9r offshore South America and thus correlate age wise to the more well-known anomalies offshore South Africa. Nevertheless, the data also suggest that the anomalies interpreted to be older than M9 are likely not true seafloor-spreading lineations on either margin. Of course, since they represent two conjugate margins, the two margins also share a number of characteristics, such as showing segmentation linked to transfer zones / segment boundaries and variations in melt volumes within individual margin segments and along the margin.

5.6 Rifting and Volcanism

The generation of two major types of rifted continental margin, magma-poor and volcanic, is an interesting feature of plate separation processes. It is therefore very interesting to find that southernmost segments on either margin in the South Atlantic largely signs of major volcanic activity. Again, it is likely that the oblique rifting direction during the pre-break-up phase resulted in the margin architecture in the southernmost segments which resemble a sheared margin and does not resemble the style of typical magma-poor margins. The relationship of SDRs with magnetic anomalies (see also 5.1) shows that volcanism along the continental margin was coupled to propagation and bound to the margin segments. This propagation and the delay of rift propagation at segment boundaries is further shown in Chapter 4 to be a possible explanation for the localization of melt and the production of excess melt along the rift. Magnetic models show that assuming a dominantly basaltic, mostly magnetizable composition for the SDRs results in plausible volumes of magnetized material to generate the large margin parallel positive magnetic anomaly on both margins. From both magnetic data and the multi-channel seismic data it can conclusively said that the change from magma-poor to volcanic rifted margin in the South Atlantic is very abrupt, within 10s of km. A clear indicator for the commencement of true oceanic seafloor spreading, the oldest seafloor-spreading magnetic anomaly is M9 (~135 Ma), older anomalies (e.g. M11 (~137 Ma)) are likely linked variations within the sets of offshore volcanics. Structures of the offshore volcanics described in this thesis are very variable. They are not continuous laterally, nor are their steepness, thickness or length. After the onset of volcanism, the area covered by the SDRs reaches its greatest value, decreasing north of Orange Segment Boundary. It is only with the presumed influence of Walvis Ridge volcanism in the north of the study area that the covered area increases again. As discussed in 5.4, there is no systematic increase in volcanic volumes towards the Tristan da Cunha hot-spot. Further, the superposition of SDR sequences suggests episodicity of volcanic emplacement, likely separated by periods of sedimentation and erosion. This is more obvious in the older SDR sequences in the southern part of the study area. Pre-M5 magnetic seafloor spreading lineations provide a timespan for the emplacement of break-up related volcanism and the consequent change towards regular seafloor spreading.

5.7 Outlook

The dataset presented in this study is of unique quality, especially considering the length of the acquired data profiles. Covering of both continental, oceanic and transition domain is necessary to understand continental break-up processes (or subduction processes on applicable active margins). However, as commonly concluded for most scientific studies, more data would also be helpful in the South Atlantic, especially on the Namibian continental margin near Walvis Ridge, where far-offshore data are scarce.

The implied need for more data also holds true for publically available drilling data, especially ultra-deep wells, preferably in the volcanic sequences discussed in much detail in this thesis as seaward-dipping reflector sequences. The precise composition and possible erosion surfaces and interlayered sediments of these sequences provide the biggest opportunity to learn something new and exciting about the late break-up phase of the South Atlantic (and other, comparable break-up systems).

The detailed magnetic data in the southernmost South Atlantic shown here could be used in the future to improve global or regional plate reconstruction models in this tectonically complicated and fascinating area.

The suggested connections of offshore to onshore structures need further campaigns in the off- and onshore domains of the margins, as age and directional information would benefit the interpretation of these connections. This also holds true for investigations regarding the linkage between transfer zones and volcanism.

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WORK EXPERIENCE

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Responsibilities	Re-processing and interpretation of seismic data with **ProMAX** and **GeoFrame**. Integrating data into **GIS** and plate reconstruction models. **Presentation** and **publication** of the results
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Position held	**Research scientist** at the Marine Research Group during **Research cruise** with RV Meteor in the North Sea.
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EDUCATION

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Focal points	Ph.D. thesis used **ProMAX, GeoFrame, ArcGIS, GPlates** and compiled and interpreted a large geophysical dataset of the **South Atlantic**.
10/2004 to 07/2010	**Gottfried Wilhelm Leibniz Universität**, Hannover, Germany
Degree	Diploma in Geosciences (Dipl.-Geow.)
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LIST OF PUBLICATIONS

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PUBLICATIONS IN PEER-REVIEWED JOURNALS

Koopmann, H., Brune, S., Franke, D., Breuer, S., 2014. Linking rift propagation barriers to excess magmatism at volcanic rifted margins. Geology, Advance online publication. http://dx.doi.org/10.1130/G36085.1

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