Structural constraints on Gondwana breakup along the East African margin

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ABSTRACT

The paleoposition of Madagascar in Gondwana and its southward movement during Gondwana breakup is still the subject of considerable discussion. In this thesis, the Davie Fracture Zone, which is assumed to represent a major transform fault that guided Madagascar´s southward drift from a position adjacent to the coasts of Somalia/Kenya/Tanzania to its present-day position, is investigated using 2D marine reflection seismic data. The aim of this thesis is to further constrain rifting and seafloor spreading phases creating the West Somali Basin and Mozambique Basin, off East Africa, in order to contribute to an improved understanding of Gondwana breakup. Offshore northern Mozambique, Tanzania and Kenya, there is no evidence for the presence of a major transform fault. Several of the structures that have been interpreted as evidence for the Davie Fracture Zone, e.g. the Walu Ridge offshore Kenya and the eastern boundary of the Kerimbas Basin, are in fact related to Late Cretaceous volcanism and inversion in Kenya as well as the Neogene evolution of the East African Rift System. Offshore Tanzania, geophysical data do not show basement structures that may be correlated to a major transform fault. Northwest of Madagascar, to the east of the Davie Fracture Zone, a wide area of stretched basement, not consisting of normal oceanic crust, is observed. This basement has been affected by two deformational phases, associated with an initial phase of NW-SE directed rifting and early seafloor spreading and a N-S directed transform deformation phase correlated with the southward drift of Madagascar. Similar structures are observed to the south, where a narrow transition from continental to oceanic crust of the Mozambique Basin is observed. At the foot of the continental slope in the Mozambique Basin and Riiser-Larsen Sea, close to Davie and Gunnerus Ridge, the basement is deformed and fractured and sediments overlying the deformation zone are deformed, implying a post-breakup deformation phase. The western flank of Gunnerus Ridge, Antarctica, is interpreted as a transform margin, similar to Davie Ridge, implying that they are conjugate features. It is likely that a first phase of rifting and early seafloor spreading in the Mozambique Basin/Riiser-Larsen Sea was replaced by a transform deformation phase, overprinting the continent-ocean transition. The second phase of deformation corresponds to the strike-slip movement of Madagascar and Antarctica. These results question most plate kinematic reconstructions, which model a straight, southward displacement of Madagascar along the Davie Fracture Zone and imply that the Davie Fracture Zone represents the continent-ocean boundary at the western edge of the West Somali Basin. In this thesis, it is suggested that the West Somali Basin opened by initially oblique SW-propagating rifting and seafloor spreading. An important new aspect is the more southerly pre-breakup position of Madagascar with a N-S oriented alignment in Gondwana. This scenario implies that there is no need for a counterclockwise rotation of Madagascar subsequent to breakup that is implicit in many reconstruction models.

**Keywords**: Gondwana breakup; Davie Ridge; reflection seismic data

KURZFASSUNG

Die Paläoposition von Madagaskar und seine Südwärtsbewegung während des Gondwana-Zerfalls sind bisher wenig verstanden. In dieser Arbeit wird die Davie Transformstörung, von der angenommen wird, dass sich Madagaskar entlang dieser Störung von einer Position an der Küste von Somalia/Tansania/Kenia an seine heutige Position bewegte, mit marinen reflexionsseismischen Methoden untersucht. Das Ziel dieser Arbeit ist es, frühe Phasen von Krustendehnung und Meeresbodenspreizung, die zur Bildung des West Somali Beckens und des Mozambik Beckens führten, zu belegen und so zu einem verbesserten Verständnis des Gondwana-Zerfalls beizutragen. Vor den Küsten von Nord-Mosambik, Tansania und Kenia gibt es keine Hinweise für eine Transformstörung. Einige der Strukturen, die als Beweis für die Präsenz einer Transformstörung angenommen wurden, z.B. der Walu-Rücken vor Kenia und die östliche Flanke des Kerimbas-Grabens, sind die Folge von spätkreidezeitlichem Vulkanismus und Inversion in Kenia und der fortschreitenden neogenen Entwicklung des Ostafrikanischen Riftsystems. Vor Tansania zeigen die reflexionsseismischen Daten keine Krustenstrukturen, die mit einer Transformstörung korreliert werden können. Nordwestlich von Madagaskar, östlich der in der Literatur interpretierten Davie Transformstörung, liegt eine weite Zone von gedehnter Kruste nicht-ozeanischen Ursprungs. Diese Kruste wurde von zwei Deformationsphasen beeinflusst, die mit einer initialen, NW-SO gerichteten Phase von Dehnung und Meeresbodenspreizung und einer N-S gerichteten Transformphase, die mit der Südwärtsbewegung Madagaskars in Verbindung gebracht wird, assoziiert wird. Im Süden erfolgt entlang der Davie Transformstörung ein abrupter Übergang von kontinentaler zu ozeanischer Kruste des Mosambik Beckens. Am Fuß des Kontinentalhanges im Mosambik Becken und in der konjugierenden Riiser-Larsen See, sind die Kruste und überlagernde Sedimente intensiv deformiert und gestört, was eine Deformation nach dem Zerfall von Gondwana anzeigt. Die westliche Flanke des Gunnerus-Rückens, eines Krustenfragments mit vermutlich kontinentalem Ursprung, wird als Transformstörung interpretiert. Der Gunnerus-Rücken ist die konjugierende Struktur zum Davie-Rücken vor Madagaskar. Es ist wahrscheinlich, dass eine initiale Phase von Dehnung und Meeresbodenspreizung im Mosambik Becken/Riiser-Larsen See durch eine Transformphase ersetzt wurde, die den Kontinent-Ozean-Übergang überprägt hat. Die zweite Deformationsphase korreliert mit der Südwärtsbewegung von Madagaskar. Diese Ergebnisse stellen Plattenrekonstruktionen in Frage, die eine lineare, südwärtsgerichtete Bewegung von Madagaskar modellieren und den Kontinent-Ozean-Übergang entlang der Davie Transformstörung annehmen. In dieser Arbeit wird vorgeschlagen, dass sich das West Somali Becken durch initial schräge, südwestwärts fortschreitende Dehnung und Meeresbodenspreizung öffnete. Ein wichtiger neuer Aspekt ist die südlichere, N-S orientierte Paläoposition von Madagaskar in Gondwana, die keine Rotation Madagaskars entgegen dem Uhrzeigersinn erfordert, wie es in vielen Rekonstruktionen impliziert ist.

Schlagwörter: Gondwana-Aufbruch; Davie Rücken; Reflexionsseismik

1   Introduction

1.1   Gondwana breakup and the paleoposition of Madagascar

The supercontinent Gondwana was an amalgamation of several landmasses consisting of a western (largely South America, Africa and Arabia) and an eastern part (Madagascar, Antarctica, India and Australia) (Figure 1.1). The movements during its early dispersal commencing in the Early Jurassic (~184 Ma; Nguyen et al., 2016) remain poorly constrained due to uncertainties about the timing and directions of the rifting and earliest seafloor-spreading phases and the position and structural style of the continent-ocean transition. However, in all plate tectonic models of Gondwana breakup, Madagascar´s pre-breakup position and its pathway during the southward drift plays a crucial role in the positioning of the main plates of East Gondwana (Figure 1.1).
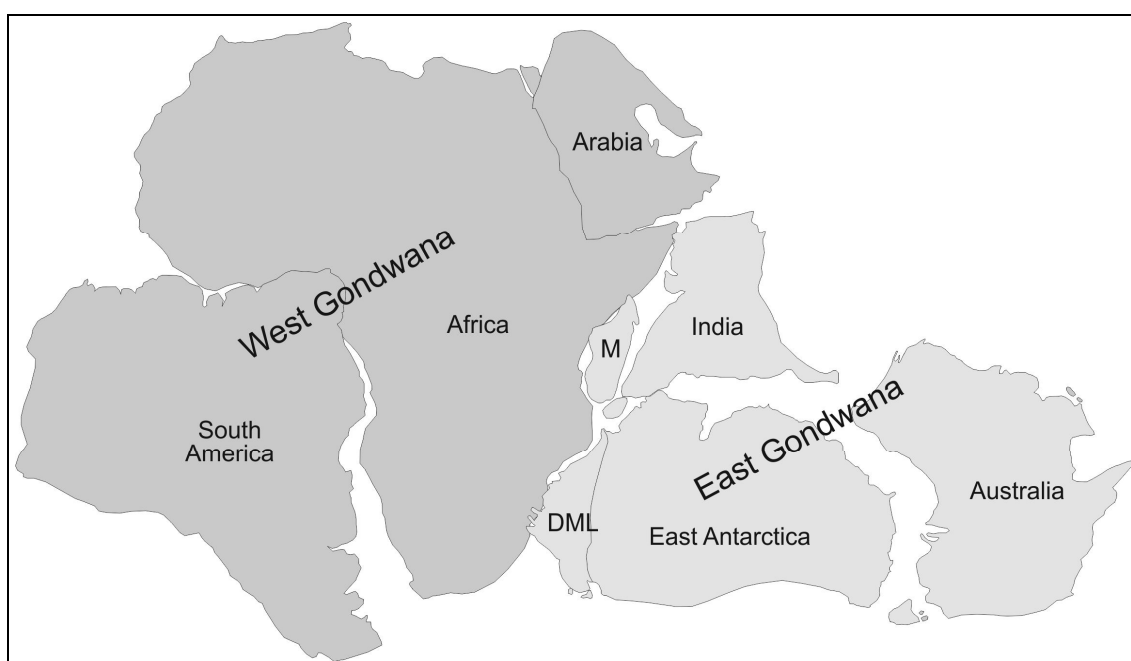
Figure 1.1: Schematic reconstruction map of Gondwana illustrating the general arrangement of the main plates of East and West Gondwana (modified from Torsvik and Cocks, 2013). DML= Dronning Maud Land, M= Madagascar.

During the last decades, many studies focused on the reconstruction of the pre-breakup configuration (e.g. Cox, 1992; Davis et al., 2016; Eagles and König, 2008; Jokat et al., 2003; Leinweber and Jokat, 2012; Marks and Tikku, 2001; Martin and Hartnady, 1986; Nguyen et al., 2016; Phethean et al., 2016; Reeves, 2014; Reeves et al., 2016; Roeser et al., 1996; Smith and Hallam, 1970; Torsvik and Cocks, 2013). In general, there is consensus, that breakup between East and West Gondwana occurred at 170-180 Ma (e.g. Gaina et al., 2013; Leinweber and Jokat, 2012; Nguyen et al., 2016) and led to the

formation of several old ocean basins located off the East African continental margin. The Mozambique Basin (and its East Antarctic conjugate, the Riiser-Larsen Sea) was formed following the separation of Antarctica from Africa, while the West Somali Basin results from the separation of Madagascar from Africa (Figure 1.2).

So far, it has been proposed that the Mozambique Basin and West Somali Basin opened almost simultaneously in NW-SE direction (e.g. Gaina et al., 2013) without independent movements of small plates (Davis et al., 2016; Eagles and König, 2008; Reeves et al., 2016). It has also been suggested from the interpretation of marine magnetic anomalies and fracture zones in the basins (Figure 1.3) (e.g. Coffin and Rabinowitz, 1987; Gaina et al., 2013; Leinweber and Jokat, 2012) as well as from the study of seismic sections, outcrops and wells on- and offshore Madagascar, Tanzania, Kenya and Somalia (e.g. Coffin and Rabinowitz, 1988; Montenat et al., 1996) that the directions of rifting and most likely earliest seafloor spreading may have changed from ~NW-SE to a N-S direction during the early opening of the oceanic basins (e.g. Leinweber and Jokat, 2012; Reeves et al., 2016). However, the timing of this change of spreading directions is still uncertain with ages ranging from ~159 Ma (Leinweber and Jokat, 2012) and ~153 Ma (Reeves et al., 2016) to ~150 Ma (Phethean et al., 2016).

Oceanic crust preserved from seafloor spreading in the basins has been dated by the identification of marine magnetic anomalies (Figure 1.3). Recent studies have identified M41n (~165 Ma) and M41n/M38n.2n (~165/164 Ma) as the oldest magnetic anomalies in the West Somali Basin and Mozambique Basin (Gaina et al., 2013; Leinweber and Jokat, 2012; Müller and Jokat, 2017), considerably older than in previous studies (West Somali Basin: M25 to M10, 154-134 Ma, Coffin and Rabinowitz, 1987; M21 to M0, 147-124 Ma, Segoufin and Patriat, 1980; Mozambique Basin: M2 to M22, ~148-127 Ma; Segoufin, 1978). It is widely accepted that the Riiser-Larsen Sea is the conjugate of the Mozambique Basin (e.g. Eagles and König, 2008; Jokat et al., 2003; Nguyen et al., 2016); however, it remains much less well studied in spite of an available set of geophysical data (e.g. Hinz et al., 2004; Leitchenkov et al., 2008; Roeser et al., 1996). Although it is implied from plate kinematic models that spreading started well before M25n (~154 Ma), well-defined magnetic anomalies older than M25n have not yet been identified in the Riiser-Larsen Sea (Leinweber and Jokat, 2012).

Today, it is established that Madagascar was located adjacent to the coasts of Tanzania, Somalia and Kenya and drifted southward to its present position following Gondwana breakup in the Middle Jurassic (e.g. Coffin and Rabinowitz, 1987; Heirtzler and Burroughs, 1971; Segoufin and Patriat, 1980).
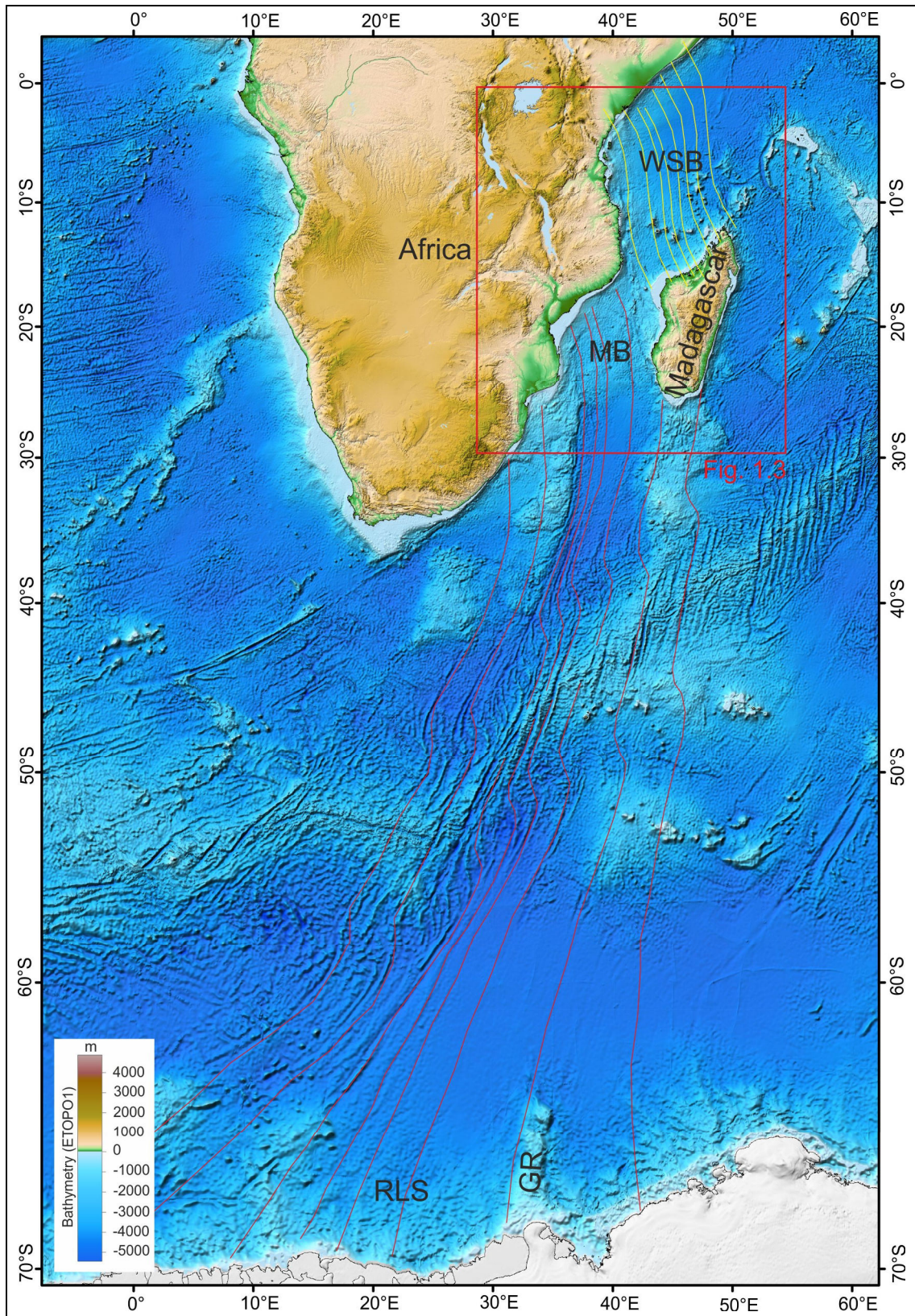
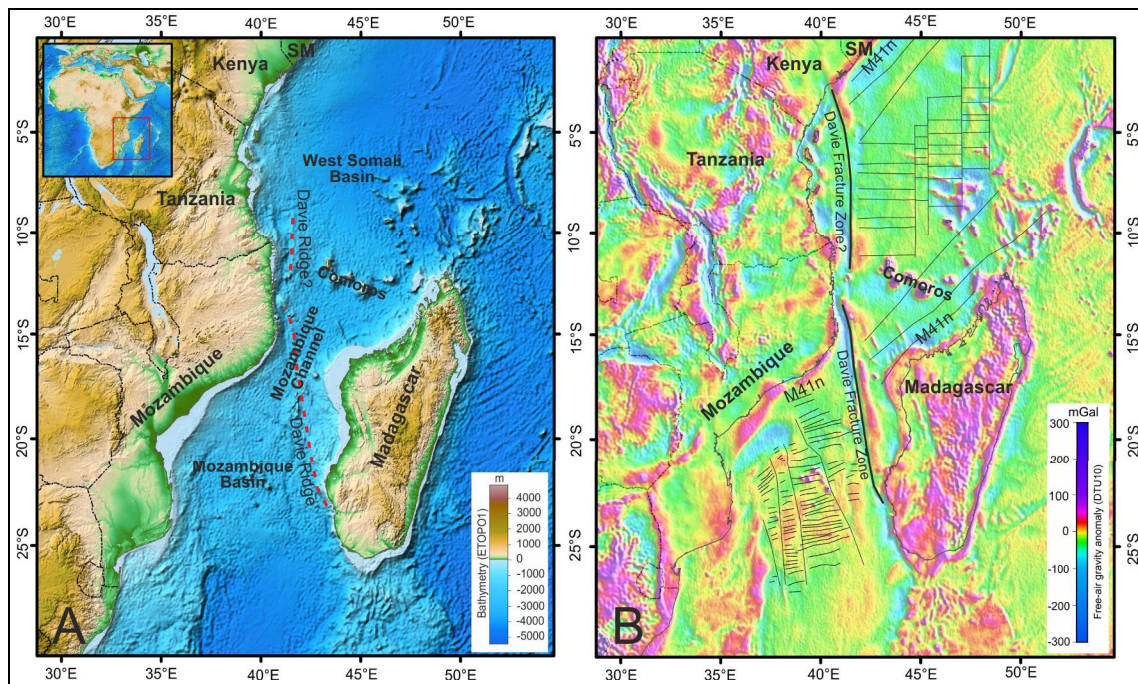**Figure 1.2:** Bathymetric map of the Africa-Antarctica corridor, the Mozambique Channel and the West Somali Basin (ETOPO1 1 arc-minute global relief model; Amante and Eakins, 2009). The purple and yellow flow lines indicate the motion of Antarctica and Madagascar relative to Africa according to Eagles and König (2008). GR= Gunnerus Ridge, MB= Mozambique Basin, RLS= Riiser-Larsen Sea, WSB= West Somali Basin.

Besides the identification of magnetic anomalies in the West Somali Basin, the Davie Ridge, a ~NNW-SSE trending bathymetric elevation rising 1-2 km above the surrounding seafloor (Figure 1.3) (Heirtzler and Burroughs, 1971) that is supposed to represent the morphological expression of the southward drift of Madagascar (e.g. Bassias, 1992; Coffin and Rabinowitz, 1987), has been proposed as evidence for Madagascar´s southward drift. The Davie Ridge is assumed to be located at the trace of a fossil transform fault, the Davie Fracture Zone (Figure 1.3), that was supposedly active from the Middle Jurassic (~160-165 Ma) to the Early Cretaceous (~123-135 Ma) (e.g. Coffin and Rabinowitz, 1987; Rabinowitz et al., 1983; Segoufin and Patriat, 1980) and therefore connects the conjugate passive continental margins of Kenya/Somalia and northern Madagascar with the passive continental margin of Mozambique. In the Riiser-Larsen Sea, the ~N-S striking Gunnerus Ridge (Figure 1.2), that is most likely of continental origin (e.g. Leitchenkov et al., 2008), is supposed to represent the southward continuation of the Davie Ridge (e.g. Figure 1.4, Nguyen et al., 2016). Its western flank has been interpreted as a strike-slip fault located along a sheared margin (e.g. Leitchenkov et al., 2008).

Figure 1.3: (A) Bathymetric map of the West Somali Basin, Mozambique Basin and the Mozambique Channel (ETOPO1 1 arc-minute global relief model; Amante and Eakins, 2009). The location of the Davie Ridge is highlighted with red dashed line. (B) Map of the gravity field of the West Somali Basin, the Mozambique Basin and the Mozambique Channel (DTU10 satellite altimeter derived free-air gravity dataset; Andersen, 2010; Andersen and Knudsen, 2009). The location of the Davie Fracture Zone is marked with thick black lines. Magnetic chrons in the West Somali Basin and the Mozambique Basin are from Gaina et al. (2013), Müller and Jokat (2017) and Leinweber and Jokat (2012). SM= Somalia.

Figure 1.4: Published reconstruction of Nguyen et al. (2016) illustrating the position of the Gunnerus Ridge, offshore East Antarctica, relative to Madagascar. GR= Gunnerus Ridge, SL= Sri Lanka.

However, there is an ongoing discussion about Madagascar´s exact position in Gondwana that suggests significant differences in reconstruction models regarding e.g. the location of the continent-ocean transition and potential rotations of Madagascar. Earlier Gondwana reconstructions from the 1970ies, based on limited geophysical information, estimate the time of breakup between Africa and Madagascar to be in the Cretaceous and propose a relatively tight fit (Figure 1.5A-C; e.g. Bunce and Molnar, 1977; Norton and Sclater, 1979; Smith and Hallam, 1970).

These studies are in general agreement with several aspects of recent Gondwana reconstructions, i.e. Madagascar´s N-S oriented alignment in Gondwana, with its southern tip close to northern Mozambique, and its slight, clockwise rotation with rotation angles of up to ~15° (Figure 1.5D-E; e.g. Coffin and Rabinowitz, 1987; Gaina et al., 2013, 2015; Torsvik and Cocks, 2013).ther models by e.g. Davis et al. (2016), Lawver et al. (1997), Leinweber and Jokat (2012), Phethean et al. (2016), Reeves et al. (2002, 2016) and Reeves (2014) propose a large counterclockwise rotation of Madagascar (up to 26°) subsequent to breakup. In these studies, a very tight fit of Madagascar and Africa and a NW-SE oriented alignment of Madagascar, with its southern tip close to southern Tanzania (Figure 1.5F-I), is suggested. Nearly all of these studies (e.g. Figure 1.5A-H) model more than 1000 km of southward displacement along a major, straight transform fault, the Davie Fracture Zone, and assume a transform continental margin at the western edge of the West Somali Basin (Figure 1.5). Early reconstructions (Figure 1.5A-D), as well as reconstructions of Reeves (2014) (Figure 1.5G) and Davis et al. (2016) (Figure 1.5H), propose an initial breakup in N-S to NNW-SSE direction, while Gaina et al. (2015) (Figure 1.5E) and Phethean et al.

(2016) (Figure 1.5I) model initial breakup by NW-SE directed rifting and early seafloor spreading with a later change of spreading direction to ~N-S.
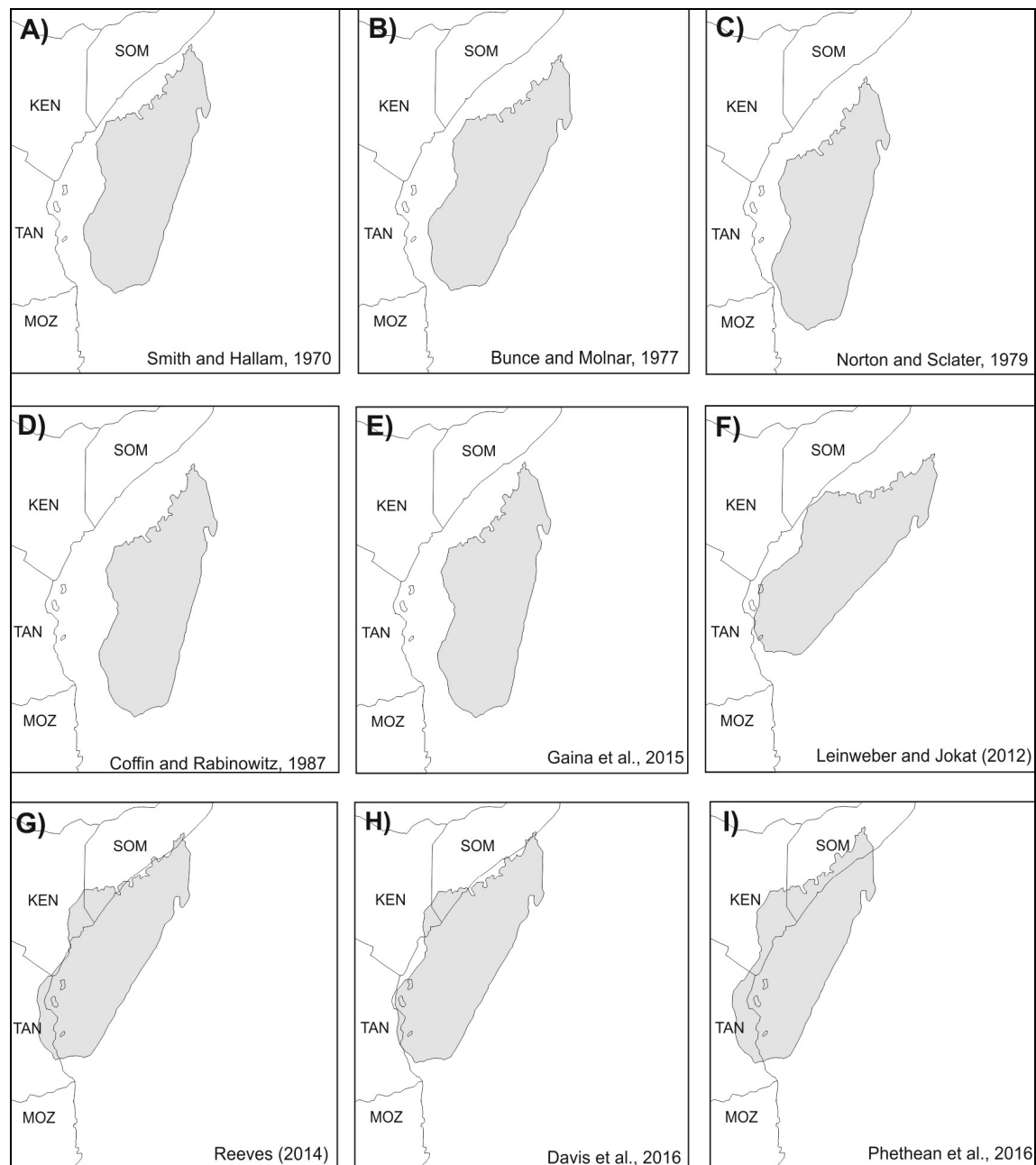
Figure 1.5: Compilation of published reconstructions of Madagascar´s pre-breakup position relative to Africa of (A) Smith and Hallam (1970), (B) Bunce and Molnar (1977), (C) Norton and Sclater (1979), (D) Coffin and Rabinowitz (1987), (E) Gaina et al. (2015), (F) Leinweber and Jokat (2012), (G) Reeves (2014), (H) Davis et al. (2016) and (I) Phethean et al. (2016). MOZ= Mozambique, KEN= Kenya, TAN= Tanzania, SOM= Somalia.

In the reconstruction of Leinweber and Jokat (2012) (Figure 1.5F), Madagascar rotates ~11° in counterclockwise direction during initial breakup in NW-SE direction, followed

by N-S directed southward drift along the Davie Fracture Zone and another rotation of 15°. Phethean et al. (2016) (Figure 1.5I) predict that the Davie Fracture Zone in the West Somali Basin rather represents an ocean-ocean fracture zone and that the continent-ocean transition is located westward of the Davie Fracture Zone. The significant differences in recent Gondwana reconstructions, where the Davie Fracture Zone is overlapped by several independently generated reconstructions (Figure 1.5A-C, Figure 1.5F-I), highlight the need for a detailed investigation of the Davie Fracture Zone (including the Davie Ridge) to better constrain timing and directions of rifting and seafloor spreading phases creating the West Somali Basin and Mozambique Basin and to contribute to an improved understanding of Gondwana breakup.

According to Bird (2001), transform (or sheared) continental margins differ significantly from passive rifted continental margins and can be defined by their three-phase evolution (Figure 1.6). First, continental crust is sheared and complex rift structures evolve with the development of intensively deformed rift sequences over rotated basement blocks. During the second stage, an active transform fault evolves that separates oceanic and continental crust. During the last step, a passive margin forms along an inactive fracture zone that separates oceanic and continental crust. Moreover, transform margins show typical characteristic geological features that differ from passive rifted margins (e.g. Bird, 2001): The transition from continental to oceanic crust is relatively abrupt, where crustal thicknesses decrease over distances of 50 to 80 km. Second, complex rift basins form along the continental side of the margin with characteristic geologic structures like wrench, normal and strike-slip faults. Third, high-standing marginal ridges form along the continental side of the margin. The formation of these ridges along the sheared margins remains poorly understood.

The two simplest explanations for the generation of the marginal ridges are that 1) they result from absorbed heat from the propagation of the ridge-transform intersection (Figure 1.6) along the plate boundary (Bird, 2001) or 2) that the uplift is the result of transpressive motions (Parsiegla et al., 2007).

Following the transform margin concept as proposed by e.g. Coffin and Rabinowitz (1987), the continent-ocean transition along the transform margin off northern Mozambique would be the Davie Fracture Zone, with the Davie Ridge as its morphological expression (Figure 1.3).
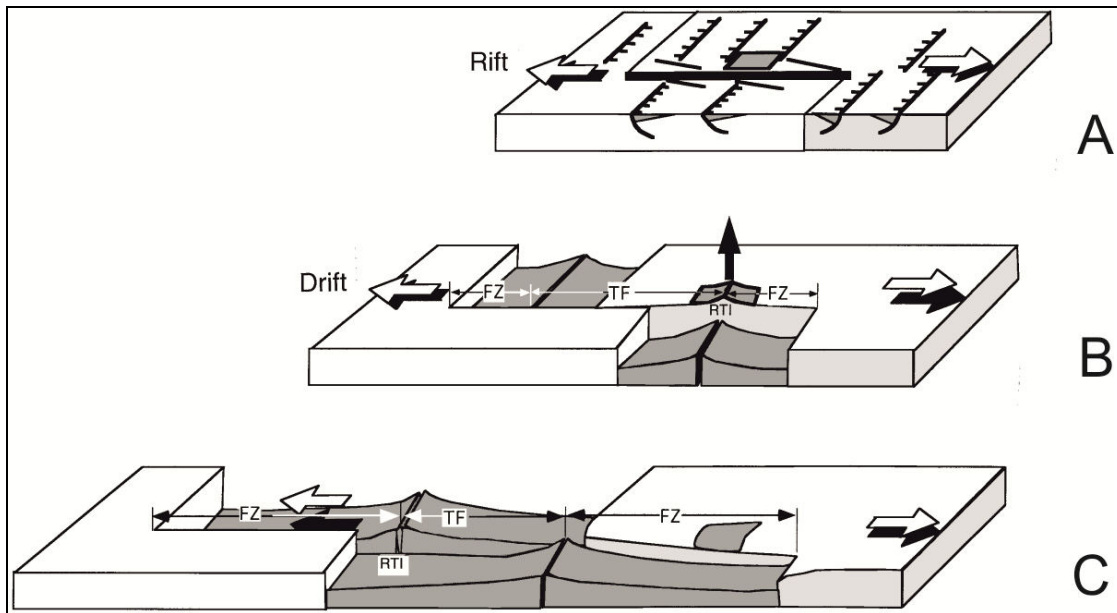
Figure 1.6: Schematic three-stage model for shear margin evolution (modified after Lorenzo, 1997). (A) rift stage: continent-ocean shearing; (B) drift stage: continent-ocean transform fault; (C) evolution of passive margin: continent-ocean fracture zone. FZ= Fracture zone, TZ= Transform fault, RTI= Ridge-Transform Intersection.

In several geophysical (e.g. Mascle et al., 1987) and plate kinematic (e.g. Coffin and Rabinowitz, 1987; Davis et al., 2016; Gaina et al., 2015) studies, the Davie Fracture Zone is interpreted as the boundary between continental and oceanic crust. However, the continent-ocean transition in the West Somali Basin and Mozambique Basin has not been conclusively determined until today. Moreover, the Davie Ridge is observed as a prominent morphological feature solely between 20°S and about 9°S (Figure 1.3). North of 9°S, ~N-S striking gravity anomalies (e.g. Rabinowitz, 1971; Scrutton, 1978) were interpreted as representing the continuation of the Davie Ridge. Subsequently, the whole feature has been termed the Davie Fracture Zone by Scrutton (1978) (Figure 1.3). South of 15°S, the N-S trending transform margin is located adjacent to the SW-NE trending volcanic rifted margin of the Mozambique Basin (Figure 1.3). Although the structural architecture of this "transition" zone is essential for Gondwana reconstructions, the location of the continent-ocean transition in the northeastern Mozambique Basin remains uncertain. Existing studies have focused mostly on the western and central parts of the Mozambique Basin (e.g. Leinweber et al., 2013; Mahanjane, 2012; Mueller et al., 2016).

Dredging and coring of the Davie Ridge revealed that it is, at least locally, built of crystalline continental basement (Bassias, 1992; Bassias and Leclaire, 1990). Crystalline basement was recovered at 14–15°S from the base of the western ridge flank and revealed gneisses and altered semi-pelites (Bassias, 1992; Bassias and Leclaire, 1990). Continental basement could also be present further north and south along the Davie Ridge, as alkaline

basalts, recovered from the southern parts of the ridge, indicate geochemical affinities with Cretaceous volcanics of southeast Africa and Madagascar (Bassias and Leclaire, 1990). The presence of intraplate basalts and the absence of ultramafic rocks are supposed to confirm the continental origin of the Davie Ridge (Bassias, 1992). This structural configuration implies a complex tectonic history that, until today, is not satisfactorily understood. Several studies suggest that the topographic high of the Davie Ridge (Figure 1.3) is the result of multiple tectonic processes (e.g. Coffin and Rabinowitz, 1988; Mascle et al., 1987). A first deformation phase certainly was the creation of the transform margin until the Early Cretaceous as a consequence of the southward motion of Madagascar relative to Africa. This phase most likely resulted in the generation of observed positive flower structures, indicating shear movements (Mascle et al., 1987). However, a couple of significant tectonic deformation phases most likely affected the Davie Ridge after the cessation of southward movement of Madagascar. According to Mascle et al. (1987), a second deformation phase could relate to the separation of India from Madagascar and the contemporary opening of the Mascarene Basin to the east of Madagascar (~ 87 Ma ago, Seton et al., 2012) and to reactivation of N-S trending tectonic features of the earlier fracture zone. This event may have been accompanied by local extensive motions related to volcanic activities along the Davie Ridge (Bassias, 1992). Tholeitic basalts, basaltic andesites and rhyolites found in several basins of the conjugate East African and Madagascan margins (Coffin and Rabinowitz, 1988) might correlate with this event. Since Mid-Eocene, the evolution of the eastern, offshore branch of the East African Rift System influenced the Davie Ridge and the surrounding area (Mougenot et al., 1986), resulting in a third phase of deformation (Mascle et al., 1987). Recently, Franke et al. (2015) found that along the northern Mozambique margin, a southward propagating rift zone correlates with the evolution of the East African Rift System since the Miocene. This rift zone generated a symmetric rift graben in the north and a NNW-SSE striking half-graben in the south. The bathymetric expression at approximately 14-9°S, that is commonly interpreted as part of the Davie Ridge (e.g. Coffin and Rabinowitz, 1987) along the Davie Fracture Zone (Figure 1.3), merely results from Plio-Quaternary rift flank uplift and is most likely not connected to the southward drift of Madagascar during the Middle Jurassic-Early Cretaceous (Franke et al., 2015).

The detailed description of the Davie Fracture Zone (including the Davie Ridge) based on the interpretation of geophysical data was unmatched prior to the writing of this thesis and the corresponding research papers (Klimke et al., 2016; Klimke and Franke, 2016; Klimke et al., submitted). Section 1.2 provides a detailed overview of the main objectives of this thesis.

1.2　Open questions and objectives

This study was conducted in cooperation with the Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe; BGR) within the project "The passive and rifted continental margin off Mozambique: Early dispersal of Gondwana and the recent influence of the East African rift system" (PAGE4). The project is funded by the German Ministry for Research and Education (Bundesministerium für Bildung und Forschung; BMBF) and was established in 2014 in collaboration with the Alfred-Wegener Institute (AWI) and the Friedrich-Alexander University Erlangen (FAU). Within the scope of the project, several geophysical datasets were acquired in the Mozambique Channel during the expedition SO231 with the German research vessel Sonne in February and March 2014. The overall aim of the project PAGE4 was to contribute to an improved understanding of Gondwana breakup by studying exemplarily the evolution of a transform margin.

The objectives of the project were focused to address several key questions:

1. What is the structural architecture of the Davie Fracture Zone (including the Davie Ridge) in the Mozambique Channel area?
2. Where is the location of the continent-ocean transition along the Davie Ridge in the Mozambique Channel?
3. Can the Davie Fracture Zone be traced northward offshore Tanzania and Kenya?
4. What is the architecture of the transition from the transform margin along the Davie Fracture Zone to the volcanic rifted margin in the northern Mozambique Basin?
5. What is the influence of the East African Rift?

The last question regarding the influence of the East African Rift was addressed in a paper by Franke et al. (2015), which I co-authored. This thesis and the corresponding research papers (chapters 3 to 5; Klimke et al., 2016; Klimke and Franke, 2016; Klimke et al., submitted) focus on the investigation of the other issues addressed in questions 1 to 4. The main task was the interpretation of the 2D reflection seismic dataset acquired during cruise SO231. Magnetic and gravity data were used to complement the results gained by the reflection seismic data. The reflection seismic dataset of SO231 was supplemented by several other reflection seismic datasets offshore Mozambique, Tanzania, Kenya and offshore Antarctica in the Riiser-Larsen Sea. Those datasets, acquired by other institutes, were to some extent made available by the Seismic Data Center and the Antarctic Seismic Data Library System (SDLS). I will give an overview of the used datasets in chapter 2.

1.3   Scientific contribution

The central questions and objectives of this thesis are addressed in chapters 3 to 5. These are individual contributions in the form of manuscripts that have been published in (Publication 1 and 2, chapters 3 and 4) or submitted to (Publication 3, chapter 5) peer-review journals.

Publication 1: **How to identify oceanic crust – Evidence for a complex break-up in the Mozambique Channel, off East Africa** by Jennifer Klimke, Dieter Franke, Christoph Gaedicke, Bernd Schreckenberger, Michael Schnabel, Harald Stollhofen, Jens Rose and Mohamed Chaheire, published in Tectonophysics 693 (2016), 436-452, https://doi.org/10.1016/j.tecto.2015.10.012.

This study focuses on the structural interpretation of 2D reflection seismic profiles covering the Davie Ridge offshore northern Mozambique. Distinct portions of stretched basement are observed east of the Davie Ridge that have been affected by two phases of deformation. The first extensional phase corresponds to rifting between Madagascar and Africa. The second transpressional phase resulted in the formation of wrench faults and probably correlates with the southward drift of Madagascar. In contrast to earlier studies that proposed a major single transform fault and an abrupt transition from continental to oceanic crust located along the Davie Fracture Zone, a wide area consisting of stretched continental basement that has been affected by strike-slip deformation is observed. It is suggested that the Mozambique Channel area to the north of Madagascar may be classified as oblique margin rather than transform margin.

For this publication, I processed two of the reflection seismic profiles (BGR14-325 and BGR14-318), interpreted all the seismic profiles and developed the seismostratigraphic concept, wrote the manuscript and prepared all figures. Dieter Franke co-wrote parts of the manuscript regarding the geophysical characterization of oceanic crust (section 3.3) and provided helpful comments and suggestions. Christoph Gaedicke, Harald Stollhofen and Mohamed Chaheire provided additional suggestions. Bernd Schreckenberger compiled the map of the first vertical derivative of the gravity data. Michael Schnabel performed seismic ray tracing with 1D-models for one OBS-station from cruise SO230. Jens Rose processed two seismic profiles of the study. All, except Christoph Gaedicke and Jens Rose, were part of the scientific party of the cruise SO231.

Publication 2: **Gondwana breakup: no evidence for a Davie Fracture Zone offshore northern Mozambique, Tanzania and Kenya** by Jennifer Klimke and Dieter Franke, published in Terra Nova 28 (2016), 233-244, https://doi.org/10.1111/ter.12214.

This publication is based on the interpretation of 2D reflection seismic data acquired by the BGR in 2014 and the reinterpretation of vintage reflection seismic data located offshore Tanzania and Kenya. The study shows that several geological features located offshore northern Mozambique and Kenya are tectonically unrelated to the evolution of the Davie Fracture Zone. Offshore Tanzania, geophysical data do not indicate structures related to major transform motion. This challenges the transform margin concept postulated in the literature. Opening of the West Somali Basin by SW-propagating oblique rifting and seafloor spreading is proposed.

For this publication, I interpreted all the seismic data including several vintage seismic profiles made available by the Seismic Data Center, University of Texas. I wrote the entire manuscript and prepared all the figures. Dieter Franke provided additional comments and suggestions.

Publication 3: **Tie-points for Gondwana reconstructions from a structural interpretation of the Mozambique Basin, off East Africa, and the eastern Riiser-Larsen Sea, East Antarctica** by Jennifer Klimke, Dieter Franke, Estevão Stefane Mahanjane and German Leitchenkov, submitted to Solid Earth.

This paper is based on the interpretation of 2D reflection seismic data of different datasets located in the Mozambique Basin and the Riiser-Larsen Sea, Antarctica. It is shown that both continental margins show a similar structural architecture. At the foot of the continental slope, in the area of the continent-ocean transition, a prominent basement deformation zone is visible, that is proposed as tie-point for Gondwana reconstructions. Sediments overlying the deformation zone are deformed with onlap and toplap geometries, implying a post-breakup deformation phase. It is proposed that an initial, NW-SE directed extensional phase that led to rifting and localized seafloor spreading, was replaced by a N-S directed transform deformation phase. This transform motion occurred along the Davie Ridge offshore Mozambique and the Gunnerus Ridge offshore Antarctica, which are proposed to be conjugate features.

For this publication, I interpreted all the seismic data including a seismic dataset located in the Riiser-Larsen Sea, off Antarctica, made available by the Antarctic Seismic Data Library System (SDLS). I wrote the entire manuscript and prepared all the figures. Dieter Franke, Estevão Stefane Mahanjane and German Leitchenkov provided additional comments and suggestions.

2 Methods

In this chapter, I give an overview of the basic principle of 2D marine reflection seismic data acquisition and briefly describe the datasets used in this thesis. It also includes a description of my specific work on the reflection seismic data, which serve as a basis for the development of the geological models and concepts presented in chapters 3 to 5.

2.1 Principles of 2D marine multichannel seismic data acquisition

2D marine multichannel reflection seismic (MCS) data are the main type of geophysical data used in this thesis. They are acquired during marine expeditions, where the equipment is towed behind a seismic survey vessel, which moves through the water at constant speed (Figure 2.1). A controlled, artificial seismic energy source, mostly so-called airguns (air-pulse generators), is used to generate sound waves. These waves travel from the source through the strata and are reflected at layer boundaries due to a change in acoustic impedance to be picked up by marine receivers, so-called hydrophones (Figure 2.1). The acoustic impedance is defined as the product of the density of the medium and the seismic velocity, which varies among different rock layers (Yilmaz, 2001). The hydrophones are installed in streamers, which are several kilometers long cables and are towed behind the vessel. So-called birds and the tail buoy control the depth and position of the streamer (Figure 2.1).
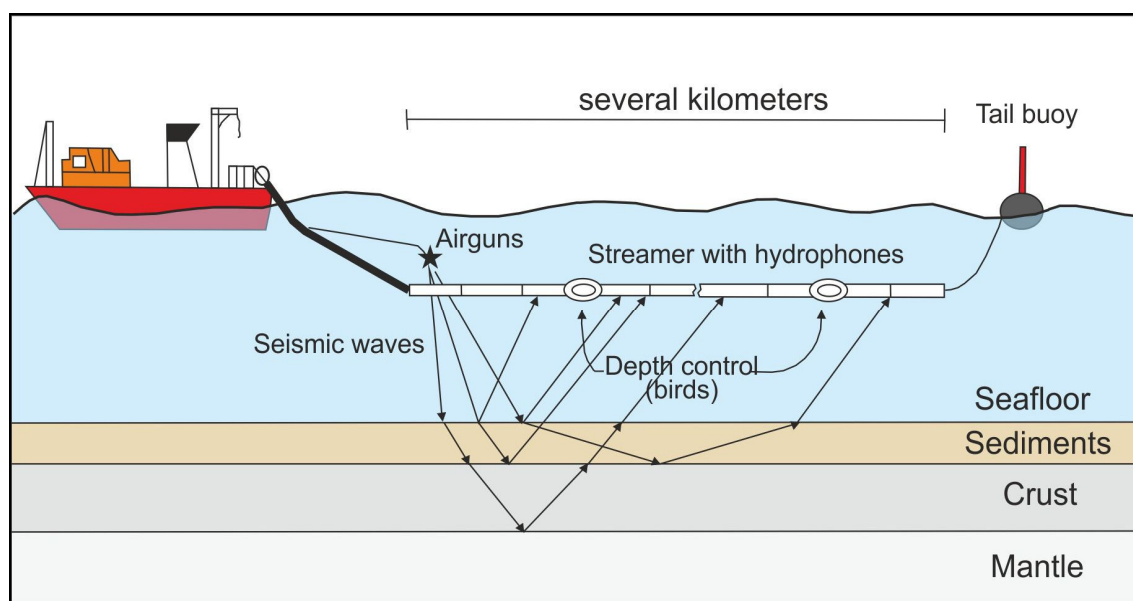
Figure 2.1: Simplified sketch of 2D marine reflection seismic data acquisition. Seismic waves produced by the airguns travel through the water column and the subsurface and are reflected at lithological boundaries, where a change in the acoustic properties of the medium occurs. So-called birds are used to control the streamer´s position. The tail buoy locates the position of the end of the streamer.

The time from the energy impulse to the registration of the signal with the hydrophones is called two-way travel time (TWT). This time is given on the vertical axes of the seismic sections presented in chapters 3 to 5. After the registration of the signal, it is converted to electronic, digital data that have to be processed with special software before it can be interpreted.
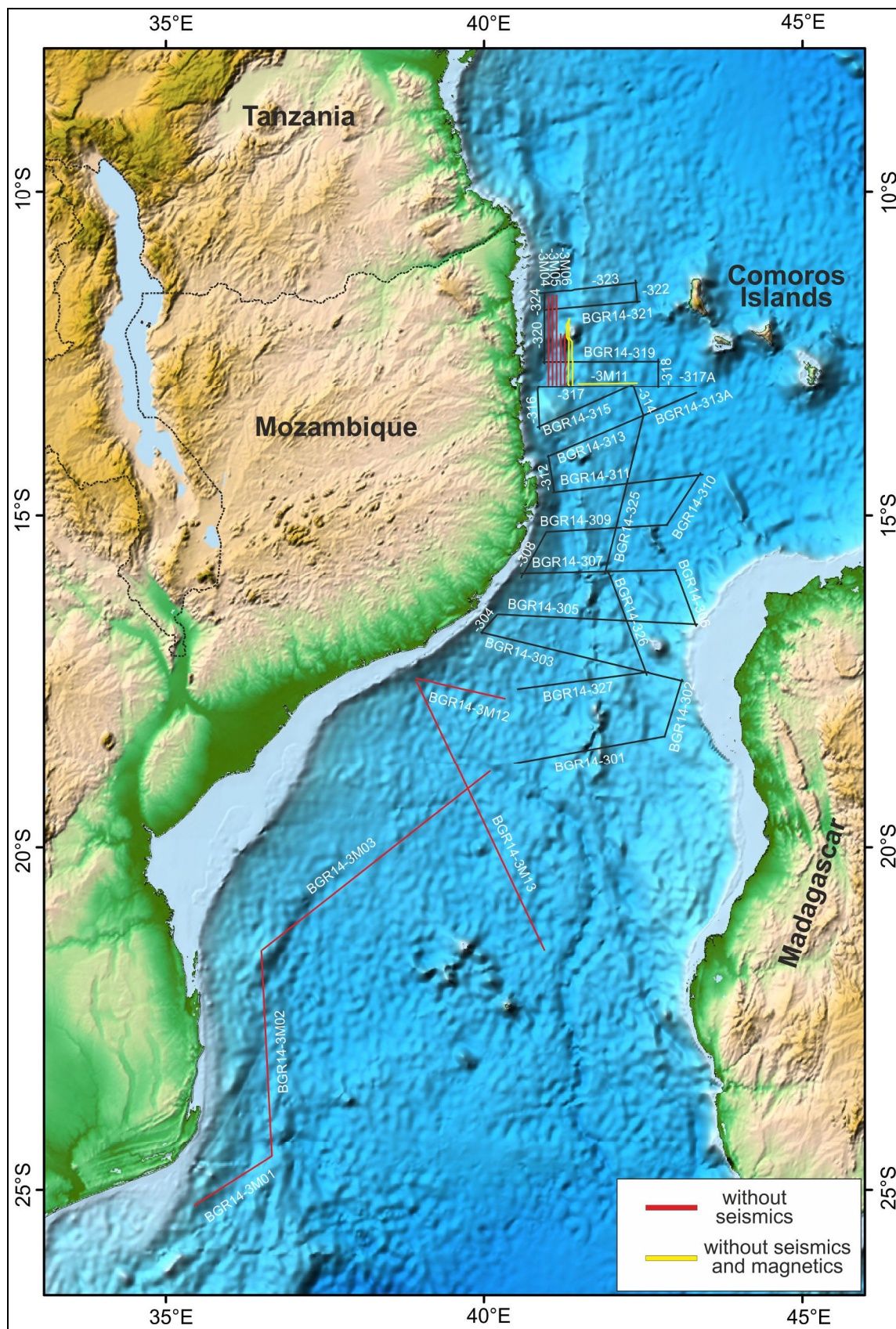
2.2 The BGR14 geophysical dataset

2.2.1 Acquisition of the geophysical profiles

During the cruise SO231 with the German RV Sonne in 2014, the BGR acquired an extensive set of geophysical profiles in the Mozambique Channel off northern Mozambique and Madagascar (Figure 2.2). Besides the 4300 km of 2D reflection seismic data on 27 profiles (Figure 2.2), magnetic, gravity and bathymetric datasets were acquired. The MCS data were recorded with a Seal streamer of 4050 m active length that comprised of 324 channels and was towed at a depth of 12 m. The sample rate was 2 ms with a record length of 14 s. The source was two G-Gun airgun arrays with a total volume of 3100 in^3, towed at 6 m depth. The source was fired every 50 m. For a detailed description of the acquisition parameters, it is referred to chapter 3.4.

In total, the magnetic dataset covers 6750 km on 39 profiles (Figure 2.2) and was acquired with a towed SeaSpy gradiometer system consisting of two scalar Overhauser sensors and one fluxgate vector magnetometer with two fluxgate sensors mounted on the observation deck above the bridge on the ship. The gravity and bathymetry datasets cover 7081 km on 42 profiles (Figure 2.2). Gravity data were acquired with the BGR-owned sea gravimeter system KSS32M. The gravity data are connected to the IGSN71 reference system and free air gravity values were calculated. Bathymetric mapping of the seafloor was conducted continuously during the cruise using the ship´s SIMRAD EM120 multibeam echosounder.

For this thesis, I mainly worked with the reflection seismic dataset of the cruise SO231, complemented by the respective magnetic and gravimetric sections. I was part of the scientific party of the cruise and contributed to the onboard preliminary interpretation of the seismic data. I was also responsible for the onboard processing of one third of the 27 reflection seismic profiles acquired during the cruise. During my thesis, I reprocessed several of the reflection seismic profiles, that were used for Publication 1 (chapter 3). Therefore, I give a brief overview of the processing of the SO231 reflection seismic data in section 2.2.2.

Figure 2.2 (previous page): Survey plan of the SO231 cruise in the Mozambique Channel. Geophysical data acquired during this cruise form the basis of this thesis. Several seismic profiles of the dataset were processed by me (see also section 2.2.2) prior to the stratigraphic and structural interpretation (section 2.4 and chapters 3 to 5).

2.2.2   Seismic processing of the BGR14 2D reflection seismic profiles

The aim of reflection seismic data processing is to create a high-resolution image of the subsurface where all reflectors are displayed at the correct subsurface position. During the processing, the seismic data are converted from seismograms, showing wavelets with different amplitudes at every reflective layer boundary for individual shots and receivers, to seismic sections. Important processing steps to improve the signal quality, among others, are steps improving the vertical resolution, attenuating noise (unwanted signal) and removing multiple reflections (of e.g. the seafloor) (Figure 2.3). After these steps, the data are stacked and migrated to get the seismic sections presented in chapters 3 to 5. Stacking significantly improves the signal-to-noise ratio, as multiple seismograms covering the same depth point are summed up so that random noise is eliminated. This method is called Common-Mid-Point Method or Common-Depth-Point Method. Before or after stacking, the data are migrated, where reflections of non-horizontal reflectors are moved to their correct subsurface position. The process of migration concentrates the scatter energy around a point source (e.g. a faultblock edge) that appears on stacked sections as diffractions, on the apex on the diffraction curve. There is an extensive number of literature about the principles behind seismic processing (e.g. Sheriff and Geldart, 2006; Yilmaz, 1987, 2001) and of software for the computation of the different algorithms. The BGR uses the commercial software ProMAX 2D for the processing of 2D reflection seismic datasets. In the following, I briefly describe the most important processing steps I used for the BGR14 dataset:

1. Geometry setup: Assignment of source-receiver coordinates.
2. SEGD input: Resampling of the data to 4 ms; Header statics to correct the time difference from the trigger signal of the acquisition system and the production of the acoustic signal of the airguns.
3. Removing of bad traces, e.g. noisy channels (hydrophones).
4. Brute stack to check the geometry setup and the overall data quality by applying a simple velocity model.
5. Removing of the noise (unwanted signal) in the data by applying a Butterworth bandpass filter (3-100 Hz filter with a 18db/octave low roll-off and a 72 db/octave high roll-off) by allowing only a band of usable frequencies to pass (Figure 2.3).

6. A predictive deconvolution algorithm is applied to suppress bubble energy and enhance vertical resolution by shortening the impulse length (Figure 2.3).

7. Picking of the stacking velocities in CDP gathers at regular intervals of 3 km along the lines (Figure 2.4). 11 CDPs are combined into a supergather for improving the signal/noise ratio. Horizontal reflectors are displayed as hyperbola branch, as the traveltime of seismic waves covering the same depth point increases with the offset between source and receiver ("moveout"). During velocity analysis, the correct velocity for each reflector is determined, which allows to remove the hyperbolic moveout ("normal-moveout correction").

8. Multiple suppression using the Surface-Related Multiple Estimation (SRME) (Figure 2.3). Multiple reflections of e.g. the seafloor often complicate the interpretation as they overlie primary signals. This tool uses reflector picks of prominent horizons, e.g. the seafloor, and the velocity field picked during step 7 to estimate the position of multiple reflections. After multiple estimation, the calculated multiples are subtracted from the input data.

9. FK-filtering to remove tailbuoy noise (Figure 2.3).
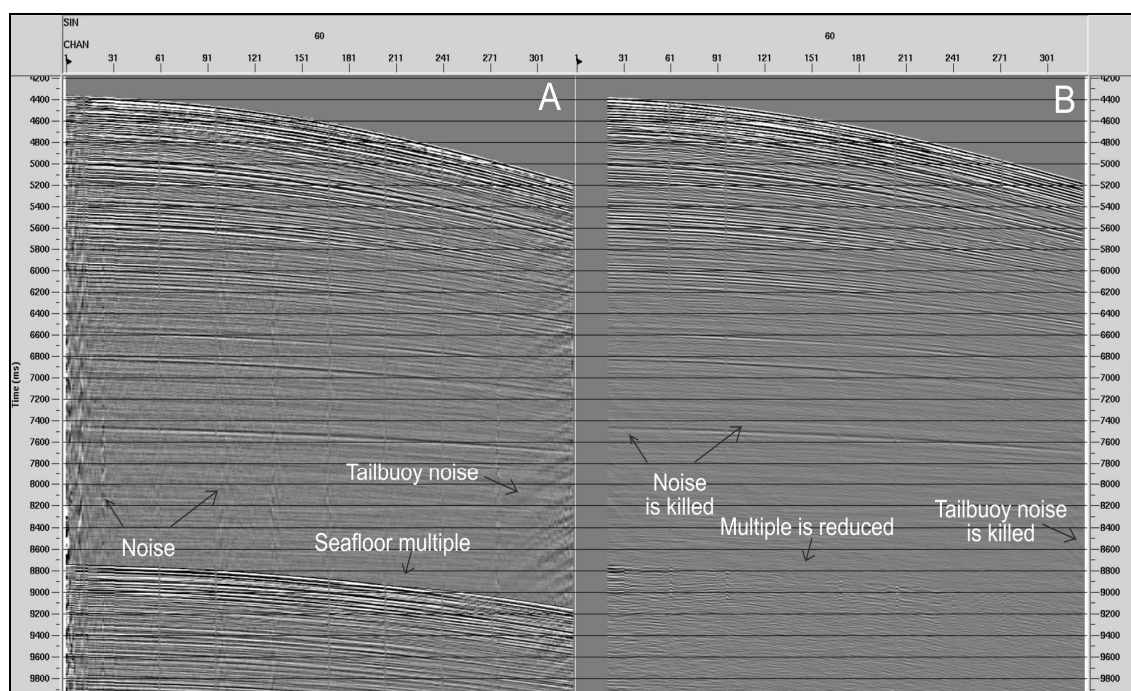
Figure 2.3: A shot gather of profile BGR14-325 before (A) and after (B) prestack-processing. Data above the seafloor reflector (water) has been cut off. (A) shows the unedited seismic data with prominent multiple reflections, noisy channels and tailbuoy noise that overlies primary signals. (B) shows the shot gather after application of filtering techniques, multiple reduction (SRME) and deconvolution.

10. A prestack Kirchhoff Depth migration was performed on common-offset gathers. A migration velocity field (interval velocities) based on residual moveout analysis was generated. Every reflector is moved to its correct subsurface position.

11. CDP stacking. All traces of a CDP gather are vertically stacked, so that every trace covering the same depth point is summed into one trace. The trace generated after stacking corresponds to a "zero-offset" shot-receiver-configuration, where shot and receiver are located at the same position.

12. Application of amplitude corrections for spherical divergence based on the velocity field generated in step 7.

13. The seismic depth sections are converted back to time domain using the velocity field generated in step 7.
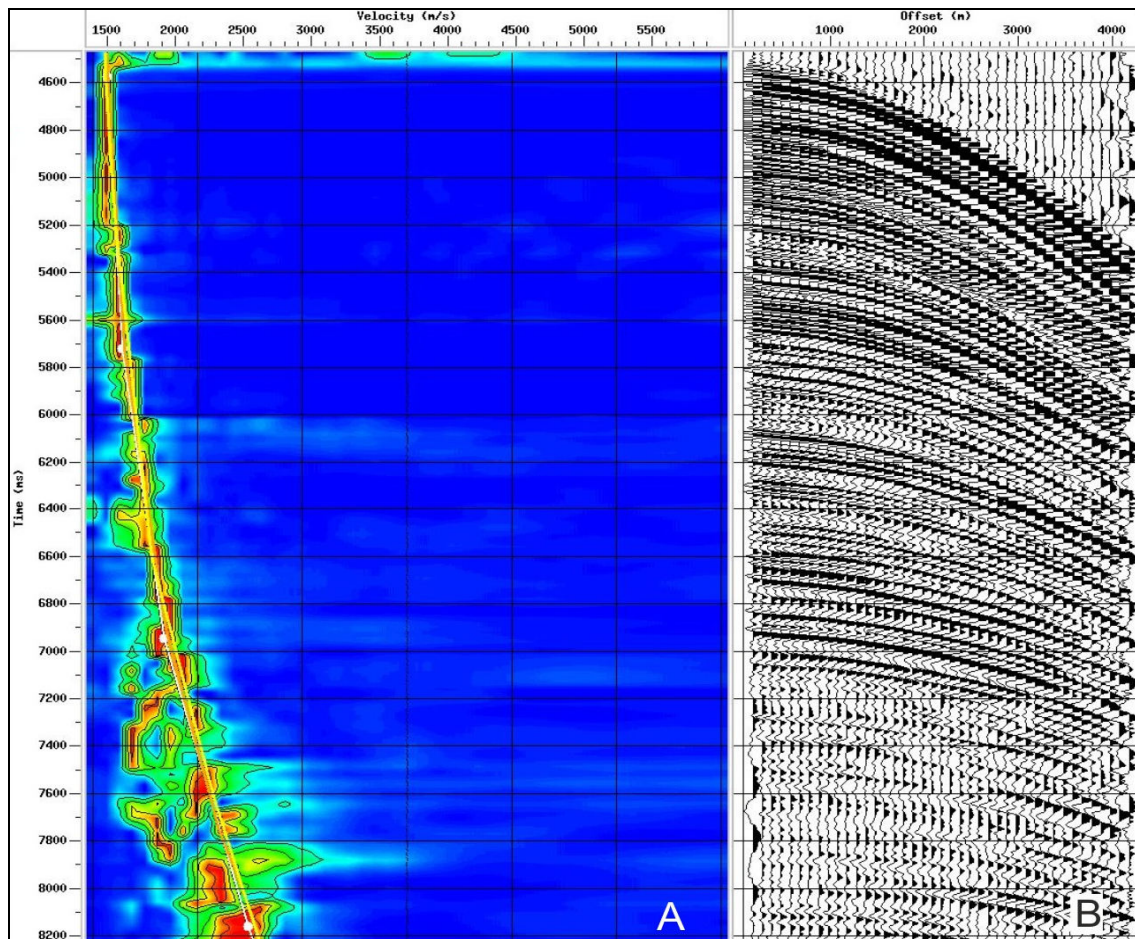
Figure 2.4: RMS velocity picking in ProMAX 2D. (A) Semblance window that shows the magnitude of stacked traces as a function of time and velocity. (B) Corresponding hyperbolas in the "supergather" panel.

It needs to be emphasized that seismic processing workflows are iterative and take a lot of computation time, what makes seismic processing very time-consuming. Especially the steps 8 and 10 (SRME and prestack depth migration) rely on a correct velocity field and the velocities can be determined best in prestack data without multiple reflections. Therefore, velocity picking has to be repeated several times after multiple suppression and migration.

2.3   Complementary 2D reflection seismic datasets used in this thesis

For Publication 2 and 3 (chapter 4 and 5), besides the BGR14 dataset, other 2D reflection seismic datasets acquired by different institutes were used.

The MCS dataset of cruise V3618 in the West Somali Basin, used in Publication 2 (chapter 4), was acquired with the RV Vema in 1980. The data were made available by the Seismic Data Center, University of Texas, Institute for Geophysics.

Two profiles of the Mbwg00 dataset, used in Publication 3 (chapter 5), were provided by the National Petroleum Institute of Mozambique. The dataset includes 8 profiles (~1300 km) located in the Mozambique Channel, acquired by Western Geophysical in 2000.

The RAE43 reflection seismic dataset, used in Publication 3 (chapter 5) and located in the eastern Riiser-Larsen Sea, off East Antarctica, was acquired by Polar Marine Geosurvey Expedition during a survey with RV Akademik Alexander Karpinsky in 1998. The dataset was made available through Antarctic Seismic Data Library System (SDLS) under the auspices of the Scientific Committee on Antarctic Research and the Antarctic Treaty.

2.4   Seismic stratigraphic and structural interpretation

After processing, the seismic profiles were loaded into specific seismic interpretation software. All seismic interpretation in this thesis was handled on UNIX seismic workstations using the GeoFrame/IESX™ software package of Schlumberger.

The seismic interpretation techniques used in this thesis are based on standard seismic stratigraphic interpretation methods (e.g. Catuneanu et al., 2011; Mitchum et al., 1977). It included mapping of key horizons and fault structures in the time domain (TWT), the determination of reflection terminations along unconformities, i.e. onlap, downlap, toplap geometries or erosional truncations, and the valuation of specific reflection attributes such as reflection continuity, amplitude, frequency and polarity (Mitchum et al., 1977). The reflection configuration within depositional sequences (parallel, subparallel, wavy, hummocky, contorted, discontinuous, chaotic, reflection-free) was

analyzed to gain information about depositional processes, erosional and tectonic events (Mitchum et al., 1977).

Eventually, the seismic observations were constrained by DSDP well Site 242 that is located in the Mozambique Channel and is crossed by two reflection seismic profiles of the BGR14 survey (chapter 3). Additionally, DSDP well Site 241 in the West Somali Basin was used for the interpretation of the VEMA (V3618) reflection seismic dataset (chapter 4). The seismic interpretation was also stratigraphically correlated with several previous offshore studies in the Mozambique Channel, the Mozambique and West Somali Basins and the Riiser-Larsen Sea (e.g. Castelino et al., 2015; Coffin and Rabinowitz, 1987, 1988; Franke et al., 2015; Leitchenkov et al., 2008; Mahanjane, 2012, 2014; Mascle et al., 1987; Mougenot et al., 1986). Magnetic anomaly interpretations (e.g. Gaina et al., 2013; Leinweber and Jokat, 2012; Rabinowitz et al., 1983) provided an additional age constraint, as reflectors merging with the top of the oceanic crust or terminating against oceanic crust were observed (chapters 3 to 5). Magnetic and gravity data of cruise SO231 were used to verify the seismic interpretation of e.g. magmatic effusives and oceanic crust (chapters 3 and 4).

The interpreted sections of the seismic data, as well as maps and sketches illustrating the geodynamic evolution of the study area based on the interpretation of the data, are shown in chapters 3 to 5.

3   Evidence for a complex breakup in the Mozambique Channel, off East Africa

Remarks

Abstract

The identification of oceanic crust at rifted margins plays a crucial role in academic research understanding rifting mechanisms and the architecture of continent-ocean boundaries, and is also important for hydrocarbon exploration extending into deeper water. In this paper, we provide a workflow for the determination of the crustal nature in the Mozambique Channel, east of Davie Ridge, by presenting a compilation of several geophysical attributes of oceanic crust at divergent margins. Previous reconstructions locate the Davie Ridge at the trace of a transform fault, along which Madagascar drifted to the south during the breakup of Gondwana. This implies a sharp transition from continental to oceanic crust seaward of Davie Ridge.

Using new multichannel seismic profiles offshore northern Mozambique, we are able to identify distinct portions of stretched basement east of Davie Ridge. Two phases of deformation affecting the basement are observed, with the initial phase resulting in the formation of rotated fault blocks bounded by listric faults. Half-grabens are filled with wedge-shaped, syn-extensional sediments overlain by a prominent unconformity that northward merges with the top of highly reflective, mildly deformed basement, interpreted as oceanic crust. The second phase of deformation is associated with wrench faulting and probably correlates with the southward drift of Madagascar, which implies that the preceding phase affected basement generated or modified prior to the opening of the West Somali Basin. We conclude that the basement is unlikely to consist of normal oceanic crust and suggest that the first extensional phase corresponds to rifting between Madagascar and Africa. We find evidence for a wide area affected by strike-slip deformation, in contrast to the earlier proposed major single transform fault in the

vicinity of Davie Ridge and suggest that the Mozambique Channel area to the north of Madagascar may be classified as an oblique rather than sheared margin.

3.1 Introduction

Much effort has been made in recent years to delineate the boundary between continental and oceanic crust at both magma-poor and volcanic rifted margins. However, due to a lack of good-quality geophysical datasets, sheared continental margins have been much less well studied. The delineation of continent-ocean transitions plays an essential role in academic research investigating plate tectonic models, rifting mechanisms and ocean formation. Furthermore, it is also crucial for hydrocarbon exploration that moves further offshore and relies on understanding the continent-ocean transition to locate potential source and reservoir rocks and to effectively model heat flow and maturity.

Sheared margins are expected to consist of sharp transitions from continental to oceanic crust (e.g., Bird, 2001). Although the continent-ocean transition at sheared margins is generally considered easy to delineate, the continent-ocean transition offshore Mozambique and Madagascar has not yet been conclusively interpreted.

This study presents a structural interpretation of new offshore multichannel seismic data integrated with potential field data and seismic velocity information from an OBS station, located seaward of Davie Ridge in the Mozambique Channel (Figure 3.1). The Davie Ridge has been hypothesized to represent the morphological expression of the southward drift of Madagascar from the Middle Jurassic to the Early Cretaceous following Gondwana breakup (e.g., Coffin and Rabinowitz, 1987; Heirtzler and Burroughs, 1971; Rabinowitz et al., 1983; Segoufin and Patriat, 1980). In the Mozambique Channel, an abrupt change from continental to oceanic crust to the east of Davie Ridge has previously been interpreted, mainly based on reflection seismic and potential field datasets (e.g., Coffin and Rabinowitz, 1987; Mascle et al., 1987). Here we challenge this interpretation that is widespread in the literature.

We examined the basement structure to the east of Davie Ridge using a set of N-S and E-W trending seismic profiles. Distinct portions of highly stretched basement more than ~100 km east of the Davie Ridge are identified, in an area that previously was consistently considered as oceanic (e.g., Coffin and Rabinowitz, 1987; Mascle, 1987; Segoufin and Patriat, 1980). We observe half-grabens, filled with wedge-shaped, syn-extensional sediments above rotated basement fault blocks. The area has been affected by a second phase of deformation, associated with wrench faulting that we connect with southward drift of Madagascar.
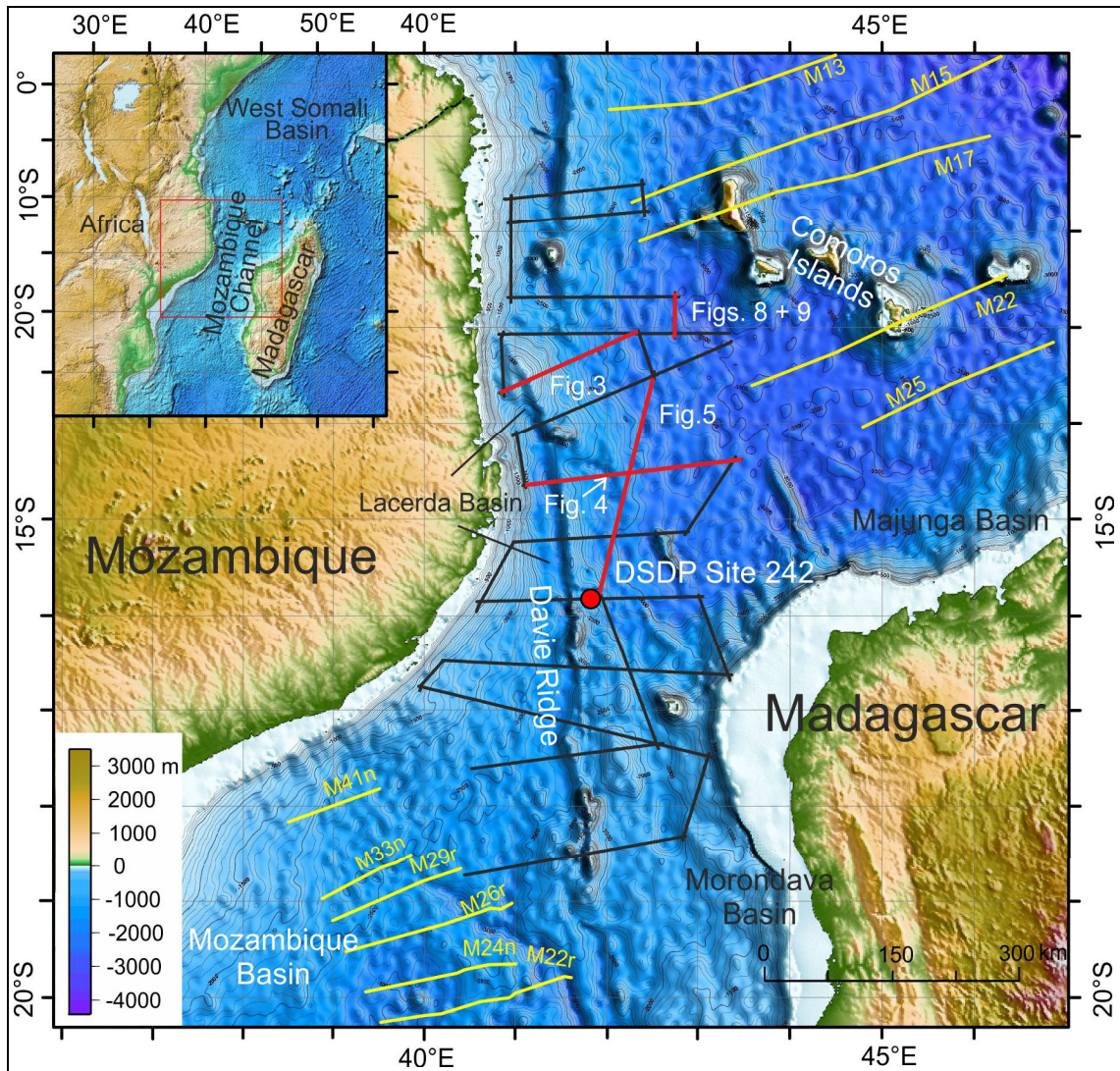
Figure 3.1: Base map of the study area in the Mozambique Channel showing the location of the geophysical profiles acquired during RV Sonne cruise SO231 (black lines). Red dot marks the location of DSDP Leg 25 Site 242 at the eastern flank of Davie Ridge (Simpson and Schlich, 1974). Magnetic lineations in the West Somali Basin are shown according to Rabinowitz et al. (1983). Magnetic lineations in the Mozambique Basin are taken from Leinweber et al. (2013). Locations of reflection seismic profiles shown in Figures 3.3, 3.4, 3.5, 3.8 and 3.9 are indicated by red lines.

We present a compilation of several geophysical properties of oceanic crust at divergent margin settings that contributes to a reliable differentiation of oceanic crust from continental or exhumed mantle domains. By application of the presented "workflow", we discuss the possibility that the observed rotated basement fault blocks represent extended oceanic crust, but we conclude that this is unlikely the case. Our main arguments against oceanic basement are 1) the estimated large crustal thicknesses prior to deformation of ca. 9 km, 2) top basement velocities of ~6.6 km/s, 3) a first deformational (extensional) event occurring prior to the formation of oceanic crust in the West Somali Basin and 4) the lack of any distinct spreading anomalies in the data.

Based on these new findings, we discuss implications for the formation of the Mozambique Channel.

3.2   Geological setting

The Davie Ridge traverses the Mozambique Channel in a N-S direction, extending from the northern coast of Mozambique to the southwestern coast of Madagascar (Figure 3.1). It is widespread in the literature that the Davie Ridge is located at the trace of a fossil transform fault that was active during the Middle Jurassic (~ 165 Ma) and Early Cretaceous (~120 Ma) (e.g., Bassias, 1992; Coffin and Rabinowitz, 1987; Mascle et al., 1987). This transform fault is interpreted to result from the relative motion of Africa and Madagascar, where Madagascar moved from its original position in the Gondwana supercontinent, adjacent to the coasts of Tanzania, Somalia and Kenya to its present position (e.g., Bassias, 1992; Coffin and Rabinowitz, 1987; 1988; Heirtzler and Burroughs, 1971; Rabinowitz et al., 1983; Scrutton, 1978; Segoufin and Patriat, 1980).

Prior to break-up of East (Madagascar, India, Antarctica and Australia) and West (South America and Africa) Gondwana in the Middle Jurassic (Gaina et al., 2013), polyphase Karoo rifting between Madagascar and East Africa occurred. According to Schandelmeier et al. (2004), rifting happened during three successive tectonic stages. The first phase of rifting (Permian) was accompanied by a significant sinistral transtensional component. After a short transtensional period in the latest Permian (second stage), NW-SE directed extension (third stage) prevailed during the Triassic. During evolution of the Mozambique Channel, intracontinental basins on the continental side of the Davie Ridge were generated that display prominent extensional and compressional structures (Mahanjane, 2014).

The Davie Ridge separates the Mozambique Basin from the West Somali Basin, both basins being formed during N-S to NNW-SSE directed breakup of East and West Gondwana (Gaina et al., 2015; Figure 3.1). Nevertheless, the timing of oceanic spreading based on the interpretation of magnetic anomalies in the West Somali Basin is still subject of considerable discussion. This is mainly due to the fact that, if present, the earliest oceanic crust formed in the Jurassic Magnetic Quiet zone, with very few, if any, distinct seafloor spreading anomalies. Gaina et al. (2013) and Gaina et al. (2015) suggest the presence of magnetic anomaly M40ny/M41 (~ 166 Ma) as the oldest and M2 (~ 127 Ma) as the youngest magnetic anomaly in the West Somali Basin, extending earlier interpretations of Rabinowitz et al. (1983) (M10-M25; ~155 Ma to 134 Ma) and Segoufin and Patriat (1980) (M0-M21; ~ 147 Ma to 124 Ma). However, the crustal nature of the West Somali Basin in the Mozambique Channel south of the Comoros Islands (Figure 3.1) is not conclusively determined and magnetic data do not clearly

evidence an oceanic origin. The presence of oceanic crust has been questioned by a number of detailed studies, published 30 to 50 years ago, when geophysical data and drilling cores were collected in this area. Talwani (1962) concluded from isostasy that the crust under the Mozambique Channel cannot be typical oceanic crust. Lort et al. (1979) found a change in frequency and amplitude of magnetic anomalies occurring at the Comoros Islands and suggested a transition from oceanic crust in the north to continental crust in the southern part of the West Somali Basin. Rabinowitz et al. (1983) later explained the low amplitudes of the magnetic signatures with the Jurassic Magnetic Quiet zone that is supposedly located between magnetic anomaly M25 and positive slope anomalies on both, the Madagascan and East African margins.

Dredging and coring of Davie Ridge revealed that it is, at least locally, built of crystalline continental basement (Bassias, 1992; Bassias and Leclaire, 1990). Crystalline basement was recovered at 14-15°S from the base of the western ridge flank and revealed gneisses and altered semi-pelites which are covered by clastic sediments and carbonate oozes (Bassias, 1992; Bassias and Leclaire, 1990). Further north, alkaline basalts are unconformably overlain by volcanic breccias and conglomerates, Miocene bioclastic limestones and Plio-Quaternary oozes. Along the southern parts of the ridge, basalts, basaltic breccias cemented with an Eocene carbonate matrix and karstified Miocene limestones were recovered (Bassias, 1992; Bassias and Leclaire, 1990). This structural configuration implies a complex tectonic history that, until today, is not satisfactorily understood.

Based on the interpretation of single-channel reflection seismic data covering the Davie Ridge, Mascle et al. (1987) suggested that after cessation of the southward drift of Madagascar, N-S trending tectonic features of the Davie Ridge were reactivated in the Late Cretaceous. This is suggested to have resulted from the separation of India from Madagascar and the opening of the Mascarene Basin to the east of Madagascar (at ~87 Ma; Seton et al., 2012). Tholeitiic basalts, basaltic andesites and rhyolites found in several basins of the conjugate East African and Madagascan margins (Coffin and Rabinowitz, 1988) may correlate with this event. Onshore Madagascar, $^{40}Ar/^{39}Ar$ dating of these rocks provide mean ages of ~83 Ma (Storey et al., 1995) and ~87 Ma (Torsvik et al., 1998) and suggest a short duration of the volcanic phase of no more than 6 or 8 Ma, respectively. The duration of magmatism is further constrained by U–Pb zircon and $^{40}Ar/^{39}Ar$ biotite ages, ranging ~ 92-87 Ma (Melluso et al., 2005; Torsvik and Cocks, 2013). These dates correlate with U-Pb zircon ages from western India (St. Mary islands) (Melluso et al., 2009; Torsvik et al., 2000). Bassias and Leclaire (1990) also link the generation of the seamounts along Davie Ridge to local extensions during the

Late Cretaceous. The reactivation of former extensional faults is also recorded for the on- and offshore Majunga Basin in NW Madagascar (Razafindrazaka et al., 1999).

3.3   Geophysical characterization of oceanic crust

Before considering a characterization, a definition of oceanic crust that particularly allows a distinction from continental fragments in the oceanic domain, is needed. We may start with a definition of oceanic crust as mafic crust, generated by steady-state seafloor spreading at mid-ocean ridges.

Our understanding of oceanic lithosphere has experienced dramatic changes from extensive research in the past years. There is widespread oceanic crust in which the upwelling of molten mantle rock is able to keep up with or even exceed the extension of the lithosphere and to generate a regular, layered, fully igneous crust ("Penrose" three-layer model, referred to as "normal oceanic crust" in the following). However, there is also slow-spread crust where the melt supply at various degrees is insufficient to keep up with extension, and is supplemented by tectonic extension (Dick et al., 2003; Larsen et al., 2009). In the latter case, tectonic extension at the seafloor exposes deep crustal to upper mantle sections (Cannat et al., 2006).

The upper section of normal oceanic crust is composed of lavas overlying a sheeted dyke complex. These units are formed by dykes intruding into rocks overlying a magma chamber, with lavas erupting at the ocean floor. In contrast, magma-poor spreading is accommodated by localized deformation along mylonitic shear zones in the upper mantle and - at lower temperatures - brittle faults (Kelemen et al., 2007). These shear zones and faults rotate and uplift passive blocks of residual peridotite (e.g., Péron-Pinvidic et al., 2007; Whitmarsh et al., 2001), that may be misinterpreted as rifted continental crust. It is an open question if the process that generates the latter portions of oceanic lithosphere can be called "seafloor spreading" at all (Russell and Whitmarsh, 2003; Srivastava et al., 2000) and therefore is sometimes termed "transitional" crust, "proto-oceanic" crust or "magma-poor" oceanic crust.

Additional problems come from inherent uncertainties in geophysical data that are often difficult to quantify. Moreover, it is problematic to resolve the nature of the crust using a single geophysical characteristic in isolation (e.g. seismic velocity structures), as those characteristics are often ambiguous when trying to discriminate between crustal types. Thus, typically a variety of geophysical data is used for a conclusive interpretation of the crustal type.

In the following, we describe several geophysical properties (magnetic signatures, crustal thicknesses, seismic velocities, and structural images as derived from reflection seismic data) of oceanic crust that can be used in combination to unequivocally identify

crustal types at divergent margins. In Table 1, we summarize the characteristics of oceanic crust, as derived from geophysical data, for different types of divergent margins (normal oceanic crust – volcanic rifted margins, abnormal oceanic crust – magma-poor margins and transform margins).

Table 1: Characteristics of oceanic crust at different tectonic settings.

Characteristics	Normal oceanic crust (Penrose model)	Abnormal oceanic crust	
	Volcanic rifted margins	Magma-poor margins	Transform margins
Crustal Thickness	- Average thicknesses of 7. 1± 0.8 km (White et al., 1992) - Extremal bounds 5.0 – 8.5 km (White et al., 1992) - the earliest mafic crust is thicker than typical oceanic crust due to high-velocity lower crustal bodies (e.g. South Atlantic – Becker et al., 2014)	- Thicknesses of 2-6 km - absence of oceanic Layer 3 (e.g. Funck et al., 2003; Lau et al., 2006 – Iberia-Newfoundland) - Moho reflection may be absent due to exhumed mantle peridotites	- Average thicknesses at fracture zones: 4.0 ± 1.3 (White et al., 1992) - Côte d´Ivoire: ~4.4 km (Edwards et al., 1997); thickness of Layer 3 is reduced to 2-3.5 km (Edwards et al., 1997) - Agulhas-Falkland Fracture Zone: 4 km (Becker et al., 2012)
Seismic structure and architecture	- Typically 2s TWT between top oceanic basement and Moho reflection	- Generally, the interval between top oceanic basement and Moho reflection is smaller than at normal oceanic crustal settings, as oceanic crust is often unusually thin (e.g. South Atlantic - Becker et al., 2012; Hopper et al., 2004 – Flemish Cap, Newfoundland) - At magma-poor margins, Moho reflection may be absent, as the crust-upper mantle boundary is often gradational (Minshull, 2009)	
	- High-frequency diffractive reflections in the stacked section (e.g. Figure 3.9 – this study; Coffin and Rabinowitz, 1988 -West Somali Basin) - Flat or hummocky high-amplitude reflections in the migrated section (e.g. Figure 3.8 – this study)		
Magnetics	- Linear seafloor spreading anomalies reflect reversals of the earth´s magnetic field embedded in magnetizable rocks (Vine and Matthews, 1963) - Formation of oceanic crust during magnetic quiet periods may lead to weak anomalies that are difficult to correlate, e.g. Jurassic Quiet Zone and Cretaceous	- Exposed uppermost mantle peridotite ridges may acquire remnant magnetizations during serpentinization, e.g. Iberia-Newfoundland (Sibuet et al., 2007) - elongated syn-extensional intrusions may mimic seafloor spreading anomalies (e.g. Russel and Whitmarsh,	- Linear seafloor spreading anomalies may be present (e.g. South Atlantic – Becker et al., 2012)

	Quiet Zone	2003 - Iberia)	
Seismic velocities	- Layer 2: 5.1± 0.7 km/s, Layer 3: 6.8± 0.3 km/s (White et al., 1992) - Sharp Moho transition to > 7.8 km/s (White et al., 1992)	- Frequently, velocities indicative of Layer 3 are absent (e.g. Funck et al., 2003; Lau et al., 2006 – Iberia-Newfoundland)	- Layers with velocities representative for Layer 3 are thinner than in normal oceanic crust (e.g. Edwards et al., 1997) - A gradual transition between crustal and mantle velocities may be observed (e.g. Sage et al., 1997 – Ghana/Côte d´Ivoire)
Deformation patterns	- Normal faults develop due to bending-related faulting close to the spreading center, i.e. during the first million years (Buck et al., 2005) - Amount and size of faults correlates with spreading velocity (Carbotte and Macdonald, 1994) - Only in the first 20 Ma after formation of an oceanic basin, the strength is less or equal to the surrounding continental lithosphere; deformation of older oceanic lithosphere is an exception, as it will focus in the surrounding continental domain (Vauchez et al., 1998) - deformation of mature oceanic crust can be considered an exception, because of the much higher integrated strength of oceanic lithosphere with respect to continental lithosphere		
Lithology	Penrose model type: Lavas overlying sheeted dykes and gabbros Examples: -Equatorial Pacific (Wilson et al., 2006) -Pacific south of Costa Rica rift, Hole 504B (Dick et al., 2006)	Various amounts of basaltic and gabbroic rocks with peridotites Examples: Iberia, ODP Site 1070 (Whitmarsh et al., 2001): pegmatite gabbro and depleted subcontinental serpentinized peridotite with gabbro veins; no basaltic rocks - Mid-Atlantic ridge 15°20´: gabbroic rocks intrusive into peridotite (ODP Leg 209; Kelemen et al., 2007).	Low crustal thicknesses indicate a deficit in magma-supply; peridotites with few magmatic features may be expected

3.3.1 Magnetic signature

Magmatic oceanic crust is usually characterized by lineated seafloor spreading anomalies that reflect reversals of the earth´s magnetic field embedded in magnetizable rocks of the seafloor (Vine and Matthews, 1963). The magnetic signature is a robust indicator for the presence of oceanic crust, if it can be excluded that other rocks (that are not mafic and were not emplaced by steady-state seafloor spreading) are the origin of the magnetization. This is particularly problematic at the continent-ocean-transition along magma-poor margins (Bronner et al., 2011), where elongated mantle peridotite ridges that acquired significant amounts of magnetization during serpentinization can mimic linear magnetic anomalies (Sibuet et al., 2007). Furthermore, elongated syn-extensional intrusions in continental crust may mimic seafloor spreading anomalies (Russell and Whitmarsh, 2003). Offshore Newfoundland, an anomaly, earlier interpreted as seafloor spreading anomaly M3, turned out to lie within thinned continental crust (Funck et al., 2003). The prominent J magnetic anomaly in the Newfoundland–Iberia rift system does not correspond to the beginning of the M sequence of seafloor-spreading anomalies, but instead represents a pulse of magmatism that may have triggered continental breakup prior to seafloor spreading (Bronner et al., 2011). In the South China Sea, seismic reflection and wide-angle data show that extended to hyper-extended continental crust is present more than 200 km south of an area, where previously seafloor-spreading anomalies C17 to C12 and thus oceanic crust has been interpreted (e.g. McIntosh et al., 2013).

Therefore, at extensional settings where continental crust was extremely thinned and exhumation of subcontinental mantle is observed in the vicinity of relatively thin oceanic crust, it typically is difficult to identify oceanic crust solely on the basis of magnetic data.

On the other hand, the absence of seafloor spreading anomalies is no robust indication for the absence of oceanic crust. There is the possibility that oceanic spreading fabric is masked by subsequent magmatism. In some oceanic basins, the crust formed during magnetic quiet periods, where resulting anomalies are weak and difficult to correlate. There are varying explanations for magnetic quiet zones, such that the polarity of the earth´s magnetic field did not change its direction over this period of time (e.g. Cretaceous Normal Superchron (approx. 121 to 83 Ma ago); Granot et al., 2012), that rapid field reversals resulted in closely spaced polarity intervals with very weak anomalies (e.g. Jurassic Magnetic Quiet Zone, Roeser et al., 2002) or that oceanic crust was formed during low paleofield strength (e.g. Early Cretaceous, Dodd et al., 2015).

In the Somali Basin, the Jurassic Magnetic Quiet Zone, which is generally regarded as a combination of rapid field reversals and low field strength might be the cause for the lack

of distinct magnetic lineations over inferred oceanic crust (e.g. Coffin and Rabinowitz, 1987; Rabinowitz et al., 1983).

3.3.2   Crustal thickness

Normal oceanic crust is relatively thin compared to continental crust and displays average crustal thicknesses of 7.1 ± 0.8 km with extremal bounds of 5.0 to 8.5 km (White et al., 1992). This results in the typical 2 s (two-way traveltime; TWT) interval between the top of the oceanic basement and the Moho in reflection seismic data.

Crustal thickness can be determined by refraction seismic experiments, but also from Moho reflections in reflection seismic data (if reliable velocity information is at hand) supported by gravity modelling. Gravity data (at times in combination with magnetic data) are used to validate velocity models based on wide-angle seismic experiments, but in addition offer the possibility to test different interpretations.

Along volcanic rifted margins, the earliest mafic crust is considerably thicker than typical oceanic crust, partly caused by the presence of high-velocity lower crustal bodies showing velocities of 7.3-7.6 km/s. Typically, the mafic crust thins seaward to normal oceanic crustal thickness over a distance corresponding to a few million years of accretion (e.g. Becker et al., 2014; Holbrook et al., 1994; Koopmann et al., 2014b). According to our definition, this would be the transition from excess magmatism to steady-state mafic crust generated by seafloor spreading at mid-ocean ridges.

At magma-poor continental margins, oceanic crust shows thicknesses of 2-6 km and frequently, Layer 3 is absent; e.g. at the Newfoundland Flemish Cap (Funck et al., 2003; Lau et al., 2006). The onset of steady-state seafloor spreading is difficult to determine at such margins, but apparently the first magmatic oceanic crust is slightly thicker than the adjacent attenuated continental crust/exhumed mantle domain (e.g. Lau et al., 2006).

A reduction in oceanic crustal thickness has also been observed at transform margins and in the vicinity of fracture zones (e.g. White et al., 1992). In the latter case, the average thickness of oceanic crust decreases to 4.0 ± 1.3 km (White et al., 1992). This has also been reported for the Ghana-Cote d´Ivoire transform margin, where the oceanic crust adjacent to the marginal ridge shows thicknesses of ~4.4 km (Edwards et al., 1997) and lacks velocities indicative of oceanic Layer 3 (Sage et al., 1997). A thickness of about 4 km for the magmatic portion of the oceanic crust has been reported along the Agulhas-Falkland Fracture Zone (Becker et al., 2012).

When considering crustal thickness, it should also be noted that highly stretched "hyperextended" margins may have continental crustal thickness values similar to typical oceanic crustal thicknesses (e.g., Van Avendonk et al., 2009).

3.3.3 Seismic velocities

The typical velocity signature of either oceanic or continental crust can be used to support the interpretation of additional geophysical datasets. From seismic refraction experiments it is known that continental crust subdivides into three layers with typical velocity ranges: an upper crustal layer (6.0-6.3 km/s), a middle crustal layer (6.6-6.8 km/s) and a lower crustal layer (6.8 and 7.2 km/s) (Christensen and Mooney, 1995). In contrast, Layer 2 and Layer 3 of oceanic crust are characterized by velocities of 5.1 ± 0.7 km/s for Layer 2 and 6.8 ± 0.3 km/s for Layer 3 (White et al., 1992). Below both types of crust, a sharp Moho transition to velocities of ~8.0 km/s occurs (Christensen and Mooney, 1995; White et al., 1992). A significant p-wave anisotropy of up to ~ 10% is expected (Cole et al., 2002), but is generally not considered due to limited azimuthal sampling.

At magma-poor margins, seismic velocities at the top of basement seaward of distinct continental crust are below ~5.0 km/s, lower than what is typically observed either in continental or in adjacent oceanic crust (Minshull, 2009). In most cases, velocities rise steeply to reach values of >7.0 km/s at 2-4 km beneath top basement and normal mantle values of >7.8 km/s are reached at 5-6 km beneath top basement (Minshull, 2009). At the continent-ocean transition along magma-poor margins, a normal oceanic Layer 3 often is absent. According to Minshull (2009), a distinction between exhumed and serpentinized mantle and adjacent oceanic and thinned continental crust can be made based on high p-wave velocities at shallow depths and a lack of oceanic Layer 3; these characteristics normally indicate exhumed mantle. High-velocity lower crustal bodies are found below either thinned and intruded continental crust or oceanic upper crust, and the base is much deeper than 5-6 km below top basement, typical for serpentinization.

3.3.4 Seismic structure and architecture

The rigidity of the oceanic lithosphere results in relatively little deformation away from plate boundary zones. Thus, typically, oceanic crust can be differentiated from the continental domain by a flat or hummocky high-amplitude reflection pattern in reflection seismic profiles. While the high-amplitude top reflection results from the pillow basalts of the oceanic crust, a wavy reflection pattern may develop due to inherited structures during the formation of the oceanic crust. Below the oceanic crustal reflections, a Moho reflection may be visible due to the density and velocity contrast between oceanic crust and upper mantle. At magma-poor rifted margins, especially at the continent-ocean transition, the crust-upper mantle boundary is often gradational and thus lacking a distinct Moho reflection (Minshull, 2009). Continental crust at rifted margins is characterized by half-grabens or rotated fault blocks that are bounded by listric normal faults. In many cases, stratigraphic successions in rift-related basins can be subdivided into pre-, syn- and post-rift sequences (Martins-Neto and Catuneanu, 2010) with sedimentary pre-rift

sequences in the acoustic basement being a robust indication for the presence of underlying continental crust.

The challenge in the interpretation of multichannel seismic data is to distinguish extended continental from faulted oceanic crust. In many cases, normal faults are observed in oceanic crust that predominantly develop due to bending-related faulting close to the spreading center, i.e. during the first few Ma (Buck et al., 2005). The amount and size of the faults correlates with the spreading velocity. Regions of superfast spreading are characterized by the largest numbers of short faults, the smallest average fault spacing and throw, and the highest fault density (Carbotte and Macdonald, 1994). Because of small-scale faulting, oceanic crust is often characterized by high-frequency diffractive reflections in the stacked sections (e.g., Coffin and Rabinowitz, 1988 for the West Somali Basin) and high-amplitude, multi-reflector bands in the migrated sections. Such small-scale faults in oceanic crust are distinctly different from major basin-bounding faults in the continental domain. However, the main question is if faulting in oceanic crust can produce faults similar in size to rift-related faulting affecting continental crust. According to Buck et al. (2005), the pattern of faulting produced by stretching at spreading centers is controlled by the rate of magmatic accretion and amagmatic periods are not required to produce large-offset faults as proposed earlier (Carbotte and Macdonald, 1990). Only during the first 20 Ma after formation of an oceanic basin, the strength of the oceanic lithosphere may be less than or equal to the surrounding continental lithosphere (Vauchez et al., 1998). This means that, generally, extensional deformation will focus in the surrounding continental areas rather than deform more than 20 Ma old oceanic crust.

Later deformation, i.e. deformation of mature oceanic crust, can be considered as an exception, because of the much higher integrated strength of oceanic lithosphere with respect to continental lithosphere. There are few examples of deformed oceanic lithosphere, either showing reverse faulting (e.g. Carton et al., 2014) or normal faulting (Sager et al., 2013; Salisbury and Keen, 1993). The normal faults are particularly interesting, because in the examples provided by these authors, the normal faults are listric and there are distinct syn-extensional sediments filling the corresponding half-grabens.

However, the earlier identified faulted oceanic crust off the coast of Nova Scotia, originally related to volcanic episodes at a slow spreading ridge modified by tectonic rotation (Salisbury and Keen, 1993), was subsequently identified as highly thinned continental crust based on OBS data (Funck et al., 2003; Wu et al., 2006). The central Indian Ocean around the Ninety East Ridge is particularly prone to deformation (Carton et al., 2014) and there are a large number of compressional faults and folds, strike-slip faulting and normal faulting (Sager et al., 2013). However, Moeremans and Singh (2014) suggested that parts of the Ninety East Ridge are of continental origin.

Based on our studies and the literature review, we conclude that the presence of listric normal faults bounding graben structures filled with wedge-shaped syn-extensional sediments can be considered as an indication for the absence of oceanic crust. However, if rifts develop through multiphase extension, extensional deformation in the transitional or proto-oceanic domain may be misinterpreted as indicative for the presence of continental crust.

3.4 Data acquisition, processing and modelling

3.4.1 Reflection seismic data

Geophysical data used in this study were acquired by the Federal Institute for Geosciences and Natural Resources (BGR) with R/V Sonne in February and March 2014. The 2D MCS profiles are part of a dataset comprising 27 reflection seismic lines (~4300 km; Figure 3.1). The data were recorded with a Seal streamer of 4050 m active length that comprised of 324 channels with a group spacing of 12.5 m. The sample rate was 2 ms with a record length of 14 s, where the streamer was towed at a depth of 12 m. The source consisted of two G-Gun airgun arrays starboard and portside with a total volume of 3100 in^3, towed at 6 m depth. The nominal shot point spacing was 50 m, leading to a CDP fold of 41, respectively.

The seismic profiles were processed with the commercial software ProMAX 2D. All major processing steps were applied in the prestack domain, which included prestack processing to enhance the signal quality, i.e. trace editing, predictive deconvolution, bandpass filtering, fk-filtering to remove tailbuoy noise, amplitude corrections for spherical divergence based on RMS velocities, multiple suppression using the Surface-Related Multiple Estimation (SRME) and a filter in the radon domain. A prestack Kirchhoff Depth migration was performed on common-offset gathers. For the migration, a migration velocity field based on a residual moveout analysis was generated. After several migration iterations and subsequent CDP stacking, the data were converted back to the time domain and exported to the interpretation system (GeoFrame/IESX^{TM} by Schlumberger).

3.4.2 Velocity information

Throughout the interpretation, interval velocity information as derived from stacking velocities was incorporated. To support the interpretation along the N-S profile BGR14-325, we analyzed one OBS-station from cruise SO230 (Jokat, 2014), which is situated on the E-W line BGR14-311, at the crossing point to profile BGR14-325. The station shows prominent refracted phases with a velocity of 6.6 km/s.

To estimate the depth of this layer, we performed seismic ray tracing with 1D models. We extracted a velocity-depth relationship for the sediments from the analysis of the

MCS data. For the OBS, this results in reliable velocities for a depth of at least 6 km. We extrapolated this velocity-depth trend and found a depth of 7.9 km for the 6.6 km/s refraction boundary.

3.4.3   Potential field data

Magnetic data were acquired with a towed SeaSpy gradiometer system consisting of two scalar Overhauser sensors and one fluxgate vector magnetometer with two fluxgate sensors on the ship. Gravity data were acquired using a sea gravimeter system KSS32M, manufactured by the Bodenseewerk Geosystem GmbH. The gravity data are connected to the IGSN71 reference system and free air gravity values were calculated. Potential field data are provided together with the corresponding MCS sections and are qualitatively interpreted and used for the identification of oceanic crust, as described in section 3. Gravity data were also used for the compilation of a map of the first vertical derivative presented in this paper.

3.5   Results

3.5.1   Stratigraphy

Five marker horizons were identified in the seismic profiles that can be correlated with distinct regional events in the Mozambique Channel area (Figure 3.2). The stratigraphic interpretation of the Tertiary deposits is mainly based on DSDP Site 242 that is located on the eastern flank of Davie Ridge and is crossed by two reflection seismic profiles of the survey (Figure 3.1). DSDP Site 242 penetrated 676 m of Quaternary to Upper Eocene sediments (Simpson and Schlich, 1974) and allows a good correlation for the area east of Davie Ridge. We interpreted the top of the Eocene sediments, corresponding to reflector A of Mougenot et al. (1986), as reflector TE and traced it throughout the study area (e.g. Figures 3.3, 3.4 and 3.5). Reflector TC is identified as the top of the Cretaceous strata, which correlates with reflector B of Mascle et al. (1987) and Mougenot et al. (1986). Cretaceous strata are of relatively low reflectivity, which allows a clear distinction from well-stratified, highly reflective Tertiary deposits (e.g. Figure 3.5). We identify widely distributed magmatic effusives in the southern part of the study area (Figure 3.4) which is located in the offshore Morondava Basin (Figure 3.1; Geiger et al., 2004). As the distribution of these magmatic effusives at this stratigraphic position (close to the Cretaceous/Tertiary boundary) seems limited to the Morondava Basin, we correlate them with basalts and rhyolites dated at ~83 Ma (Storey et al., 1995) and ~87 Ma (Torsvik et al., 1998) onshore Madagascar.
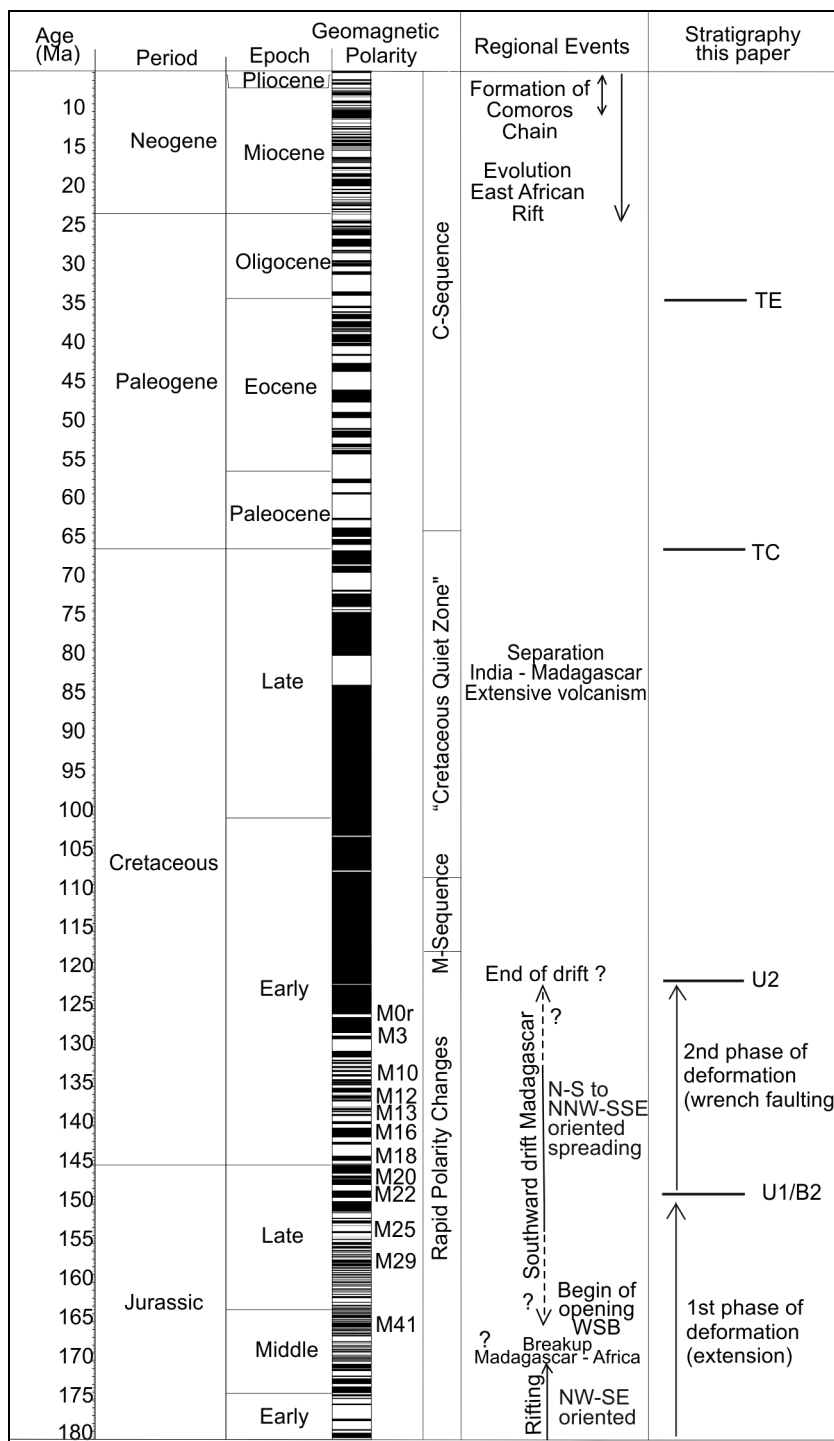
Figure 3.2: Chronostratigraphic chart outlining the stratigraphy of the Mozambique Channel used in this paper. Regional events are summarized from Bassias and Leclaire (1990), Coffin and Rabinowitz (1987), Franke et al. (2015), Gaina et al. (2013, 2015), Geiger et al. (2004), Melluso et al. (2005, 2009), Mougenot et al. (1986), Rabinowitz et al. (1983), Schandelmeier et al (2004), Segoufin and Patriat (1980), Seton et al. (2012), Storey et al. (1995) and Torsvik et al. (1998). The stratigraphy integrates data of Coffin and Rabinowitz (1987, 1988), Franke et al. (2015), Mahanjane and Franke (2014), Mascle et al. (1987) and Mougenot et al. (1986). The stratigraphic interpretation of the Tertiary sediments is mainly based on DSDP Site 242 (location in Figure 3.1). Seismic reflectors are labeled TE= Top Eocene; TC= Top Cretaceous; U2= Prominent unconformity, locally of erosional character (inferred Early Cretaceous age); U1= Distinct unconformity that seals the offset of listric basement faults (inferred Late Jurassic age); B2= Top basement (interpreted as oceanic crust). WSB= West Somali Basin.

Two distinct unconformities are identified in the seismic profiles, which mark the end of two deformational phases in the study area (Figures 3.5 and 3.6). The first unconformity, reflector U1, can be traced northward, where it merges with the top of a highly reflective multi-reflector band (reflector B2) that we interpret as oceanic crust (section 5.2). According to magnetic anomaly interpretations in the Mozambique Channel (Figure 3.1; Rabinowitz et al., 1983), the oceanic crust in this area is of Late Jurassic age (M22; ~148 Ma) which provides an indication for the age of reflector U1. However, uncertainties in the interpretation of magnetic anomalies in the West Somali Basin, as described in section 2, need to be considered. The second unconformity marks the end of wrench faulting and clearly postdates the formation of reflector U1 but predates Late Cretaceous volcanism widespread in the Morondava Basin. We correlate reflector U2 with the cessation of southward motion of Madagascar relative to Africa which is dated by M2 at ~127 Ma (Gaina et al., 2013).

3.5.2 Structural interpretation

The seismic profiles presented in this study are located in the Mozambique Channel, close to the Davie Ridge (Figure 3.1). Two E-W and NW-SE running seismic lines are shown in Figures 3.3 and 3.4. The Davie Ridge is imaged as a ridge with an elevation of a couple of hundred's milliseconds (TWT).

The basement, indicated by reflector B1, generally displays relatively low reflectivity and is horizontal and undisturbed, or only mildly deformed (e.g. Figure 3.3, distance: 80-180 km). Particularly in the west, extensional deformation affecting the basement is distinct by the presence of prominent normal faults bounding half-grabens (e.g. Figure 3.3, distance: 0-70 km; Figure 3.4, distance: 0-50 and 100-150 km). In the northern part of the study area, west of Davie Ridge, a major half-graben, the Lacerda Basin, developed (Figures 3.3 and 3.4). Basement in this area was affected by a phase of extension that led to the generation of east to northeast dipping basement blocks (e.g. Figure 3.3, distance: 0-50 km; Figure 3.4, distance: 0-50 km). Half-grabens are filled by wedge-shaped, syn-extensional sediments. In the northern part of the Lacerda Basin, the Cenozoic sediments were affected by recent extensional deformation, as many of the normal faults reach the seafloor (Figure 3.3, distance: 20-40 km). Many of the recent normal faults are situated at the position of prominent listric basement faults, which indicates a reactivation during this extensional phase (Figure 3.3, distance: 35 km). Sub-recent extension was found to correlate with the evolution of the offshore continuation of the eastern branch of the East African Rift System (Mougenot et al., 1986; Franke et al., 2015).
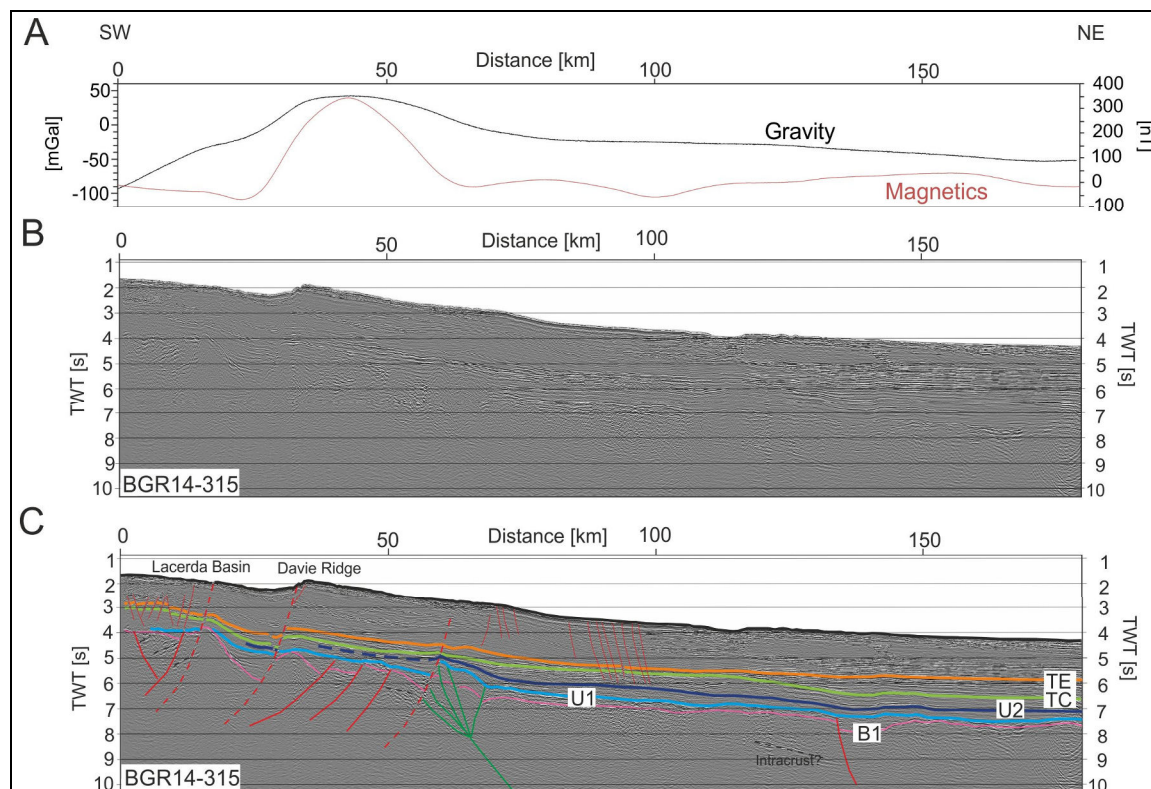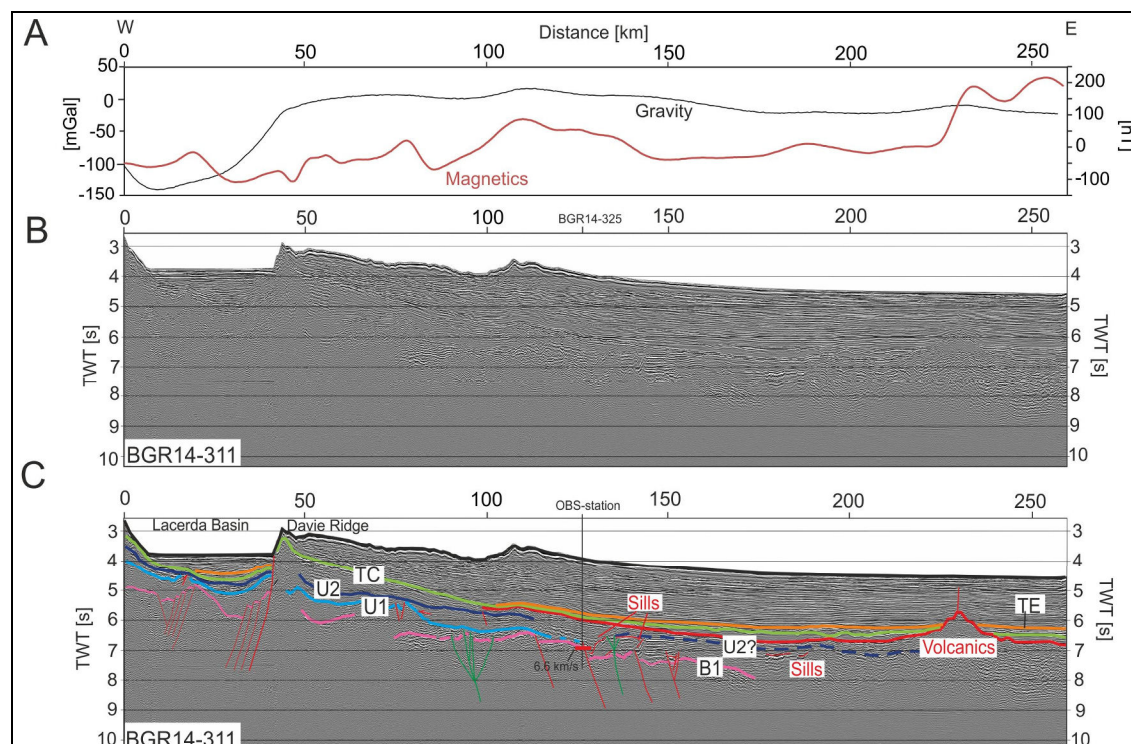
Figure 3.3: Prestack migrated profile BGR14-315 (line location in Figure 3.1). (A) Observed magnetic and free-air gravity data across the profile. At the position of Davie Ridge, magnetic and gravity data show prominent positive anomalies that may be connected with magnetic intrusions at basement depth. (B) Uninterpreted section of profile BGR14-315, overlain by (C) interpretation. Basement east of Davie Ridge is of low reflectivity and is horizontal and undisturbed or only mildly deformed. In the west, basement has been affected by prominent normal faults bounding half-grabens. Cenozoic sediments were affected by recent extensional deformation (distance: 80-100 km) and the reactivation of former listric basement faults (dashed red lines; distance: 20-70 km). Basement east of Davie Ridge has been affected by a prominent wrench fault (green), located at a distance of 60-70 km. Seismic reflectors are labeled TE= Top Eocene; TC= Top Cretaceous; U2= Prominent unconformity, locally of erosional character (inferred Early Cretaceous age); U1= Distinct unconformity that seals the offset of listric basement faults (inferred Late Jurassic age); B1= Top stretched basement.

The topography of Davie Ridge in this area merely results from Plio-Quaternary rift flank uplift and is most likely not connected to the southward motion of Madagascar during the Mid Jurassic-Early Cretaceous (Franke et al., 2015). However, the deeply buried rift structures are well in accordance with dredging and coring results (Bassias and Leclaire, 1990) and confirm that the Davie Ridge is situated in the continental domain. At the location of Davie Ridge, a prominent positive magnetic anomaly of up to 350 nT is observed (Figure 3.3) which might correlate with magmatic intrusions at basement level, indicated by high amplitude reflections below reflector B1 (Figure 3.3). Further south, the area up to 50 km east of Davie Ridge is characterized by only minor magnetic anomalies ranging between -100 and 0 nT (Figure 3.4). Towards the center of the West Somali Basin, basement depth is increasing from 4-6 s (TWT) to about 8 s

(TWT; e.g. Figure 3.3) and only minor magnetic variations of about 50 nT are observed. Sporadically, intracrustal reflections are visible on E-W oriented profiles (e.g. Figure 3.3, distance: 120-130 km). Although considerable efforts have been made, throughout the survey Moho reflections are not imaged. This is equally true for long-offset commercial seismic lines in the area (e.g., Danforth et al. 2012).

Sedimentary reflector U1 is marking the top of the deeply buried syn-extensional fill of the half-grabens. It is overlain by a well-stratified succession with relatively low amplitude but continuous reflections and is topped by reflector U2 (Figures 3.3 and 3.4). Reflector U2 is overlain by a relatively transparent sedimentary package that is characterized by subparallel, continuous reflections with low, locally medium amplitudes (Figure 3.3, distance e.g. 70-180 km; Figure 3.4, distance e.g. 50-100 km). In the southern part of the study area, which is located in the northernmost part of the offshore Morondava Basin (Figure 3.1; Geiger et al., 2004), up to 100 km wide, highly reflective bodies are intercalated in the transparent package (Figure 3.4, distance: 150-270 km). These structures correlate with positive magnetic anomalies of up to 200 nT, most likely indicating a magmatic origin of the material. The volcanics can be traced over long distances as far as ~70 km east of Davie Ridge, where a prominent magnetic anomaly of ~100 nT is observed (Figure 3.4). The stratigraphic position of the volcanics reveals that the emplacement of the magmatic rocks took place during the post-rift phase. The most prominent regional magmatic phases that are well known from Madagascar, India, and Mozambique are all of Early and Late Cretaceous age. Early Cretaceous volcanic rocks occur in several formations of the Mozambique Basin (Salman and Abdula, 1995) and the Late Cretaceous volcanic activity is reflected by basalts and rhyolites found in the Morondava Basin onshore Madagascar that provide mean ages ranging between 92-87 Ma (Melluso et al., 2005; Torsvik et al., 1998; Torsvik and Cocks, 2013). Offshore data of this study show that the volcanic effusives are frequently accompanied by sills and dikes that were emplaced subparallel to the bedding of strata and fault planes (e.g. Figure 3.4, distance: 130-190 km; Figure 3.5, distance: 60-90 km). We observe the post-rift magmatic effusives in a relatively confined area east of Davie Ridge, up to ~150 km north of the Madagascan margin. On profiles located west of Davie Ridge, magmatic effusives are not observed. Additionally, the stratigraphic position indicates that the magmatic effusives were emplaced close to the beginning of the Tertiary (Figure 3.4), as we confirm the top Eocene reflection from the DSDP drillhole 242 (Figure 3.1). Therefore, we stratigraphically correlate the highly reflective structures with Late Cretaceous (Turonian) basalts and rhyolites. The volcanic flow units are overlain by thin, transparent, drift bodies that can be well distinguished from the overlying successions. We interpret the transparent bodies as Late Cretaceous strata (~80-65 Ma; e.g. Figure

3.4, distance: 150-250 km) overlain by the Top Cretaceous reflector (TC; e.g. Figures 3.3 and 3.4) that separates transparent strata from well-stratified, subparallel, medium to highly reflective Tertiary deposits progressively onlapping onto the eastern flank of Davie Ridge (Figure 3.4).

Figure 3.4: Prestack migrated profile BGR14-311 (line location in Figure 3.1). (A) Observed magnetic and free-air gravity data across the profile. A prominent magnetic anomaly of up to 230 nT correlates with magmatic effusives of inferred Late Cretaceous age. A volcanic flow is observed in the center of the profile with up to 100 nT (distance: 100-150 km). The Lacerda Basin is characterized by a gravity low (-100 to -150 mGal). (B) Uninterpreted migrated section of profile BGR14-311, using a prestack Kirchoff algorithm, overlain by (C) seismic interpretation. Davie Ridge is visible as a ridge with an elevation of a couple of hundreds milliseconds (TWT). Basement is characterized by low reflectivity and is affected by listric faults (red) bounding half-grabens (e.g. distance: 120-150 km). In the eastern part of the profile, prominent magmatic bodies of inferred Late Cretaceous age (distance: 150-250 km) occur. Occasionally, basement and Jurassic to Early Cretaceous strata are affected by steep wrench faults (green; e.g. distance: 100 and 130 km). These are preferentially located at the position of former listric basement faults (e.g. distance: 100 km). Tertiary strata are progressively onlapping against the eastern flank of Davie Ridge. The location of the OBS-station showing prominent refracted phases with velocities of 6.6 km/s (Figure 3.7A) that coincide with the top basement reflection interpreted in the MCS data is indicated. Seismic reflectors are labeled TE= Top Eocene; TC= Top Cretaceous; U2= Prominent unconformity, locally of erosional character (inferred Early Cretaceous age); U1= Distinct unconformity that seals the offset of listric basement faults (inferred Late Jurassic age); B1= Top stretched basement.

The Tertiary sediments are mainly characterized by well-stratified successions with thicknesses of up to ~3 s (TWT). From the south to the north and from west to east, the

thickness is continuously increasing from ~1.5 s to ~3 s (TWT). The most striking observation in the Mozambique Channel is a wide zone showing rotated basement fault blocks associated with listric normal faults east of Davie Ridge (Figure 3.5, distance: 150-270 km).

The fault blocks are imaged best on N-S striking profiles and were most likely affected by ~NW-SE directed extension. This is in accordance with extensional directions observed for the late rift (NW-SE, Schandelmeier et al., 2004) and drift phase (N-S to NNW-SSE, Gaina et al., 2015) in the Mozambique Channel area. They are up to 10 km wide and most of them dip in a southward direction (Figure 3.6). The tops of the fault blocks are marked by basement reflector B1 and are generally imaged in depths of ~7 to 8 s (TWT; ~ 7-8 km; e.g. Figures 3.5 and 3.6).

Reflector B1 is characterized by medium to high amplitude reflections (Figures 3.5 and 3.6). Below reflector B1, low frequency reflections are observed. These are mostly chaotic and of high reflectivity. The analysis of one OBS-station located on profile BGR14-311 shows a clear refracted phase with a velocity of 6.6 km/s (Figure 3.7A) that coincides with the top basement reflector, adjacent to the rotated fault blocks (Figures 3.4 and 3.5).

By application of the above mentioned velocity model (Figure 3.7B), a depth-converted section of profile BGR14-325 was generated (Figure 3.5D). This depth section allows the calculation of the dip of the faults defining the domino-style blocks and is 30°- 40° in their upper portion with the dip decreasing with increasing depth. The fault planes are well imaged and can occasionally be followed up to a depth of up to 10 km (Figure 3.5D, distance: 180-250 km) or 9 s TWT on the time section, respectively (e.g. Figure 3.6, distance: 185 and 240 km). We have used the derived dip angle of the faults to calculate the crustal stretching factor (β_c = 1/sin(fault dip); Allen and Allen, 2013) in order to obtain initial crustal thickness prior to extension. The calculation results in a crustal stretching factor of the brittle upper crust of β_c = ~ 1.5. The detachment level has been estimated using bed-length balance and fault displacement of the listric faults (Davidson, 1986) and is calculated to be ~6 km below top basement. Adding to this the observed water depth of 3 km and the sedimentary overburden of 4 km, results in a present-day detachment depth of 13 km, a depth that coincides with the depth that Recq (1982) derived for the Moho in the Mozambique Channel east of Davie Ridge. As the detachment level and the depth of the Moho proposed by Recq (1982) seem to coincide, the crustal thickness prior to extension can be calculated using the crustal stretching factor of β_c= ~1.5. If we assume a detachment at Moho level, the crustal thickness prior to extension and the formation of the fault blocks, was ~9 km. If it were an intra-crustal detachment, crustal thickness would correspondingly be higher.
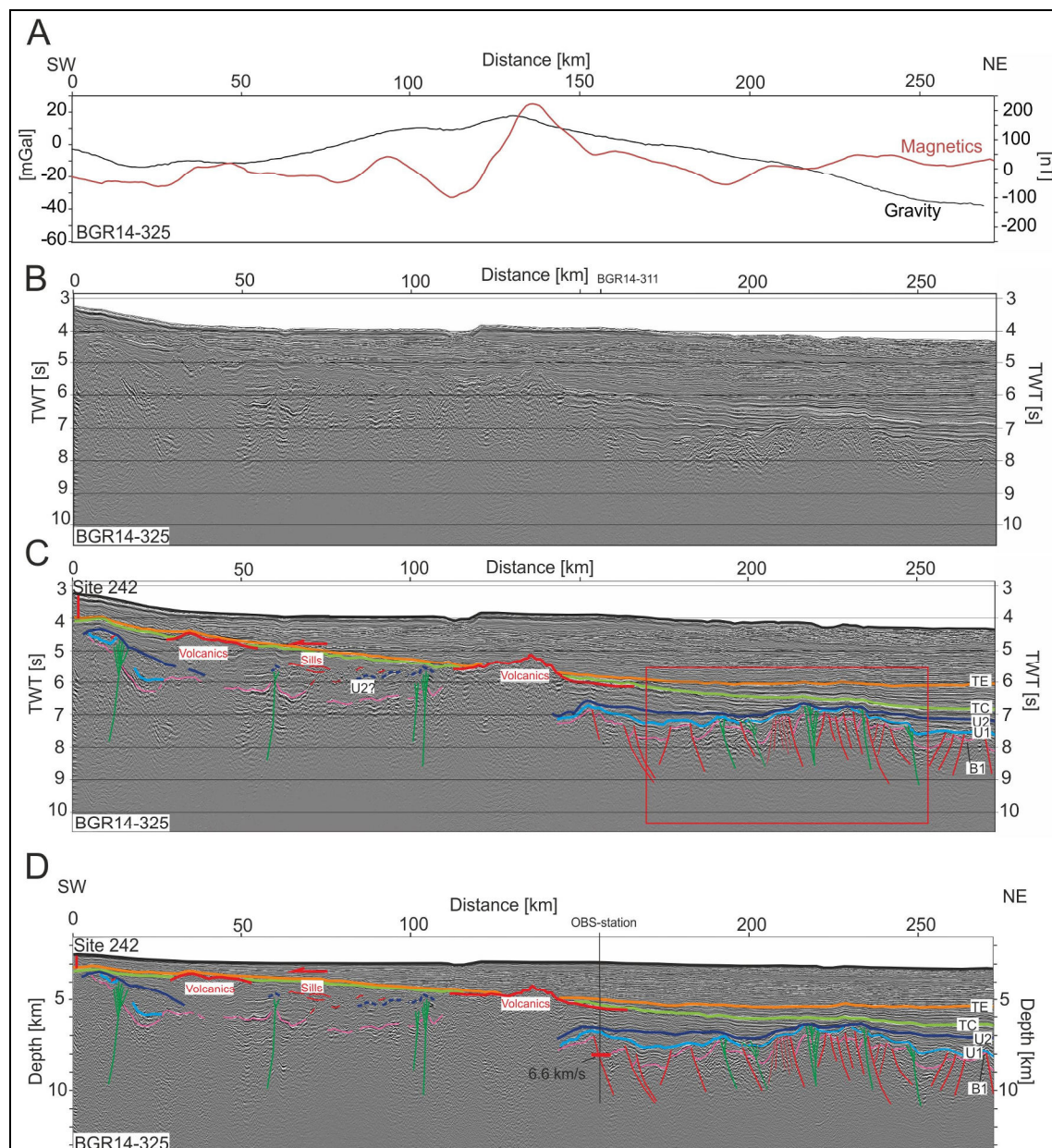
Figure 3.5: Prestack migrated section of profile BGR14-325 (line location in Figure 3.1). (A) Observed magnetic and free-air gravity data across the profile. A prominent magnetic anomaly of ~230 nT correlates with magmatic effusives of inferred Late Cretaceous age. The southwestern part of the profile is characterized by small positive magnetic anomalies of ~20-30 nT, which is connected with magmatic sills, emplaced parallel to the bedding of strata (e.g. distance: 70-100 km). (B) Uninterpreted N-S oriented reflection seismic profile BGR14-325 across the West Somali Basin near Davie Ridge, overlain by (C) seismic interpretation. The profile shows a succession of rotated fault blocks bounded by listric normal faults (red). The half-grabens are filled with wedge-shaped, syn-extensional sediments (distance: 150-270 km). A second deformational event is characterized by wrench faulting (green) in localized areas. Wrench faulting is located at the position of former listric basement faults and is accompanied by uplift and erosion of the syn-extensional infill of the half-grabens (e.g. 210-220 km). To the southwest, the profile is located in the northern part of the offshore Morondava Basin (Figure 3.1; Geiger et al., 2004). (D) Interpreted depth section of profile BGR14-325. Seismic reflectors are labeled TE= Top Eocene; TC= Top Cretaceous; U2= Prominent unconformity, locally of erosional character (inferred Early Cretaceous age); U1= Distinct unconformity that seals the offset of listric basement faults (inferred Late Jurassic age); B1= Top stretched basement.
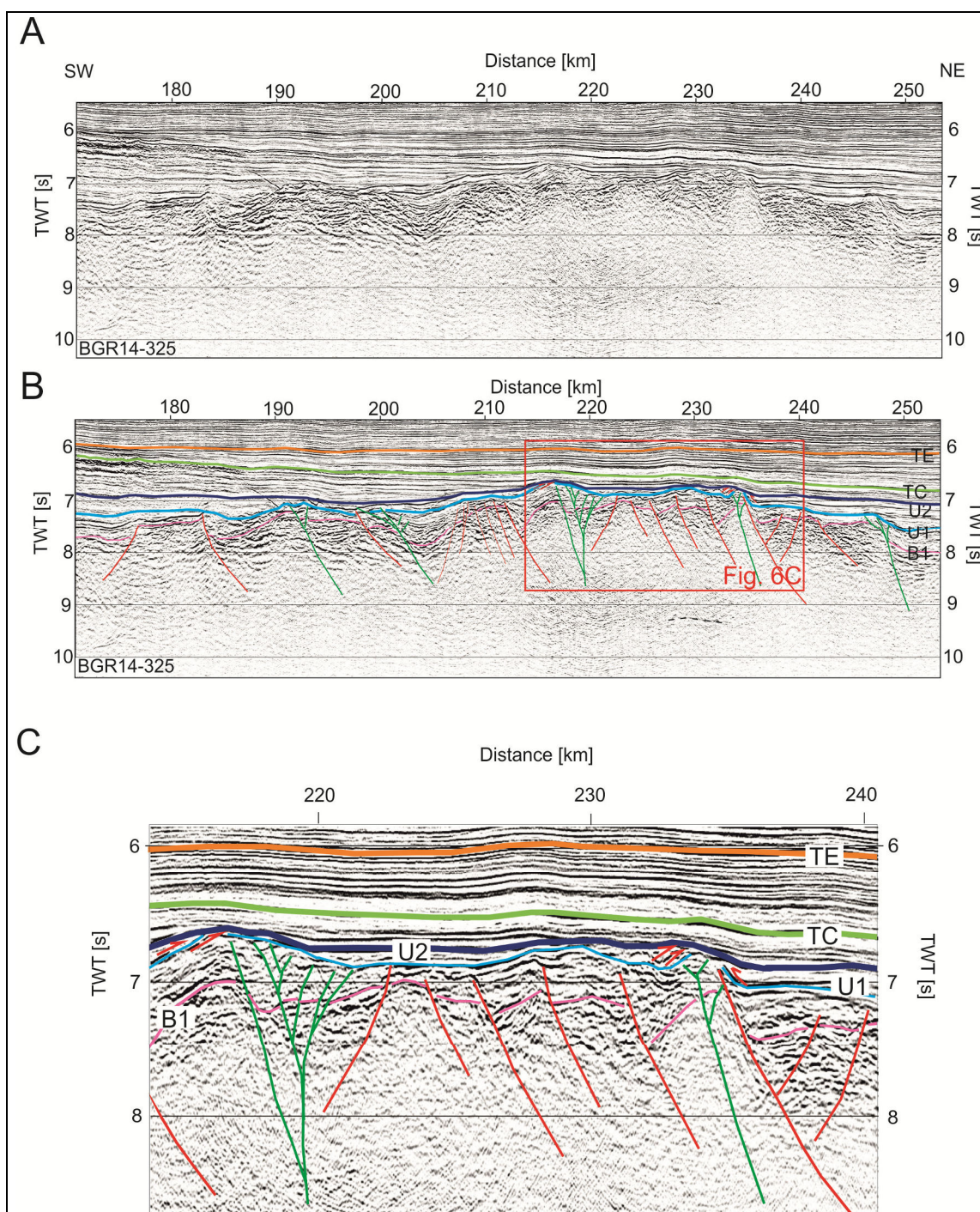
Figure 3.6: Close-up view of migrated seismic profile BGR14-325 shown in Figure 3.5 (line location in Figure 3.1). (A) Uninterpreted seismic section using a prestack Kirchoff algorithm, overlain by (B) seismic interpretation. Basement has been affected by two deformational phases, where the older phase led to the generation of rotated fault blocks bounded by listric normal faults (red). Half-grabens are filled with wedge-shaped, syn-extensional sediments. The younger event is characterized by wrench faulting (green) in localized areas. Wrench faults are located at the position of former listric basement faults and caused uplift and subsequent erosion of syn-extensional strata (e.g. distance: 215 and 235 km). (C) Close-up view of red box marked in (B). Seismic reflectors are labeled TE= Top Eocene; TC= Top Cretaceous; U2= Prominent unconformity, locally of erosional character (inferred Early Cretaceous age); U1= Distinct unconformity that seals the offset of listric basement faults (inferred Late Jurassic age); B1= Top stretched basement.

The half-grabens which formed during rotation of the basement blocks are filled with wedge-shaped, syn-extensional sediments, characterized by subparallel reflections with low to medium amplitudes (e.g. Figures 3.5 and 3.6). The top of the syn-extensional strata is formed by reflector U1 and displays high reflectivity, which enables reliable distinction from the overlying strata (Figures 3.5 and 3.6). Reflector U1 is an unconformity sealing the offset of the listric faults and thus marks the end of the extensional phase that led to the generation of the rotated basement fault blocks.

The unit overlying U1 generally is well-stratified and the reflections can be traced laterally, although they are of relatively low amplitude. The top of this unit is marked by reflector U2, which can be well identified on N-S striking profiles, where it is displayed as a prominent unconformity that locally develops erosional character (Figures 3.5 and 3.6, distance: 215-220 and 235 km). Parts of the syn-extensional sediments have been eroded at these locations (Figure 3.6C). This might indicate that the area may have been situated above sealevel at that time. As we assign reflector U2 a Mid Early Cretaceous age, erosion may correspond to a major drop in sealevel (Haq et al., 1987). Alternatively, erosion may indicate the establishment of north-south circulation from the Tethys through the West Somali Basin into the Mozambique Basin. The profiles show a distinct second phase of deformation that led to the generation of wrench faults. These appear as fan-like, steeply dipping faults that at depth converge into a single, subvertical fault. In most cases, reflector U1 is folded in an upward direction (e.g. Figure 3.3, distance: 75 km; Figure 3.6, distance: 195 km) and internal horizons are heavily deformed (e.g. Figure 3.6, distance: 220 km). The wrench faults are accompanied by uplift and subsequent erosion that is indicated by the termination of reflector U1 against reflector U2 (e.g. Figures 3.5 and 3.6, distance: 215-225 km and 235 km). Generally, reflector U2 marks the termination of wrench faulting and may correspond to the cessation of southward movement of Madagascar in the Early Cretaceous (~123 Ma, Gaina et al., 2013). At least locally, the wrench faults are situated at the location of former listric faults accounting for their reactivation (Figure 3.6). Most of the wrench faults are observed on N-S striking profiles (Figure 3.5) and the abundance increases towards the north. There (Figure 3.5, distance: 150-250 km), wrench faults are spaced at 10-20 km distance. In a narrow zone (Figure 3.5, distance: 220-240 km), wrench faulting led to uplift of basement and erosion of syn-extensional strata (Figure 3.6C). Surrounding this narrow zone, U1 is folded but not eroded and covered by strata overlain by U2. Towards the south, the spacing of the wrench faulting is decreasing to about ~50 km. At several locations, reflector TC is slightly folded at the position of the wrench faults, which could indicate a reactivation of the wrench faults towards the end of the Cretaceous. This event might correlate with the separation of India from Madagacar (~87 Ma, Seton et al., 2012).

A prominent magmatic feature is observed adjacent to the area of rotated fault blocks (Figure 3.5, distance 100-150 km) and coincides with a prominent magnetic anomaly of up to 200 nT. The volcanic flow can be traced further north to a distance of ~170 km, where anomalies of 75-100 nT are observed. Besides the magmatic features that produce prominent magnetic anomalies, the area showing the fault blocks is characterized by only minor magnetic variations around ~50 nT (Figure 3.5, distance 150 -270 km).

Towards the south, the profile (Figure 3.5) continues into the Morondava Basin (Figure 3.1; Geiger et al., 2004). Basement is rising up to ~4.5 s (TWT) and displays a prominent basement high (Figure 3.5, distance: 0-30 km). Similarly to the northern parts of the profile, basement and syn-extensional sediments have been affected by wrench faulting (Figure 3.5, distance: 20, 60 and 100 km) and reflector U1 has been eroded locally. Similar to the northern part of the N-S profile (Figure 3.5), magnetic data range between -50 and 0 nT (Figure 3.5, distance 0-100 km).

North of ~13°S, a change of the basement structure from rotated fault blocks to a high-amplitude, low-frequency multi-reflector band, located at a depth of ~7s (TWT; ~ 7-8 km) is observed (Figure 3.8). The top of this multi-reflector band, indicated by basement reflector B2, is curved and wavy (hummocky reflection configuration). The basement in this domain shows only minor internal deformation. Most important, however, when tracing reflector U1 northward, it clearly merges with the top of this multi-reflector band (Figure 3.8, distance: 15 km), which illustrates that both reflectors are most likely of the same age. This observation provides a relative age constraint between the formation of the extensional structures further south (reflector B1; before the generation of reflector U1) and the basement at this location (reflector B2; contemporaneous with the generation of reflector U1). In the stacked section, prominent diffractions are observed (Figure 3.9), which are a typical indicator for oceanic crust.
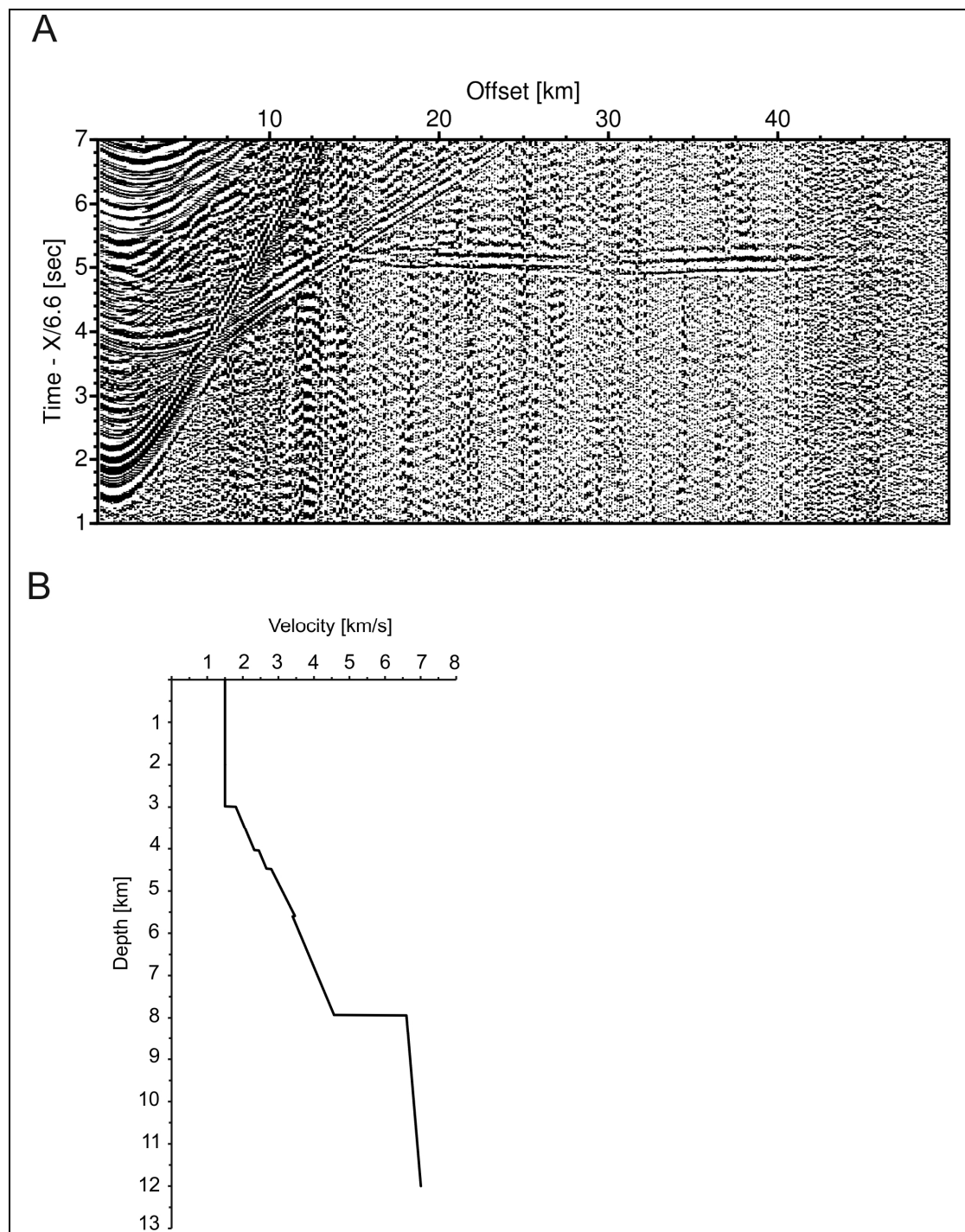
Figure 3.7: OBS-station located on profile BGR14-311 at the crossing point to profile BGR14-325 (line locations in Figure 3.1). The OBS shows a clear refracted phase with velocities of 6.6 km/s. The depth of this layer was estimated performing seismic ray tracing with 1D models. This results in a depth of 7.9 km for the 6.6 km/s refraction boundary, which coincides with the location of the basement interpreted in the MCS data (Figures 3.4 and 3.5). B) Velocity-depth profile for the OBS-station located on profile BGR14-311. The velocity-depth relationship for the sediments was extracted from the analysis of the multichannel seismic data and extrapolated to find the depth of the 6.6 km/s refraction boundary (7.9 km).
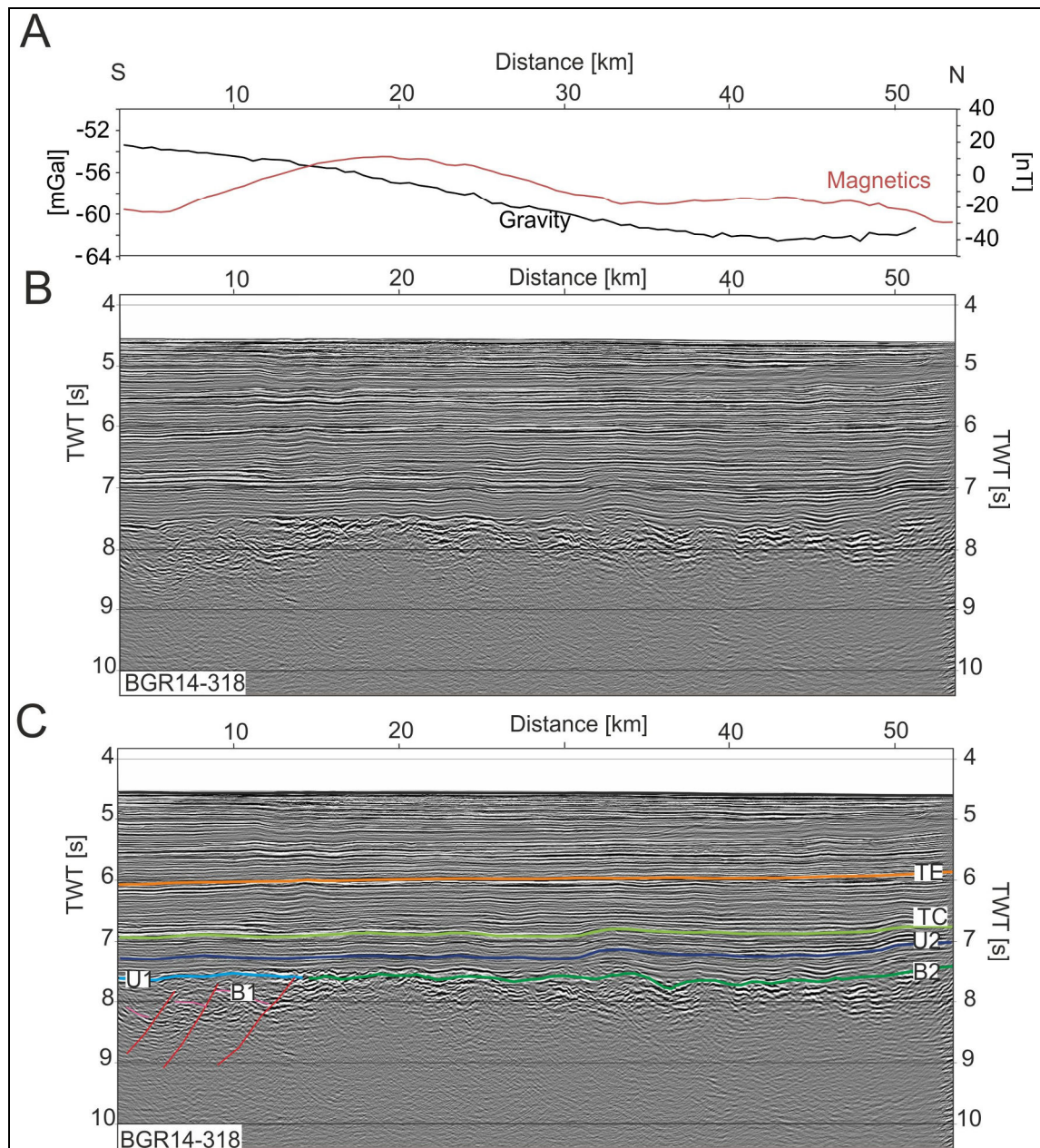
Figure 3.8: Prestack migrated section of profile BGR14-318 (line location in Figure 3.1). (A) Observed magnetic and free-air gravity data across the profile. The data show only small-scale magnetic variations with an anomaly of up to 15 nT. (B) Uninterpreted N-S oriented reflection seismic line, overlain by (C) interpretation. The profile shows a change in basement characteristics from rotated fault blocks to a highly reflective multi-reflector band with only minor internal deformation. Reflector B2 shows a wavy, hummocky like reflection. When tracing reflector U1 northward, it clearly merges with Reflector B2, providing a relative age constraint between the formation of the extensional structures further south (earlier) and the basement at this location (later). Seismic reflectors are labeled TE= Top Eocene; TC= Top Cretaceous; U2= Prominent unconformity, locally of erosional character (inferred Early Cretaceous age); U1= Distinct unconformity that seals the offset of listric basement faults (inferred Late Jurassic age); B2= Top basement (interpreted as oceanic crust); B1= Top stretched basement.

The reflection pattern strongly resembles the seismic image of oceanic crust in the northern part of the West Somali Basin (Coffin and Rabinowitz, 1988). Thus we interpret this area as being formed by oceanic crust that, according to magnetic anomaly interpretations in the West Somali Basin (e.g. Gaina et al., 2013; Rabinowitz et al., 1983), is of Late Jurassic age (~M22; 148 Ma). Magnetic values range between -30 and 20 nT (Figure 3.8) and are of very low amplitude, which is consistent with results of Lort et al. (1979) who observed a change in frequency and amplitude of magnetic variations in the West Somali Basin from south to north of the Comoros Islands.

3.6   Discussion

3.6.1   What is the nature of the crust in the Mozambique Channel east of Davie Ridge?

On N-S trending seismic sections, located seaward of Davie Ridge, e.g. in Figure 3.5, we observe a wide area dominated by rotated fault blocks bounded by listric normal faults (Figure 3.10A). The question arises, whether this region is composed of heavily faulted oceanic crust, exhumed serpentinized mantle or extended continental crust. In the following, we will discuss the different options with respect to structural images derived from MCS data, crustal thicknesses, seismic velocities and magnetic signatures, as established in section 3.3.

It is widely accepted that the transition from continental to oceanic crust at transform margins typically occurs over distances of not more than 50 to 80 km (Bird, 2001); in many cases even narrower transition zones exist. At the southernmost Argentine margin, the transition occurs over distances of 15-19 km (Becker et al., 2012) and at the Cote d´Ivoire – Ghana transform margin, the transition is particularly rapid and occurs over distances < 10 km (Edwards et al., 1997; Mascle et al., 1997). The prominent ridges that form along the continental side of the margins are typically located at the trace of the transform fault and should therefore indicate the transition from continental to oceanic crust (e.g. Edwards et al., 1997; Mascle et al., 1995).

In the Mozambique Channel near the Davie Ridge, the transition from continental to oceanic crust is difficult to deduce. On E-W oriented profiles, the most distinct basement characteristic is the relatively low reflectivity that distinctively differs from that of the inferred oceanic crust observed in the northern part of the study area (Figure 3.8). The reflection pattern of the oceanic crust is dominated by high-amplitude multi-reflector bands with a curved and wavy reflection configuration in the migrated section (Figure 3.8) and closely spaced diffractions in the stacked section (Figure 3.9). The basement does not display any significant internal deformation and shows similarities to seismic images of Mid/Late Jurassic oceanic crust in the West Somali Basin (Coffin and Rabinowitz, 1988). This high reflectivity of the top oceanic crustal reflection results from pillow basalts of the oceanic crust and should be also observed east of Davie

Ridge, if normal oceanic crust of Jurassic age was present in this area. From elsewhere it is known that even heavily faulted oceanic crust that is dissected by normal faults, remains highly reflective (e.g. South Atlantic – Becker et al., 2012; Koopmann et al., 2014a).
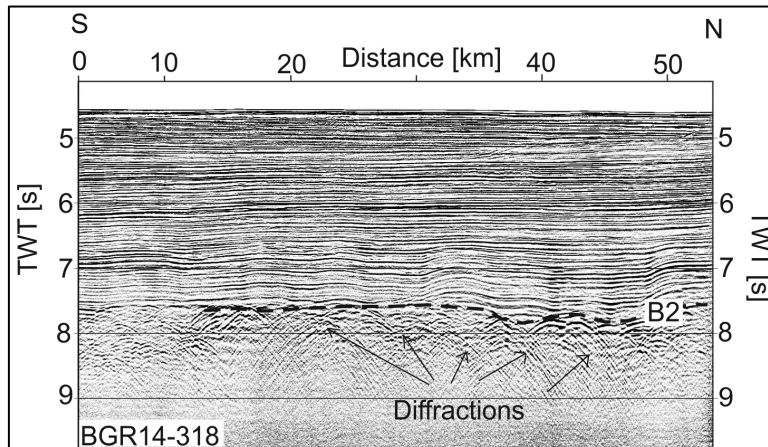
Figure 3.9: Uninterpreted stacked section of profile BGR14-318 (line location in Figure 3.1). The profile shows a succession of diffractions below Reflector B2 (dashed line), typical for oceanic crust.

In terms of the structural framework, Figures 3.5 and 3.6 image a region that has been affected by two phases of deformation. The first one is characterized by the generation of prominent listric faults bounding rotated blocks and the second led to wrench faulting in localized areas. We correlate wrench faulting with the southward motion of Madagascar relative to Africa. This leads to the conclusion that the first deformational event occurred during the rifting stage.

Seismic ray tracing with 1D-models reveals that the top basement is characterized by velocities of ~6.6 km/s (Figures 3.4 and 3.5). This is an indicator for the absence of at least oceanic Layer 2. Poorly defined magnetic anomaly interpretations in the West Somali Basin south of the Comoros Islands yield half spreading rates ranging between 18-38 mm/yr (Rabinowitz et al., 1983) and 13-33 mm/yr (Gaina et al., 2013), whereby spreading rates increase during the formation of oceanic crust (Rabinowitz et al., 1983) or vary throughout spreading (Gaina et al., 2013). The values indicate that spreading rates are continuously higher than 20 mm/yr full spreading rate, so that melt production should be sufficient throughout spreading and normal oceanic crust with Layers 2 and 3 present would be expected. Another argument against the presence of normal oceanic crust comes from the derived crustal thickness. It is known that total magmatic production is reduced in the vicinity of fracture zones, where oceanic crust is anomalously thin (White et al., 1992). From what is known of other transform margins and considering the vicinity to the Davie transform fault which is located only up to ~ 100 km westward of the investigated domain (Figure 3.1), oceanic crustal thickness

should not exceed the extremal bound (~5.3 km) for oceanic crustal thickness near fracture zones as proposed by White et al. (1992). However, the detachment level of the listric faults was calculated to be ~6 km below top basement, which implies that crustal thickness prior to extension was even higher. From the dip of the listric faults, we calculated a crustal stretching factor of ~1.5 which indicates that crustal thickness prior to extension should have reached at least 9 km. These crustal thickness values clearly exceed the range for normal oceanic crust. Magnetic data in the study area generally display only small-scale magnetic variations (with the exception of the Late Cretaceous volcanics with up to ~200 nT; Figures 3.3, 3.4, 3.5 and 3.8).

Generally, the here observed seismic reflection pattern resembles seismic images from the distal parts of magma-poor continental margins (e.g. Péron-Pinvidic et al., 2007, 2009). Reflector U1 forms a prominent unconformity above the wedge-shaped, syn-extensional sedimentary infill of the half-grabens (Figures 3.5 and 3.6) and merges with the top of a highly reflective multi-reflector band that is here interpreted as Late Jurassic oceanic crust (reflector B2), observed in the northern part of the study area (Figure 3.8). We suggest that reflector U1 may be associated with the transition from rifting to drifting following the break-up of Gondwana. Thus the underlying infill of the half-grabens may be classified as the syn-rift strata deposited during rifting, subsequently resulting in the opening of the West Somali Basin. Reflector U1 can be traced to the Lacerda Basin, which is clearly located in the continental domain and most likely results from Gondwana breakup in the Middle Jurassic. Strata overlying reflector U1 may then correspond to post-rift development.

In the distal part of magma-poor rifted margins, extensional allochthons form and continental crust is often stretched by lithospheric stretching factors >5 before breakup, e.g. in the South China Sea (Ding et al., 2013) or at the Iberian, Norwegian and UK rifted margins (Davis and Kuznir, 2004). At the Newfoundland margin, continental crust thins from ~28 to ~6 km over a distance of ~20 km (Van Avendonk et al., 2009). We propose that the listric faults observed in Figures 3.5 and 3.6 sole out at a common detachment, which has been calculated to be ~13 km beneath the seafloor. If we assume a continental origin for the rotated basement blocks, the lithospheric stretching factor β_l, calculated with an initial crustal thickness value of ~35 km (Recq, 1982 for the East African margin) and a final crustal thickness of ~6 km (based on calculated detachment level of 13 km and the crustal stretch factor of ~1.5), is $\beta_l = $ ~5.8 and therefore is similar to other rifted margins.

Often, serpentinized peridotites are unroofed at magma-poor margins, e.g. at the Iberian-Newfoundland margin, which is the best-known example of mantle exhumation during the latest stage of continental rifting (e.g., Péron-Pinvidic et al., 2009; Sibuet et al., 2007; Whitmarsh et al., 2001). Lavier and Manatschal (2006) proposed that extreme crustal

thinning at magma-poor margins may be accomplished by a system of conjugate concave downward faults that form a very thin crust (<10 km) by exhumation of mid-crustal and mantle material. In those models, initial decoupling of upper crustal from lower crustal and mantle deformation is accomplished by weakening of the middle crust (Lavier and Manatschal, 2006). Above the exhumed middle crustal or mantle rocks, extensional upper crustal allochthons may rest (Lavier and Manatschal, 2006). Basement velocities derived from one OBS station (Figures 3.4, 3.5 and 3.7) may therefore well fit in the range of middle continental crust (6.3-6.6 km/s; Christensen and Mooney, 1995) or serpentinized mantle peridotites (5-8 km/s, depending on the serpentinization level; Minshull, 2009). Serpentinized mantle peridotites may also explain the presence of subdued magnetic anomalies in some areas of the Mozambique Channel.

Based on magnetic variations and high basement velocities observed in the data (~6.6 km/s), the presence of serpentinized mantle cannot be ruled out; in fact, low amplitude, weakly linear magnetic anomalies are often present at the continent-ocean transition of magma-poor continental margins, where serpentinized continental mantle peridotites have been exposed (e.g. Whitmarsh et al., 2001). Furthermore, there is no evidence for a clear Moho reflection observed in the seismic data, which is consistent with the interpretation of the absence of crustal rocks and the presence of serpentinized mantle (Minshull, 2009).

3.6.2   Implications for the formation of the Mozambique Channel

Based on our observations from the geophysical dataset, we propose that the examined domain east of Davie Ridge (Figures 3.3-3.6 and 3.10A) does not consist of normal oceanic crust. Our new data support the hypothesis that in the Mozambique Channel area a component of rifting prevailed prior to dominant transform motion. A map of the first vertical derivative of the gravity field for the West Somali Basin and the Mozambique Channel area reveals prominent NW-SE oriented structures on both the Madagascan and Tanzania/Kenya continental margins (Figure 3.10B). These may be correlated with NW-SE directed extension during the early opening of the West Somali Basin and are consistent with the here observed first deformational phase (e.g. Figures 3.5 and 3.6). Some of the NW-SE oriented structures are situated at the position of the Late Cretaceous volcanics observed in the seismic profiles (Figures 3.4 and 3.5), which accounts for their overprinting during a later tectonic phase, probably in the Late Cretaceous. Following the interpretation of the strike of the spreading center (e.g. Gaina et al., 2013), a major change in the direction of deformation occurred at the Jurassic/Cretaceous boundary (~M20, Figure 3.10B) from NW-SE extension to dominant N-S spreading (Figure 3.10B). Changes in the direction of deformation are typically observed at oblique margin settings (e.g. the Gulf of Aden; Autin et al., 2010a), where the orientation of the earliest rift structures differs significantly from the strike of late synrift structures and the strike of the

Gulf (Leroy et al., 2010). Similar to the results in this study, allochthonous relics of continental crust may rest upon the exhumed mantle in the area of a wide continent-ocean transition (Autin et al., 2010b; Leroy et al., 2010). We assume that once breakup between Madagascar and East Africa had occurred and oceanic crust had started to form at mid-ocean ridges in the West Somali Basin, already stretched and thinned basement was additionally deformed by transform motions, affecting a wide region to the east of Davie Ridge (Figure 3.10A). This area is suggested to have drifted to its present position along with Madagascar.
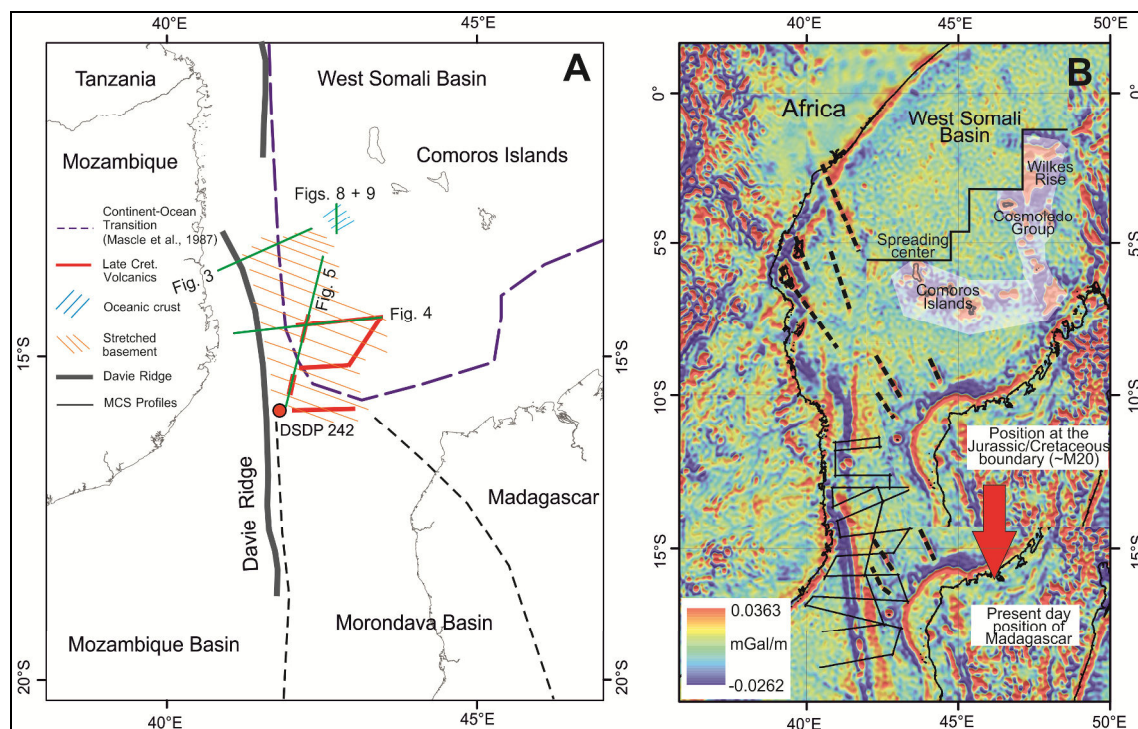
Figure 3.10: (A) Sketch map illustrating the location of the stretched basement observed in the study area to the east of Davie Ridge. Red lines show the distribution of the inferred Late Cretaceous volcanics. The location of Figures 3.3-3.5 and 3.8-3.9 is indicated by green lines. The continent-ocean transition as proposed by Mascle et al. (1987) is shown as dashed purple line. The outline of the Karoo-aged Morondava Basin is shown as grey dashed line according to Geiger et al. (2004). (B) Map of the first vertical derivative of the gravity field for the West Somali Basin and the Mozambique Channel area. The map was prepared using the DTU10 satellite altimeter derived free-air gravity data set (Andersen, 2010; Andersen and Knudsen, 2009). A Butterworth lowpass filter (8th order, 20 km cutoff wavelength) was applied to reduce the typical small-scale undulations before calculating the vertical derivative using the Fast Fourier Transformation based methods of the Generic Mapping Toolbox GMT5 (Wessel et al., 2013). Madagascar was shifted to its pre-drift location relative to Africa at the Jurassic/Cretaceous boundary (~M20) by using magnetic anomaly interpretations of Rabinowitz et al. (1983) and Gaina et al. (2013). Prominent NW-SE trending structures on both the Madagascan and Tanzania/Kenya continental margins (dashed) may be correlated with NW-SE directed extension during the early opening of the West Somali Basin. The commonly interpreted strike of the spreading center implies N-S directed spreading since the Jurassic/Cretaceous boundary.

The observation of likely Late Jurassic first oceanic crust in the study area (~M22, ~148 Ma; Rabinowitz et al., 1983) implies a significant difference of ~20 Ma in the initiation of drifting in the West Somali Basin compared to other studies that proposed that drifting commenced in the Middle Jurassic (~170Ma; Gaina et al., 2013). A possible explanation for this age difference is a progressive opening of the West Somali Basin from east to west in a zipper-like succession along individual rift zones, similar to the northward propagating opening of the South Atlantic (e.g. Jackson et al., 2000). This would also explain the age difference between reflector U1 and "Mid Jurassic break-up unconformities" observed in the Majunga (Razafindrazaka et al., 1999) and Morondava Basins (Geiger et al., 2004) and illustrates that break-up in a magma-poor, highly extended setting has to be regarded as a poly-phase process through time and space (Gillard et al., 2015; Péron-Pinvidic et al., 2007). Bunce and Molnar (1977) observed the trends of four buried ridges in the eastern part of the West Somali Basin that run approximately parallel to Davie Ridge and suggested that those ridges may have guided the southward drift of Madagascar relative to Africa. However, uncertainties in the available interpretation of magnetic anomalies in the Mozambique Channel south of the Comoros Islands (e.g. Gaina et al., 2013; Rabinowitz et al., 1983) have to be considered. Even in the northern part of the study area, where most likely normal oceanic crust with typical seismic characteristics exists, magnetic signatures are of relatively low amplitude (Figure 3.8 and Lort et al., 1979), suggesting that oceanic crust may have formed during the Jurassic Magnetic Quiet Zone (Coffin and Rabinowitz, 1987; Rabinowitz et al., 1983). As oceanic crust in the northern part of the study area is located in direct vicinity of the Comoros Islands (Figure 3.10A), it has most likely been structurally overprinted by the same phase of Neogene volcanism that formed the Comoros Islands. Based on the low amplitudes and a change of frequency of the magnetic anomalies in the southern part of the West Somali Basin, Lort et al. (1979) suggested a transition from oceanic crust in the north to continental crust in the southern part of the West Somali Basin. This is in accordance with the observations in this study, as the presence of stretched continental crust or serpentinized mantle is proposed south of the first oceanic crust. The assumption of stretched continental crust south of the Comoros Islands would imply that breakup between Madagascar and Africa occurred shortly before the Jurassic/Cretaceous boundary (~M22), which is significantly later than was assumed by previous workers (e.g. Coffin and Rabinowitz, 1987; Gaina et al., 2013). Moreover, this would challenge existing models regarding Gondwana reconstructions that assume a more or less contemporaneous opening of the West Somali and the Mozambique Basins between the same two plates (e.g. Eagles and König, 2008).

3.7   Conclusions

Based on the interpretation of reflection seismic data, potential field data and p-wave velocity information from an OBS station, we found evidence for the absence of normal oceanic crust east of Davie Ridge, off northern Mozambique, and draw the following conclusions:

1. A wide area east of Davie Ridge is occupied by a succession of rotated basement blocks, bounded by listric normal faults.

2. The area has been affected by two deformational phases. The first led to the generation of rotated blocks bounded by deep-reaching listric faults. Half-grabens were filled with wedge-shaped, syn-extensional sediments and are overlain by a prominent unconformity that seals the listric faulting. The second phase of deformation is associated with wrench faulting in localized areas and is accompanied by uplift and subsequent erosion of the syn-extensional infill of the half-grabens.

3. At about 13°S, the prominent unconformity overlying syn-extensional strata is merging with the top of highly reflective basement showing only minor internal deformation that is here interpreted as (Late Jurassic) oceanic crust. Therefore, the unconformity may be associated with the transition from rifting to seafloor spreading in the West Somali Basin.

4. We correlate wrench faulting with southward drift of Madagascar, which implies that the preceding extensional deformation took place before the first oceanic crust was generated in the West Somali Basin.

5. We find evidence for a wide area which has been affected by strike-slip deformation, in contrast to the earlier proposed major single transform fault in the vicinity of Davie Ridge.

6. From the structural data we propose that the Mozambique Channel area to the north of Madagascar is not a sheared margin but rather is suggested to be classified as oblique continental margin.

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4 No evidence for a Davie Fracture Zone offshore northern Mozambique, Tanzania and Kenya

Remarks

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

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Abstract

Plate tectonic reconstructions assume a major inactive transform fault, the Davie Fracture Zone, in the West Somali Basin, along which Madagascar is thought to have migrated southwards following Gondwana breakup in the Mesozoic. Based on the interpretation of reflection seismic data, we show that the Walu Ridge offshore Kenya and the Kerimbas Basin offshore northern Mozambique are tectonically unrelated to the southward motion of Madagascar and correlate with Late Cretaceous volcanism and inversion in Kenya and the evolution of the East African Rift System, respectively. Offshore Tanzania, geophysical data do not show basement structures indicating the presence of a major transform fault. These results challenge the commonly supported transform margin concept and imply a more southerly pre-breakup position of Madagascar within Gondwana. Opening of the West Somali Basin by SW-propagating oblique rifting and seafloor spreading is proposed.

4.1 Introduction

During the early days of the theory of plate tectonics, there was a heated debate about the paleoposition of Madagascar. Several authors concluded that Madagascar has remained in its present position with respect to Africa at least since the Mid-Mesozoic (e.g. Darracott, 1974; Flower and Strong, 1969), while others have proposed an eastward (e.g. Flores, 1970; Wright and McCurry, 1970), or a southward (e.g. Heirtzler and Burroughs, 1971) motion of Madagascar from its original position adjacent to the East African coast (see also discussions in Darracott, 1974; Heirtzler and Burroughs, 1971; McElhinny et al., 1976).

In 1970, Heirtzler and Burroughs (1971) discovered a bathymetric elevation in the Mozambique Channel and proposed that this ridge, the Davie Ridge, represents the expression of the transform fault resulting from the relative southward motion of Madagascar with respect to Africa. The Davie Ridge has been observed as a prominent

morphological feature between 20°S and about 9°S, while north of 9°S a relative gravity minimum (Scrutton, 1978) extending northward to 5°S and a gravity high striking across the continental margin until its intersection with the Kenyan margin near 2.5°S (Rabinowitz, 1971) were interpreted as representing the continuation of that basement Davie Ridge (Figure 4.1). The entire feature has subsequently been termed the "Davie Fracture Zone" by Scrutton (1978).
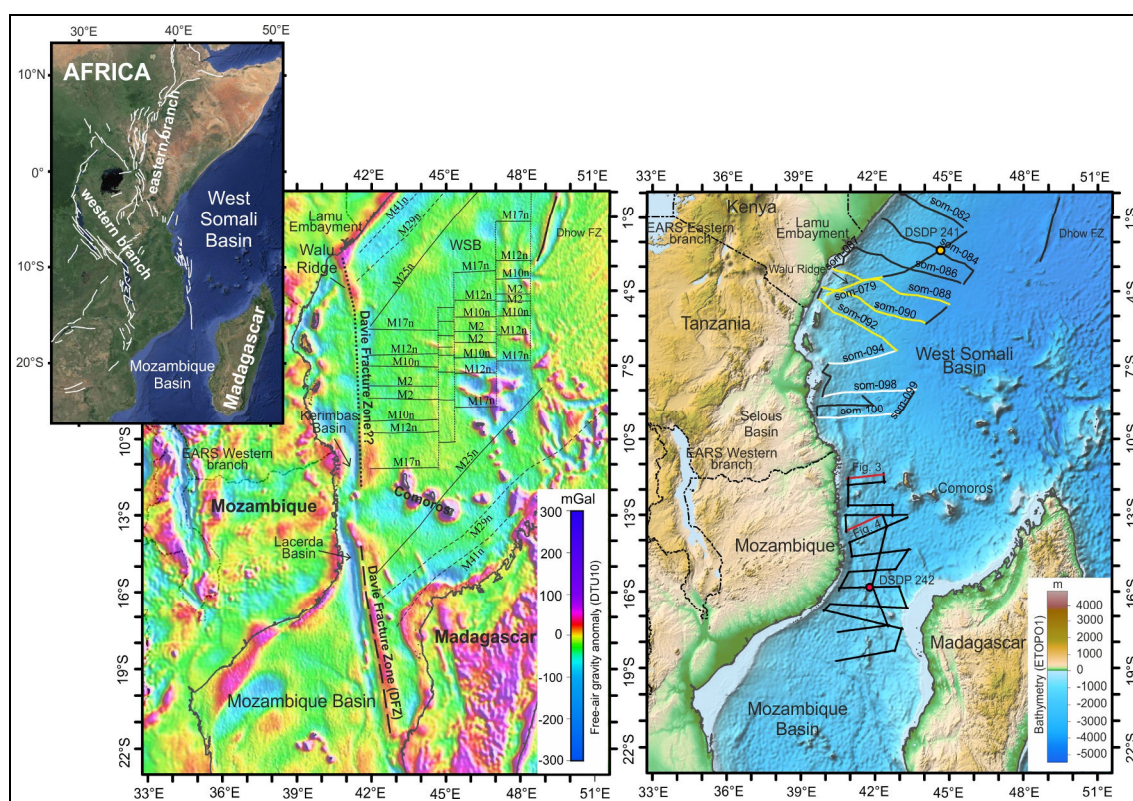
Figure 4.1: Left: Map of the gravity field of the West Somali Basin and the Mozambique Channel area (DTU10 satellite altimeter derived free-air gravity data set; Andersen, 2010; Andersen and Knudsen, 2009). Magnetic lineations in the West Somali Basin are according to Gaina et al. (2013). Magnetic anomalies M29n and M41n (dashed lines) of Gaina et al. (2013) are not interpreted in other studies, e.g. Rabinowitz et al. (1983) and Coffin and Rabinowitz (1987). EARS= East African Rift System; WSB= West Somali Basin. The inlay shows the main faults of the western and eastern branches of the East African Rift System (modified after Franke et al., 2015; main faults are taken from Chorowicz, 2005 and Macgregor, 2015). Right: Bathymetric map of the West Somali Basin and the Mozambique Channel area (ETOPO1 1 arc-minute global relief model; Amante and Eakins, 2009). Black lines show the locations of geophysical profiles acquired during RV Sonne cruise 231 offshore northern Mozambique and of seismic profiles acquired with RV Vema in 1980 offshore Tanzania and Kenya (Coffin and Rabinowitz, 1987, 1988). Locations of Figures 4.3 and 4.4 (red lines), 4.5 (white lines) and 4.6 (yellow lines) are indicated. The positions of DSDP sites 241 and 242 are highlighted with yellow and red dots.

Today, close to, if not all plate tectonic reconstructions assume a major, straight transform fault in the West Somali Basin (Figure 4.1), along which Madagascar,

together with Seychelles–India–Antarctica–Australia, is suggested to have migrated southward for more than 1000 km (Coffin and Rabinowitz, 1987, 1988; Eagles and König, 2008; Gaina et al., 2013; Heirtzler and Burroughs, 1971; Lawver et al., 1997; Müller et al., 2008; Norton and Sclater, 1979; Rabinowitz et al., 1983; Reeves, 2014; Reeves and De Wit, 2000; Schettino and Scotese, 2005; Scrutton, 1978; Segoufin and Patriat, 1980; Seton et al., 2012).

In this contribution, we show that there is no geological evidence confirming the existence of a major transform fault at the suggested position of the Davie Fracture Zone north of 9°S in the West Somali Basin. We rather suggest a much more southerly pre-breakup position of Madagascar within Gondwana and opening of the West Somali Basin by SW-propagating oblique rifting.

4.2   Gondwana breakup and the paleoposition of Madagascar

The geometry of Gondwana reassembly has undergone repeated refinements over the years, but there is still a debate over the position of Madagascar in Gondwana. Close to all reconstructions propose a paleoposition of Madagascar adjacent to the present-day shorelines of Somalia, Kenya and Tanzania and model more than 1000 km southward displacement along a major, straight transform fault. Implicit in these models is the assumption of a transform continental margin at the western edge of the West Somali Basin. Ongoing discussion concentrates mainly on a potential rotation of Madagascar during the southward displacement.

Some reconstructions (e.g. Eagles and König, 2008; Reeves, 2014; Reeves et al., 2002) propose a large counterclockwise rotation of Madagascar (up to 20°) subsequent to breakup. These studies place Madagascar´s southern tip close to southern Tanzania (Figure 4.2A). Other models by e.g. Gaina et al. (2013, 2015) or Torsvik and Cocks (2013) suggest that Madagascar was located in Gondwana in a general N-S oriented alignment, with Madagascar´s southern tip close to northern Mozambique and smaller rotation angles, if any (Figure 4.2B). Weak and ambiguous east-west-trending Mesozoic magnetic anomalies (Gaina et al., 2013; Rabinowitz et al., 1983; Segoufin and Patriat, 1980) in the West Somali Basin have been invoked to validate the concept of a transform margin along the Mozambique-Tanzania-Kenyan margin (Figure 4.1). However, the exact timing of the initiation of seafloor spreading in the West Somali Basin remains uncertain, with the first identifiable magnetic anomaly ranging between M25 (~ 155 Ma) (Coffin and Rabinowitz, 1987; Rabinowitz et al., 1983) and M41n (~167 Ma) (Gaina et al., 2013).

It also has to be kept in mind that the crustal nature of the West Somali Basin is not conclusively determined and that the continuous presence of oceanic crust in the West Somali Basin has been questioned by a number of detailed studies (e.g. Klimke et al.,

2016; Lort et al., 1979; Talwani, 1962). Moreover, the West Somali Basin was not tectonically quiet after the Early Cretaceous cessation of seafloor spreading (e.g. Coffin and Rabinowitz, 1987; Eagles and König, 2008; Gaina et al, 2013; Müller et al., 2008) and a couple of significant tectonic deformation phases including volcanism (Coffin and Rabinowitz, 1988) need to be considered to identify which phase was responsible for the formation of individual basement structures.
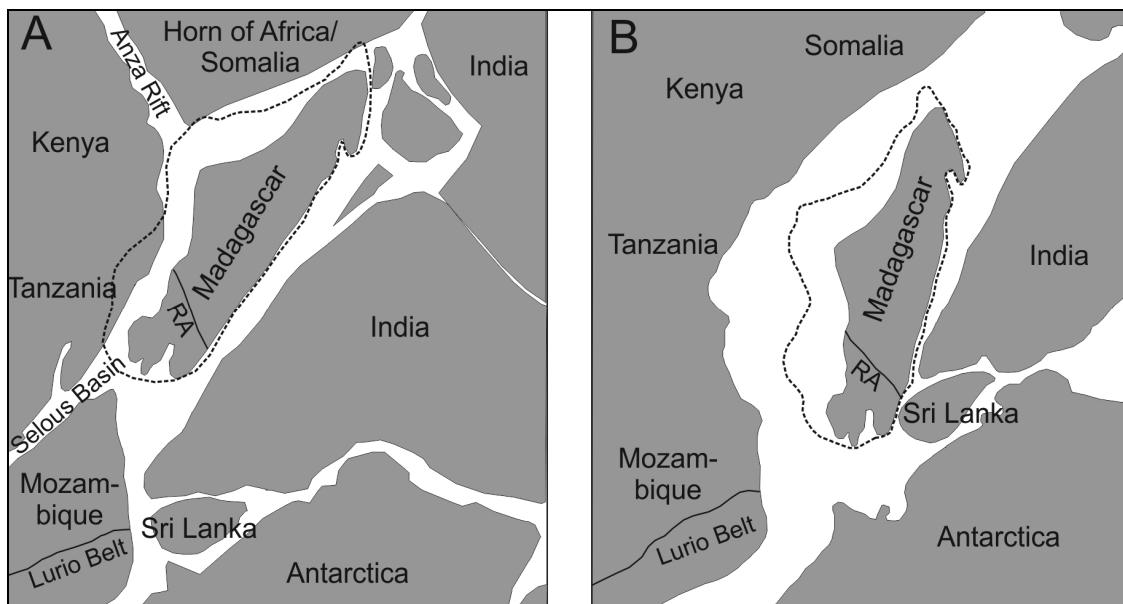
Figure 4.2: Pre-breakup configuration of East Gondwana compiled from (A) Reeves et al. (2002) and Reeves (2014) and (B) Gaina et al. (2015). RA= Ranotsara shear zone.

South of 14°S, the Davie Ridge is expressed as a prominent elevation rising ~ 1-2 km above the surrounding seafloor (Figure 4.1) and internally shows indications of shear movements, e.g. positive flower structures (e.g. Mascle et al., 1987). The interpretation of this portion of the Davie Ridge as an expression of a transform fault is not questioned in this contribution. In the following, we show that further north the previous linkage of the Davie Fracture Zone with two prominent bathymetric ridges offshore northern Mozambique and offshore Kenya is not supported by the data at hand.

4.3   Database

4.3.1   BGR14 geophysical data

The geophysical dataset was acquired by the Federal Institute for Geosciences and Natural Resources (BGR) during a cruise of R/V Sonne in early 2014. In total, the dataset comprises 27 MCS reflection seismic profiles (~4300 km; Figure 4.1). The data were recorded with a 324 channel Seal streamer with a group spacing of 12.5 m. The sample rate was 2 ms with a record length of 14 s, where the streamer was towed at a

depth of 12 m. The source consisted of two G-Gun airgun arrays with a total volume of 3100 in^3, towed at 6 m depth. The nominal shot point spacing was 50 m, leading to a CDP fold of 41, respectively. For a detailed description of the seismic processing, the reader is referred to Klimke et al. (2016). Here we present two profiles, located offshore northern Mozambique, crossing the Kerimbas and Lacerda Basins (Figures 4.3 and 4.4) and use the stratigraphic interpretation established in Franke et al. (2015) and Klimke et al. (2016).

Magnetic data were acquired with a towed SeaSpy gradiometer system consisting of two scalar Overhauser sensors and one fluxgate vector magnetometer with two fluxgate sensors on the ship. Gravity data were acquired using a sea gravimeter system KSS32M, manufactured by the Bodenseewerk Geosystem GmbH. The gravity data are connected to the IGSN71 reference system and free air gravity values were calculated. Potential field data are provided together with the corresponding MCS sections (Figures 4.3 and 4.4).

4.3.2 Vema reflection seismic lines

The MCS dataset consists of ~6000 km of 12-fold data acquired with R/V Vema in 1980 (line locations in Figure 4.1). The data were recorded with a 1200 m long Seismic Engineering streamer, and the source was two synchronized airguns (466 in^3), fired at 15-20 s intervals. The data were processed at Lamont-Doherty Geological Observatory. For details of the seismic processing, the reader is referred to Coffin and Rabinowitz (1982). We reinterpret several profiles of this dataset (Figures 4.5 and 4.6). The stratigraphic interpretation is based on DSDSP Site 241 and on the interpretation of Coffin and Rabinowitz (1987, 1988).
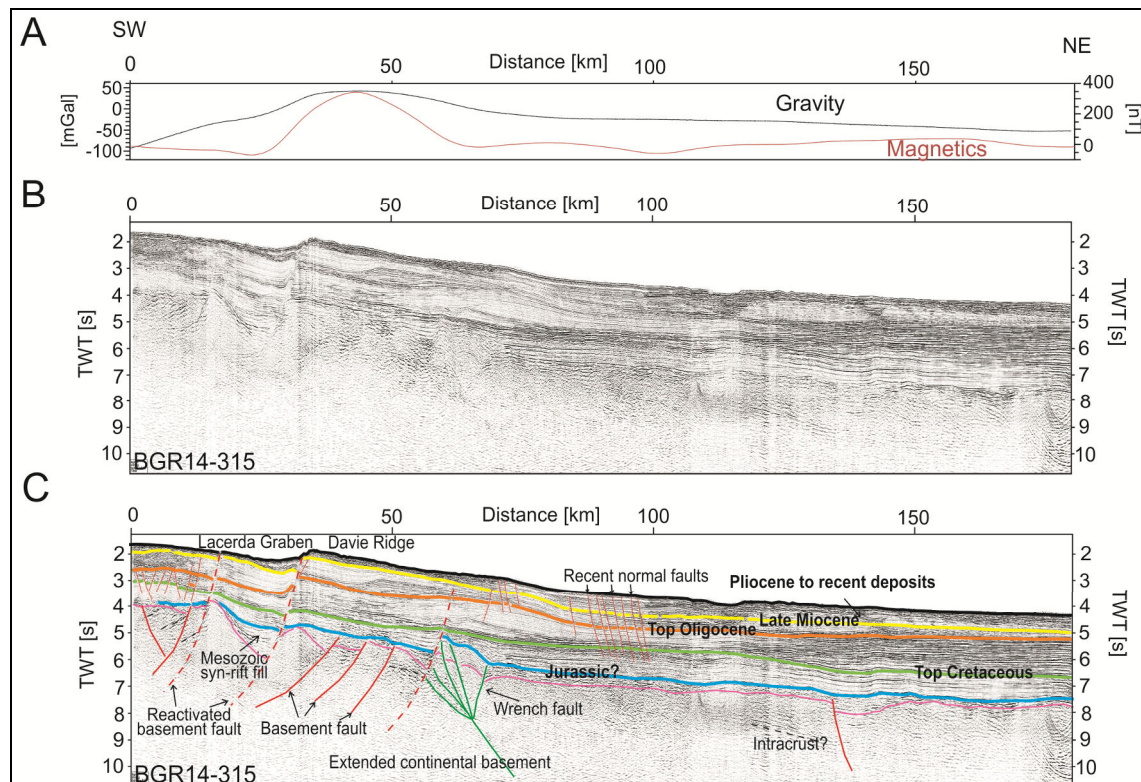
4.4 Interpretation

4.4.1 The Davie Ridge offshore northern Mozambique represents a Neogene rift flank uplift

Offshore northern Mozambique, a prominent bathymetric ridge has been proposed to represent a basement uplift, the Davie Ridge. However, Mougenot et al. (1986) found that this bathymetric ridge is related to neotectonics and is made up of thick, well stratified sedimentary layers. The structural interpretation of our new multichannel seismic profiles (Figure 4.3) confirms the previous results of Mougenot et al. (1986). The bathymetric ridge, also observable in the gravity data with anomalies up to 40 mGal (Figure 4.1), forms the eastern rim of a north-south trending Neogene rift graben, the Kerimbas Basin (Figure 4.3). The Cenozoic sediments deposited across the rift graben are affected by sub-recent extensional deformation, as many of the normal faults reach the seafloor (Figure 4.3). Late Miocene to younger strata across the rift are deposited

discontinuously, which indicates post-Oligocene rift-flank uplift resulting in the development of a modern bathymetric ridge (Franke et al., 2015). Franke et al. (2015) proposed that the mature rift graben initiated as a half-graben in the Late Miocene and further developed during the Pliocene, while most of the extensional deformation most likely took place during the Pleistocene. A similar development is found further south, where the NNW trending Lacerda Graben developed as a present-day half-graben (Figure 4.4). Rift-flank uplift and recent extension correlate with the evolution of the offshore continuation of the eastern branch of the East African Rift System (Franke et al., 2015; Mougenot et al., 1986), where a southward-propagating rift zone forms a symmetric graben in the north (Kerimbas Basin, Figure 4.3) and a half-graben (Lacerda Graben, Figure 4.4) in the south (Franke et al., 2015).
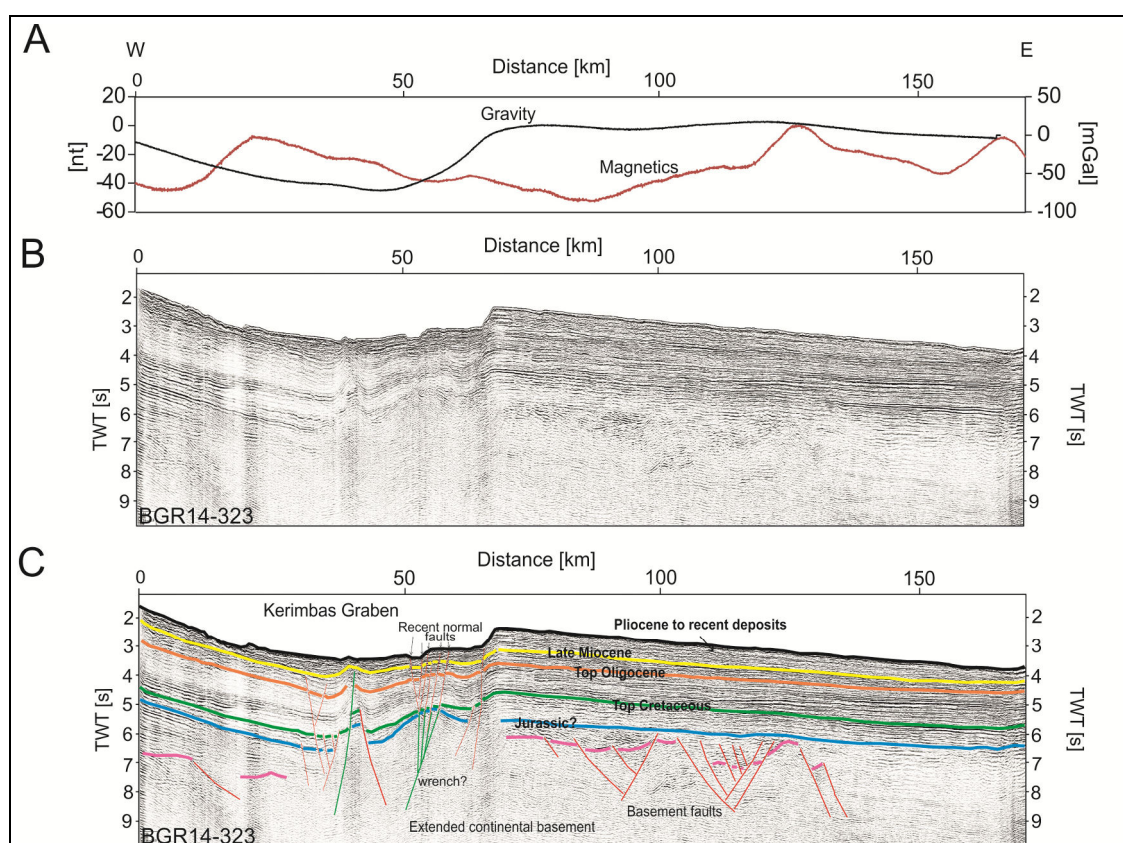
Figure 4.3: Prestack migrated profile BGR14-323 (line location in Figure 4.1). (A) Observed magnetic and free-air gravity data across the profile. (B) Uninterpreted section of profile BGR14-323, overlain by (C) interpretation, according to Franke et al. (2015) and Klimke et al. (2016). The Kerimbas Graben and its rift shoulder are made up of thick, well-stratified sediments. The Cenozoic sediments have been affected by sub-recent extensional deformation (distance: 50-70 km), as many of the normal faults reach the seafloor. A wrench fault (green lines) displacing pre-Late Cretaceous strata and the basement is visible at ~40-60 km distance in the Kerimbas Graben and might be an indication for the Davie Fracture Zone.

Figure 4.4: Prestack migrated profile BGR14-315 (line location in Figure 4.1). (A) Observed magnetic and free-air gravity data across the profile. (B) Uninterpreted section of profile BGR14-315, overlain by (C) interpretation, according to Franke et al. (2015) and Klimke et al. (2016). In the west, the basement has been affected by normal faults (thick red lines) bounding half-grabens filled with syn-rift strata. East of Davie Ridge, a wrench fault affecting the basement and probably Late Mesozoic strata is distinct (green; distance: 60-70 km). Cenozoic sediments have been affected by recent extensional deformation (thin red lines; distance: 0-20 and 80-100 km) and the reactivation of former listric basement faults (dashed red lines; distance: 20-70 km).

Therefore, the formation of the bathymetric ridge offshore northern Mozambique is completely unrelated to the southward displacement of Madagascar in the Mesozoic. The only evidence for a Davie Fracture Zone may be visible through subtle wrench faults displacing pre-Late Cretaceous strata and the basement (Figures 4.3 and 4.4) that appear in the Kerimbas Basin (Figure 4.3) and about 40 km east of the Lacerda Graben (Figure 4.4). These wrench faults occur in northward alignment of the basement Davie Ridge further south (Figure 4.1). According to our seismic data, the wrench faults gradually diminish northward until they die out at about 11°S and 13°S, respectively.

4.4.2 Absence of a transform fault offshore Tanzania

Off the coast of Tanzania, there is no continuous gravity high to delineate the location of a major transform fault zone (Figure 4.1). Instead of a gravity high, a gravity minimum was interpreted by Scrutton (1978) as a geophysical expression of a basement ridge by

assuming that the minimum is due to sediment thickening at the eastern side of the suggested basement ridge (Rabinowitz, 1971).

Reflection seismic data collected offshore Tanzania do not provide evidence for such a setting (Coffin and Rabinowitz, 1982, 1987, 1988). Occasionally, small-scale "basement highs" are imaged along the seismic reflection lines across the Tanzanian margin (Figure 4.5; Coffin and Rabinowitz, 1987, 1988). However, as already noted by Coffin and Rabinowitz (1987), no single geophysical parameter is manifested on every line crossing the proposed Davie Fracture Zone. Some of the small-scale basement structures reveal a positive magnetic anomaly, others not; some are associated with a positive gravity signal, others with a negative.

Our main point is that the margin´s architecture is distinctively different from that of other transform margins. Transform margins are typically among the easiest to delineate (Bird, 2001). This is because high-standing continental marginal ridges 50-80 km wide bounding deep sedimentary basins are formed during rupture of a transform fault, possibly enhanced by induced thermal uplift during seafloor spreading (Lorenzo, 1997). The Agulhas-Falkland Fracture Zone, for example, with its initial 1200-km long offset, is comparable in size with the proposed Davie Fracture Zone. Along the northern edge of the plateau, a prominent marginal ridge forms the Falkland Escarpment and rises as much as 2 km over the South Atlantic Ocean (Becker et al., 2012; Lorenzo and Wessel, 1997). Similar ridges are also found along the Côte d'Ivoire-Ghana transform margin, where the ridge is elevated by 2.5 km over the abyssal plain to the south (Mascle et al., 1987), and along the southern margin of the Exmouth Plateau off northwestern Australia, where stratigraphic evidence is consistent with erosional thinning by a maximum of about 3.5 km (Lorenzo et al., 1991). Even oceanic fracture zones in the West Somali Basin have a much more prominent expression (Bunce and Molnar, 1977) than the previously mentioned small-scale structures offshore Tanzania, and a fracture zone bounding continental and oceanic crust is expected to be even more pronounced.

4.4.3 The Walu Ridge offshore Kenya is a Late Cretaceous inversion structure

A N-S trending subsurface basement ridge at the Kenyan coast, the Walu Ridge, has been invoked as major evidence for transform margin development during the formation of the West Somali Basin (Scrutton, 1978). Interestingly, this structure "gradually descends to the south" (Coffin and Rabinowitz, 1987; p. 9391), as imaged by reflection seismic data, with a diminishing of the gravity signal associated with the ridge (Figure 4.1). This is contrary to what is expected for transform margin development further south. In the following, we show that the formation of the Walu Ridge clearly postdates the published ages for the formation of the oceanic West Somali Basin, thus revealing that this structure is unrelated to the southward drift of Madagascar.
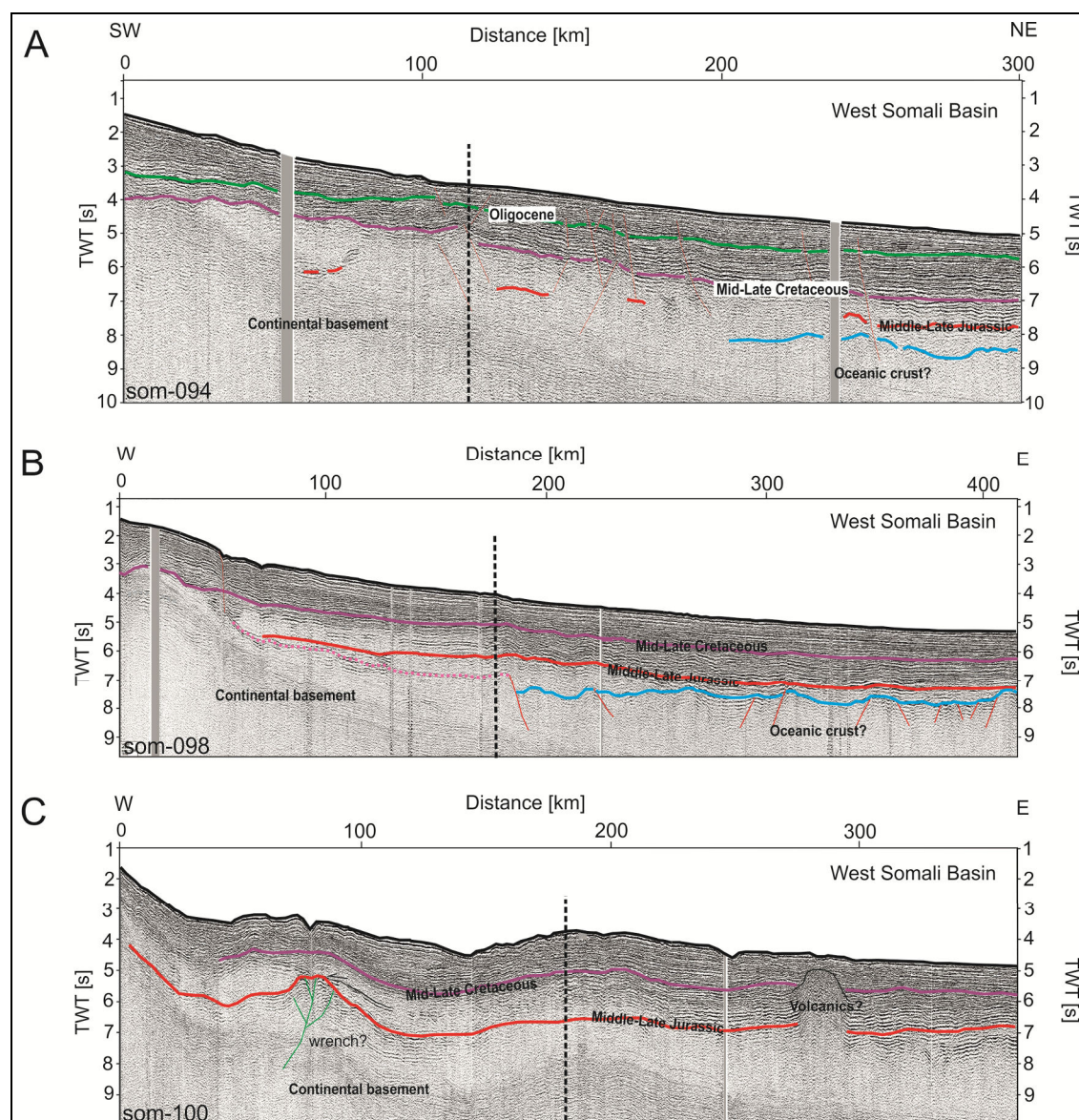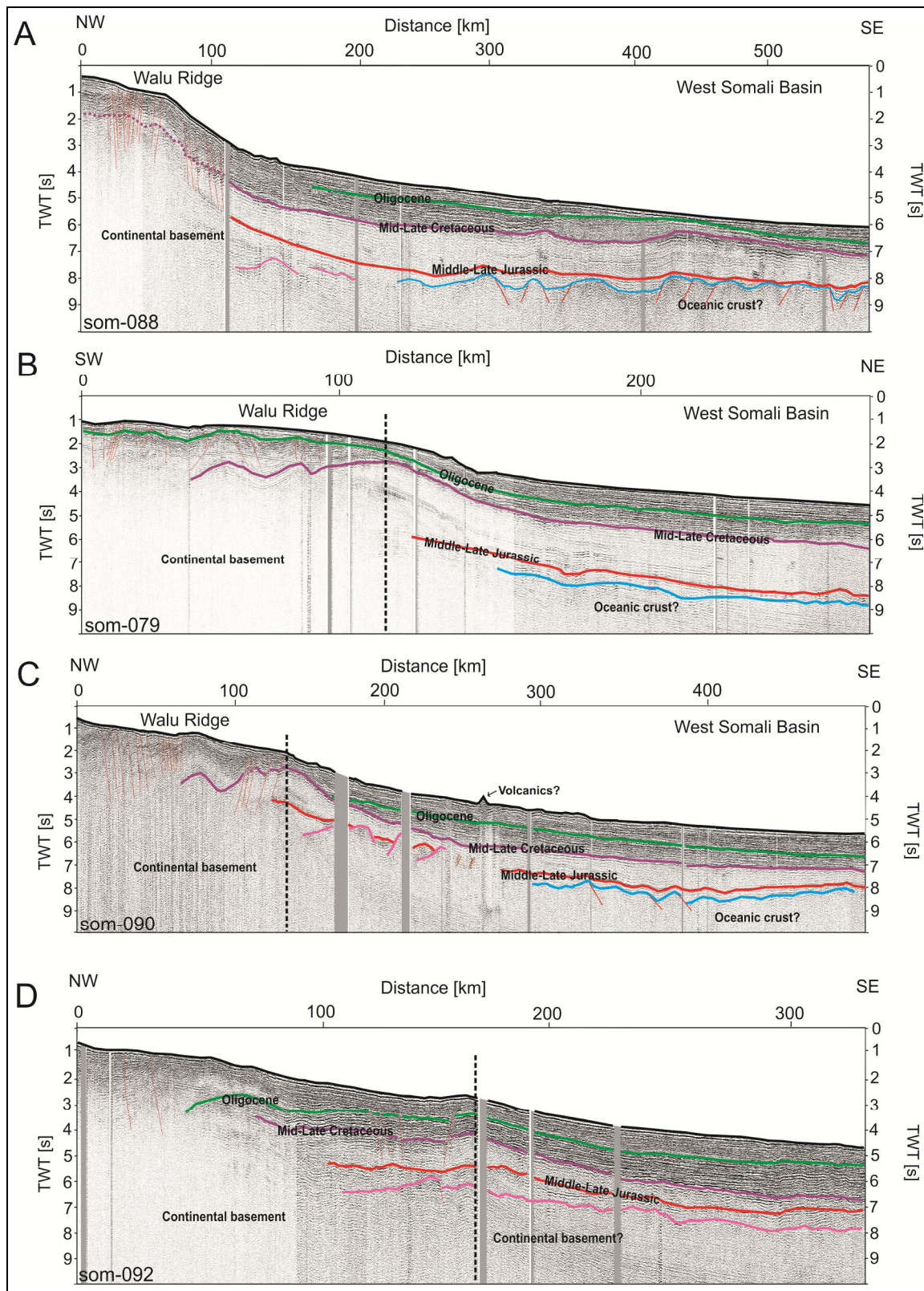
Figure 4.5: Reinterpreted seismic profiles offshore Tanzania (line locations in Figure 4.1). The stratigraphic interpretation of the Cenozoic and Cretaceous deposits is mainly based on DSDP Site 241 that is located in the northern part of the West Somali Basin and is crossed by two profiles of RV Vema cruise V3618 (Figure 4.1). We adopted the classification of major reflectors "green", "purple", "red" and "blue" of Coffin and Rabinowitz (1987, 1988). The location of the Davie Fracture Zone according to Coffin and Rabinowitz (1987, 1988) is indicated by dashed black lines. These data do not imply the presence of a major transform fault offshore Tanzania.

DSDP Site 241 (Figure 4.1), which was used by Coffin and Rabinowitz (1987, 1988) as stratigraphic control, bottomed in silt-rich Coniacian to Campanian claystones (Schlich et al., 1974). The most prominent seismic reflection horizon has either been penetrated (Schlich et al., 1974) or the well ended just above (~100 to ~200 ms TWT) (Coffin and Rabinowitz, 1987, 1988). Thus, the age of the key horizon ("purple reflector" or horizon "B") is either Turonian (Schlich et al., 1974) or Cenomanian to Albian age (~100 Ma) (Coffin and Rabinowitz, 1987). In the following, we accept the proposed age of about

100 Ma for this reflector, but want to emphasize that this is most likely an upper limit and it may well be younger. Tracing this key horizon westward to the Walu Ridge, we confirm the earlier interpretation by Coffin and Rabinowitz (1987) that this horizon is sealing the deformation resulting in the formation of the Walu Ridge (Figure 4.6). Younger strata are onlapping the structure. However, our conclusion is strikingly different from earlier interpretations. We propose that the structure formed either ~20 Ma or ~30 Ma (depending on the preferred age interpretation of seafloor-spreading anomalies) after cessation of seafloor spreading and after Madagascar reached its final position. A younger Turonian age of the reflector (Schlich et al., 1974), would add an additional ~10 Ma age difference. The only way to invoke a relationship between the Walu Ridge and the formation of the West Somali Basin is to argue that was already present in the Middle/Late Jurassic and was reactivated afterwards. The deeper sections of the vintage seismic data do not allow a conclusive interpretation, but we consider it likely that the ridge resulted from a previously existing Early Cretaceous rift basin in prolongation of the Anza Rift (Bosworth and Morley, 1994; Frizon de Lamotte et al., 2015; Cruciani and Barchi, 2016). An earlier, Late Jurassic to Early Cretaceous formation of the Walu Ridge is unlikely also from regional observations. During Middle Jurassic time, marine conditions became established in the Lamu Embayment (Figure 4.1) and continued from Callovian into at least Early Cretaceous time (Coffin and Rabinowitz, 1988). Therefore, there was subsidence or, at least, no uplift during breakup of the West Somali Basin and the earlier proposed initial development of a major transform margin. Only during the Late Cretaceous a transition from deep-water to shallow-water facies is recognized in the Lamu Embayment, prior to the absence of Paleocene strata and the unconformable deposition of middle Eocene strata (Coffin and Rabinowitz, 1988). This indicates an uplift of the margin well after cessation of seafloor spreading in the West Somali Basin. This timing fits well with the Turonian through Early Paleocene development of the Walu-Kipini high in the Lamu Embayment (Nyagah, 1995), the onshore prolongation of the Walu Ridge, and is recorded as a widespread latest Cretaceous and Early Tertiary period of wrench-faulting and basin inversion in northern Africa (Bosworth and Morley, 1994). Also, the analysis of seismic data offshore Kenya and Somalia indicates that the Lamu Basin deep-water fold-and thrust belt was active from the Late Cretaceous to the Early Miocene, and almost all of the deformation occurred before the Late Pliocene (Cruciani and Barchi, 2016). In coastal Tanzania, the recorded high sedimentation rate at the Santonian/Campanian transition also indicates a tectonic uplift affecting the source areas during that time (Said et al., 2015).

Figure 4.6 (previous page): Reinterpreted seismic profiles offshore Kenya (line locations in Figure 4.1). The stratigraphic interpretation of the Cenozoic and Cretaceous deposits is mainly based on DSDP Site 241, which is located in the northern part of the West Somali Basin and is crossed by two profiles of RV Vema cruise V3618 (Figure 4.1). We adopted the classification of major reflectors "green", "purple", "red" and "blue" of Coffin and Rabinowitz (1987, 1988). The location of the Davie Fracture Zone according to Coffin and Rabinowitz (1987, 1988) is indicated by dashed black lines. The Mid-Late Cretaceous reflection seals the deformation resulting in the formation of the Walu Ridge (A-C), which implies that the Walu Ridge formed after the cessation of seafloor spreading in the West Somali Basin. Profile D shows a reverse reactivation of presumably Mid-Late Cretaceous age (distance: 170-200 km) that most likely results from the same deformational event that created the Walu Ridge further north (A-C).

4.5   Discussion

We provide evidence that the bathymetric ridges offshore Kenya and offshore northern Mozambique, previously invoked as evidence for the Davie Fracture Zone, are unrelated to the southward movement of Madagascar. Although the deeper portions of the vintage seismic profiles offshore Tanzania (Figure 4.5) do not consistently allow a conclusive interpretation of the basement structure, there is no evidence for the existence of a major transform fault and/or a marginal ridge at the suggested position of the Davie Fracture Zone. Rather, the continental margin of Tanzania shows marked differences from other transform margin settings worldwide. One important argument in favor of a transform margin concept was the identification of Mesozoic magnetic anomalies in the West Somali Basin (Rabinowitz et al., 1983; Segoufin and Patriat, 1980). However, these are generally weak, difficult to correlate and may have been misidentified. Moreover, the general E-W orientation of the Late Jurassic to Early Cretaceous magnetic anomalies (see Figure 4.1) is not in accordance with the trend of the Davie Ridge (south of 9°S), which is mainly NNW-SSE (Figure 4.1) and contradicts a simple transform margin concept. It is worth noting that the location of the continent-ocean transition in the West Somali Basin, especially offshore Tanzania and Kenya, has not been conclusively interpreted until today. Although the interpretation of magnetic anomalies may indicate an oceanic origin of the entire West Somali Basin, the crustal nature has been debated in several studies at various places in the West Somali Basin (e.g. Klimke et al., 2016; Lort et al., 1979; Talwani, 1962). Even though the Davie Ridge south of 14°S indicates strike-slip deformation resulting from the southward displacement of Madagascar in the Mesozoic, the evolution and origin of this portion of the Davie Ridge has not been unequivocally determined. We suggest that it has been affected by several complex tectonic phases after the cessation of southward movement of Madagascar, including the NE-SW opening of the Mascarene Basin east of Madagascar in the Late Cretaceous and widespread Late Cretaceous volcanism. The lack of evidence for a major transform fault and a prominent marginal ridge offshore

Kenya and Tanzania raises the question about the opening of the West Somali Basin. We do not have a conclusive model at hand because this would require –at least- a good understanding of the structure and architecture of the conjugate north Madagascan and Somali continental margins, which are considerably underexplored.

In our view, a possibility to explain the opening of the West Somali Basin without invoking a 1000 km transform fault is initially oblique SW- propagating rifting and seafloor spreading in the West Somali Basin (Figure 4.7). Within such a concept, the propagator would come close to the southern Tanzanian coast, where it would join with a transform fault that is expressed today as a prominent basement high between Madagascar and Mozambique (Figure 4.1).

Once this connection was established, N-S to NNW-SSE-trending rifting and seafloor spreading in both the West Somali Basin and the Mozambique Basins could have initiated. Such a setting implies that wide areas in the West Somali Basin are not made up of normal oceanic crust, generated by steady-state seafloor spreading (Klimke et al., 2016). An oblique rifting scenario (Figure 4.7) also has significant consequences for Gondwana reconstructions, especially for Madagascar´s paleoposition and its pathway during Gondwana breakup. Our findings are in agreement with recent models proposed by Gaina et al. (2013, 2015) and Torsvik and Cocks (2013) who suggest that Madagascar was located in Gondwana in a N-S oriented alignment, such that there was no need for a counterclockwise rotation (Figure 4.2B). However, the major difference from existing reconstructions is the more southerly pre-breakup position of Madagascar that is implicit within an oblique rifting scenario. In fact, Scrutton (1978) noted that the motion of Madagascar along the Davie Fracture Zone is in conflict with Madagascar's palaeomagnetic poles and that the palaeomagnetic data "would favor motion from a position only a short way north of Madagascar's present position, or even virtually no motion". Consequently, Scrutton et al. (1981) considered a shorter Davie Fracture Zone, limited to the northern end of topographic expression at about 9°S, as an equally plausible alternative. Unfortunately, Late Paleozoic and Early Mesozoic paleomagnetic data are inconclusive so far (Rakotosolofo et al., 1999) and Karoo rift basins can be cross-correlated with either position of Madagascar.

However, there are some arguments in favor of a southern paleoposition of Madagascar. The ENE-trending Lurio Belt, a Neoproterozoic to Early Paleozoic crustal shear zone (Emmel et al., 2011; Fritz et al., 2013) that approaches the shoreline in northern Mozambique at about 13°S, separates two Mesoproterozoic domains. In the southern domain, 520-480 Ma high temperature metamorphism accompanied by granitoid intrusions is evident, a setting that is also present in southern Madagascar, south of the Ranotsara shear zone (Fritz et al., 2013).
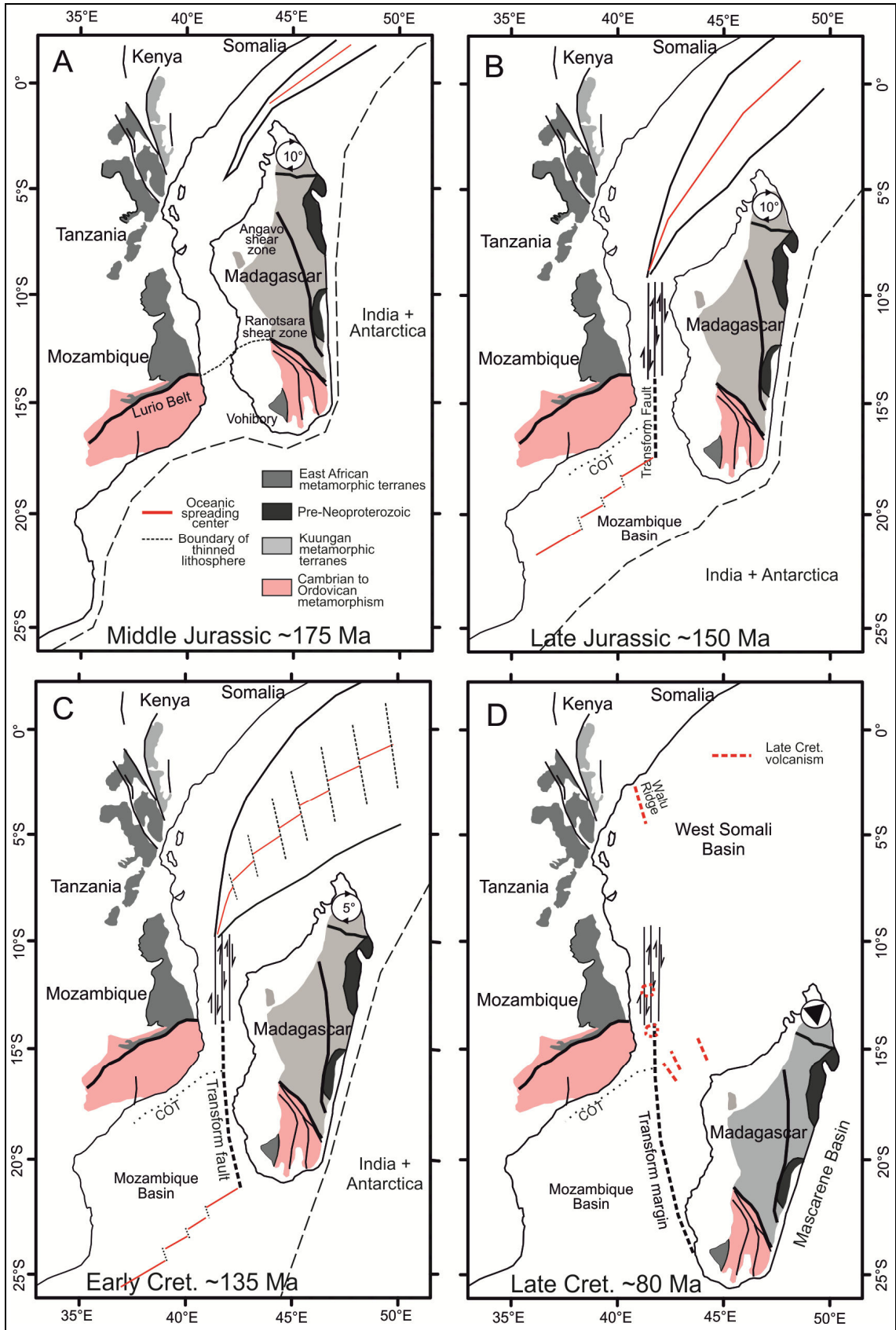
Figure 4.7 (previous page): Schematic sketch of the opening of the West Somali Basin as proposed in this paper. (A) In the Middle Jurassic (~175 Ma), breakup between East Africa and Madagascar occurs by the southwestward propagation of NW-SE directed oblique rifting and subsequent seafloor spreading. (B) Late Jurassic (~150 Ma): The SW-trending oceanic propagator joins with a N-S-oriented transform fault located between Madagascar and Mozambique. (C) Early Cretaceous (~130 Ma): N-S to NNW-SSE-trending seafloor spreading in the West Somali and the Mozambique Basin progresses. (D) Late Cretaceous (~80 Ma): seafloor spreading in the West Somali Basin has finished and Madagascar has reached its present-day position. Late Cretaceous volcanic features observed offshore northwestern Madagascar, Mozambique and Kenya (Klimke et al., 2016) are indicated by dashed red lines. COT= continent-ocean transition according to Leinweber et al. (2013).

The Ranotsara shear zone has been previously aligned with different structures in eastern Africa. However, Fritz et al. (2013), following Shackleton (1996), propose a pre-Gondwana breakup alignment of the basement provinces including a previous connection of the two shear zones. This would place Madagascar in line with our preferred oblique rifting scenario (Figure 4.7). Admittedly, within this proposition, there is a problem with a narrow fragment at the SW tip of Madagascar (Vohibory Block) that shows some affinity to Tanzanian geology. Our concept only works if this block may be correlated equally well with e.g. Antartica. Much effort appears to be necessary to derive a conclusive interpretation of the way Gondwana split up in the east. However, from our investigation, it becomes clear that the widespread "simple" models are unlikely to work.

4.6   Conclusions

We provide evidence that several of the structures that have been interpreted as evidence for the Davie Fracture Zone, e.g. the Walu Ridge offshore Kenya and the eastern boundary of the Kerimbas Basin, are in fact related to Late Cretaceous volcanism and inversion in Kenya as well as the Neogene evolution of the offshore East African Rift System. The inversion phase resulting in the formation of the Walu Ridge considerably postdates all published age estimations for the oceanic crust of the West Somali Basin, which implies that there is no relationship between this structure and a southward motion of Madagascar. Offshore northern Mozambique, the Davie Ridge represents a rift-flank uplift that originated in the Neogene, with no relationship to the displacement of Madagascar.

In between these structures, geophysical data do not show distinct basement structures that may be correlated to a single, major transform fault offshore Tanzania. Interpreting the continental margin of Tanzania as transform margin is at odds with typical transform margins worldwide.

We conclude that there is no evidence for a major single transform fault offshore northern Mozambique, Tanzania and Kenya that could favor a transform margin

concept. This calls into question the commonly assumed straight southward motion of Madagascar during the formation of the West Somali Basin. We suggest an initially southwestward propagating highly oblique rifting and seafloor-spreading phase as an alternative. A much more southerly pre-breakup position of Madagascar than in most published plate tectonic reconstructions is implied.

Chapter-specific acknowledgements

5   **Tie-points for Gondwana reconstructions from a structural interpretation of the Mozambique Basin, East Africa, and the Riiser-Larsen Sea, Antarctica**

Remarks

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Abstract

Movements within early Gondwana dispersal are poorly constrained and there is uncertainty about the position and structural style of the continent-ocean transition and the timing and directions of the rifting and earliest seafloor spreading phases. In this paper, we present a combined structural interpretation of multichannel reflection seismic profiles from offshore northern Mozambique (East Africa), and the conjugate Riiser Larsen Sea (Antarctica). We find similar structural styles at the margins of both basins. At certain positions at the foot of the continental slope, the basement is intensely deformed and fractured, a structural style very untypical for rifted continental margins. Sediments overlying the deformation zone are deformed and reveal toplap and onlap geometries, implying a post-breakup deformation phase. We propose this unique deformation zone as tie-point for Gondwana reconstructions. Accordingly, we interpret the western flank of Gunnerus Ridge, Antarctica as a transform margin, similar to Davie Ridge, East Africa, implying that they are conjugate features. We consider it likely that a first phase of rifting and early seafloor spreading in NE-SW direction was subsequently replaced by a N-S directed transform deformation phase, overprinting the continent-ocean transition. This change of the spreading directions from NW-SE to N-S is suggested to have occurred by the Late Middle Jurassic, around magnetic anomaly M38n.2n (~164 Ma). We suggest that the second phase of deformation corresponds to the strike-slip movement of Madagascar and Antarctica and discuss implications for Gondwana breakup.

5.1   Introduction

The Mozambique Basin off East Africa and the conjugate Riiser-Larsen Sea off Antarctica (Figure 5.1) resulted from the Middle Jurassic separation of East Gondwana (Madagascar, Antarctica, India and Australia) from West Gondwana (South America

and Africa). However, a consistent reconstruction of prerift configurations relies on the knowledge of the crustal types and the location and structural style of the continent-ocean boundaries.
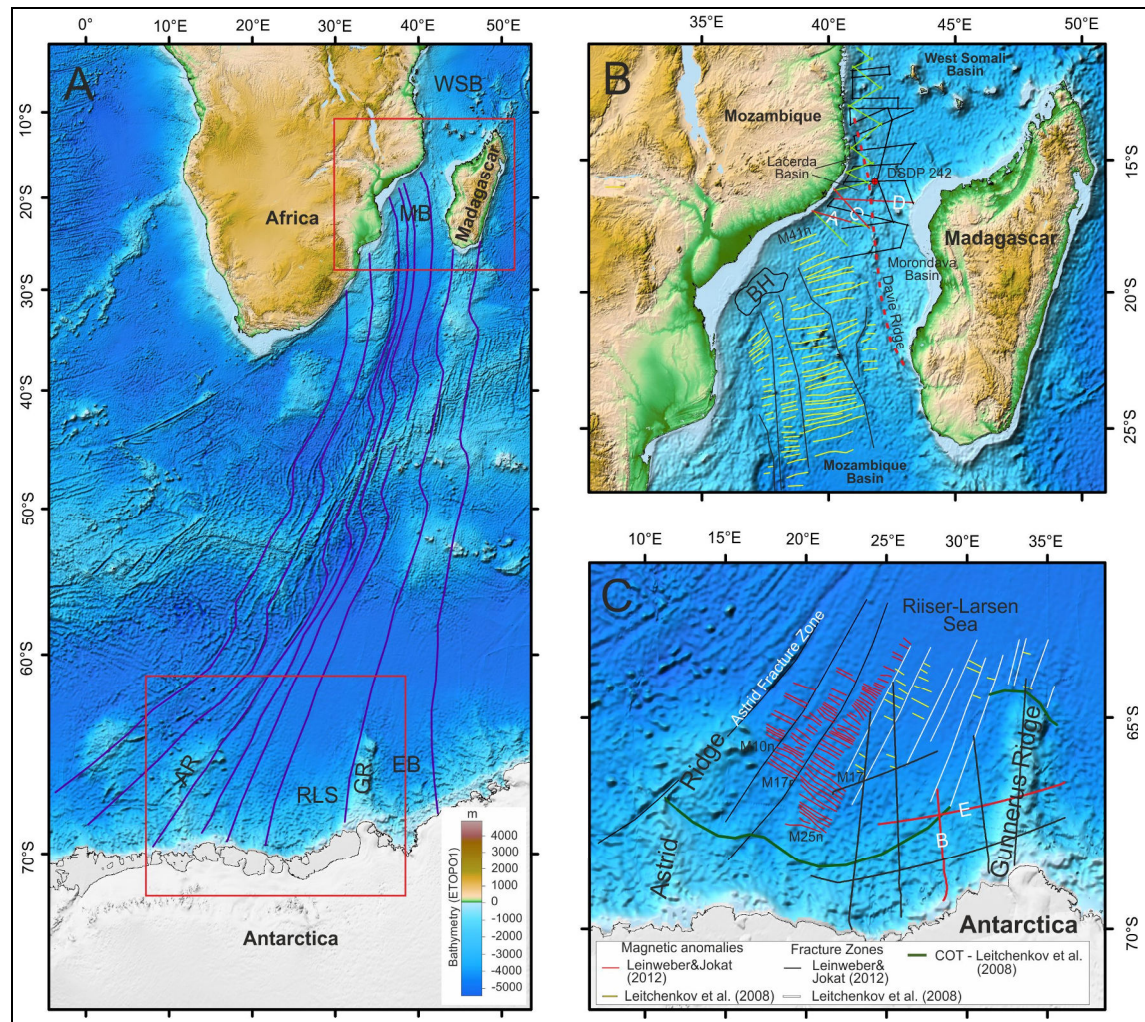
Figure 5.1: (A) Bathymetric map of the Africa-Antarctic corridor (ETOPO1 1 arc-minute global relief model; Amante and Eakins, 2009). The purple flow lines indicate the motion between Africa and Antarctica according to Eagles and König (2008). Red boxes indicate the study area in the Mozambique Basin and the Riiser-Larsen Sea. AR= Astrid Ridge, EB= Enderby Basin, GR= Gunnerus Ridge, MB= Mozambique Basin, RLS= Riiser-Larsen Sea, WSB= West Somali Basin. (B) Bathymetric map of the Mozambique Basin (ETOPO1 1 arc-minute global relief model; Amante and Eakins, 2009). Black and green lines indicate the locations of the reflection seismic profiles of the BGR14 and Mbwg00 datasets. Locations of Profiles A, C and D (Figures 5.2A, 5.4 and 5.6) are highlighted with red lines. The location of Beira High is from Mahanjane (2012). Magnetic anomalies and oceanic fracture zones compiled from Leinweber and Jokat (2012) and Müller and Jokat (2017). BH= Beira High. (C) Bathymetric map of the Riiser-Larsen Sea (ETOPO1 1 arc-minute global relief model; Amante and Eakins, 2009). Thick black lines indicate the location of the reflection seismic profiles of the RAE43 dataset. Position of Profiles B and E (Figures 5.2B and 5.7) are highlighted with red lines. Magnetic anomalies (red and yellow) and fracture zones (thin black and white lines) are compiled from Leinweber and Jokat (2012) and Leitchenkov et al. (2008). Continent-ocean transition as interpreted from Leitchenkov et al. (2008) is indicated with green line.

Therefore, the early movements within Gondwana are poorly constrained and there is a considerable debate about the timing and directions of the earliest rifting and spreading phases (e.g. Cox, 1992; Davis et al., 2016; Eagles and König, 2008; Jokat et al., 2003; Leinweber and Jokat, 2012; Marks and Tikku, 2001; Martin and Hartnady, 1986; Nguyen et al., 2016; Phethean et al., 2016; Reeves, 2014, Reeves et al., 2016; Roeser et al., 1996; Smith and Hallam, 1970; Torsvik and Cocks, 2013). The Mozambique Basin is of special importance for Gondwana reconstructions, as two end-members of rifted margins, a volcanic rifted and a transform margin can be studied in close relationship. Until today, the transition from the SW-NE trending volcanic rifted margin to the N-S trending transform margin along the Davie Ridge (Figure 5.1) remains poorly studied. Existing studies focused mostly on the sedimentary infill of the Mozambique Basin (e.g. Castelino et al., 2015; Mahanjane, 2014; Salman and Abdula, 1995), or on the crustal structure in the western and central parts of the Mozambique Basin (e.g. Leinweber et al., 2013; Mahanjane, 2012; Müller and Jokat, 2017; Mueller et al., 2016). While it is generally accepted that the Riiser-Larsen Sea is the conjugate of the Mozambique Basin (e.g. Jokat et al., 2003; Nguyen et al., 2016), it remains much less well studied in spite of an available set of modern geophysical data (e.g. Hinz et al., 2004; Leitchenkov et al., 2008; Roeser et al., 1996).

In this study, we present a combined structural interpretation of multichannel reflection seismic profiles from different datasets offshore northern Mozambique (East Africa), and the Riiser Larsen Sea (Antarctica) (Figure 5.1). The aim of this study is the investigation of basement and the earliest postrift sediments at the transition from Mozambique's volcanic rifted margin to the N-S trending transform margin along the Davie Ridge (Figure 5.1). We compare the results with the conjugate rifted margin in the Riiser-Larsen Sea off Antarctica. There, our study focuses on the transition from the rifted margin to the Gunnerus Ridge, a crustal block of supposedly continental origin (e.g. Roeser et al., 1996), which is proposed to represent a transform margin along its western flank (Figure 5.1; Leitchenkov et al., 2008).

When studying the continent-ocean transition along the conjugate margins, we identify a zone of deformed and fractured basement at the foot of the continental slope at both margins. The sediments overlying the deformation zone are deformed, implying a post-breakup deformation phase. We provide evidence that these unique structures can serve as tie-point for Gondwana reconstructions. This leads to a two-phase opening scenario for the conjugate Mozambique Basin and Riiser Larsen Sea.

5.2 Tectonic and geological setting

5.2.1 Breakup of East and West Gondwana

Several plate kinematic models describe the breakup of Gondwana along the East African margin (e.g. Cox, 1992; Davis et al., 2016; Gaina et al., 2013, 2015; Eagles and König, 2008; Leinweber and Jokat, 2012; Nguyen et al., 2016; Reeves et al., 2016). There is generally consensus that breakup took place in the Early Jurassic, at about 170-180 Ma (e.g. Gaina et al., 2013, 2015; Leinweber and Jokat, 2012; Leinweber et al., 2013; Nguyen et al., 2016). It is proposed that the Mozambique Basin and West Somali Basin opened almost simultaneously in NW-SE direction (e.g. Gaina et al., 2013) without independent movements of small plates (Davis et al., 2016; Eagles and König, 2008; Reeves et al., 2016). However, there is a considerable debate about the timing and directions of the earliest rifting and spreading phases. In most of the recent plate tectonic reconstructions, there seems a consensus that the directions of rifting and earliest seafloor spreading between East and West Gondwana were approximately NW-SE and are suggested to have changed to a N-S direction during later seafloor spreading phases (e.g. Leinweber and Jokat, 2012; Reeves et al., 2016). Oceanic crust preserved from seafloor spreading between Africa and Antarctica has been dated by the identification of marine magnetic anomalies. Recent studies tentatively identify M41n (~165 Ma; Leinweber and Jokat, 2012) or M38n.2n (Müller and Jokat, 2017) as the oldest magnetic anomaly in the Mozambique Basin, considerably older than in previous studies (M2 to M22, ~148-127 Ma; Simpson et al., 1979, Segoufin, 1978).

In the conjugate Riiser-Larsen Sea, Leinweber and Jokat (2012) identify M25n (~154 Ma) as the oldest magnetic anomaly (Figure 5.1), extending the model of Bergh (1977) and confirming previous interpretations of Roeser et al. (1996) and Leitchenkov et al. (2008), who identified M0 to M24 (~152-125 Ma). However, well-defined magnetic anomalies older than M25n were not yet identified (Leinweber and Jokat, 2012; Leitchenkov et al., 2008; Roeser et al., 1996), although it is implied that spreading started before M25n (Leinweber and Jokat, 2012).

5.2.2 Enigmatic crustal blocks in the Mozambique Basin and the Riiser-Larsen Sea

By the Late Jurassic, seafloor spreading was underway in the Mozambique and Riiser Larsen Sea Basins (e.g. Coffin and Rabinowitz, 1987; Eagles and König, 2008; Rabinowitz et al., 1983; Segoufin and Patriat, 1980; Simpson et al., 1979). The Mozambique Basin and the West Somali Basin are separated by a bathymetric elevation rising 1-2 km above the surrounding seafloor that is referred to as the Davie Ridge (Figure 5.1). It has been widely accepted that the Davie Ridge is located at the trace of a fossil transform fault that accommodated the motion of Madagascar/Antarctica with respect to Africa. This transform was active from the Late Middle Jurassic (~160-165

Ma) to the Early Cretaceous (~125-135 Ma) (e.g. Coffin and Rabinowitz, 1987; Segoufin and Patriat, 1980). Although in the West Somali Basin the presence of the Davie Ridge has been questioned (e.g. Klimke and Franke, 2016), the presence offshore west Madagascar is obvious. The Gunnerus Ridge in the Riiser-Larsen Sea may be the prolongation of the shear zone offshore Madagascar that accommodated the southward drift of Madagascar relative to Africa (Nguyen et al., 2016). (Figure 5.1). Its western flank has been interpreted as a strike-slip fault delineating a transform margin (e.g. Leitchenkov et al., 2008). The Gunnerus Ridge has been the subject of seismic and potential field studies in the last decades (e.g. Leitchenkov et al., 2008; Roeser et al., 1996; Saki et al., 1987). Based on its top basement seismic velocities of 5.8-6.1 km/s and dredged granitoid and gneissic rock samples, the Gunnerus Ridge has been ascribed a continental origin (Leitchenkov et al., 2008; Saki et al., 1987).

Other prominent crustal features in the Mozambique Basin and the Riiser-Larsen Sea are the Beira High and the Astrid Ridge, respectively (Figure 5.1). The crustal nature of the Beira High is essential for reconstructions of the prerift configuration as it controls the location of the continent-ocean transition in the western Mozambique Basin. Both, structural interpretation (Mahanjane, 2012) and seismic velocities derived from refraction seismic data (Müller et al, 2016) indicate that Beira High is made up of stretched and highly intruded continental crust. The Astrid Ridge in the western Riiser-Larsen Sea (Figure 5.1) is separated into a northern and a southern part by the Astrid Fracture Zone (e.g. Bergh, 1987; Leitchenkov et al., 2008). While Bergh (1987) proposed that the Astrid Ridge is an entirely magmatic structure, Roeser et al. (1996) proposed that N-S striking strong magnetic anomalies over the western flank of the southern part of Astrid Ridge originate from seaward-dipping reflectors and that this part is made up of continental crust.

5.3   Methods and Database

In this study, we use several marine reflection seismic datasets acquired by different institutes in the Mozambique Channel and the Riiser-Larsen Sea (Figure 5.1).

The **BGR14** dataset was acquired by the Federal Institute for Geosciences and Natural Resources (BGR) during a cruise of R/V Sonne in 2014. For a detailed description of the acquisition parameters and seismic processing, the reader is referred to Klimke et al. (2016). In this study, we present one profile striking E-W, crossing the Mozambique Basin into the Morondava Basin offshore Madagascar (Figure 5.1). For the seismostratigraphic interpretation of the areas in the Morondava Basin and the Davie Ridge, we use the stratigraphic interpretation established in Franke et al. (2015) and Klimke et al. (2016). For the Mozambique Basin, we use results from previous offshore studies (e.g. Castelino et al., 2015; Franke et al., 2015; Mahanjane, 2014).

We present two out of eight profiles of the **Mbwg00** dataset acquired by Western Geophysical in 2000, which run NW-SE and SW-NE in the Mozambique Channel (Figure 5.1). This dataset is part of the National Petroleum Institute of Mozambique archive and is contained in the study of Mahanjane (2014). For the interpretation of the profiles, we mainly use the stratigraphic framework established in Castelino et al. (2015), Franke et al. (2015) and Mahanjane (2014).

The **RAE43** reflection seismic dataset in the Riiser Larsen Sea was acquired by Polar Marine Geosurvey Expedition during a survey with the R/V Akademik Alexander Karpinsky in 1998. For a detailed description of the used equipment, the acquisition parameters, and the processing, the reader is referred to Leitchenkov et al. (2008). In this study, we show two reinterpreted profiles of this dataset (Figure 5.1) using as a basis the stratigraphic framework of Leitchenkov et al. (2008).

5.4 Results and structural interpretation

The seismic profiles shown in this paper are located in the northeastern part of the Mozambique Basin, off East Africa, and in the eastern part of the Riiser-Larsen Sea, off Antarctica (Figure 5.1) and thus cover parts of two conjugate margins resulting from the separation of Antarctica from Africa. Two profiles (Figure 5.2 and Figure 5.3) are oriented in a NW-SE direction, parallel to the spreading direction and run from the continental slope towards the abyssal plain in the Mozambique Basin and Riiser-Larsen Sea. Profile C (Figure 5.4 and Figure 5.5) trends NW-SE and runs from the Mozambique margin towards the Davie Ridge, while Profiles D and E (Figures 5.6 and 5.7) are oriented in E-W direction running across the Davie Ridge and Gunnerus Ridge, respectively. In the following, we present similarities in the structural style of the continent-ocean transition at both continental margins (4.1), with a special emphasis on the timing of the deformation observed at the foot of the continental slope (4.2). In section 4.3, we integrate the deformational event as identified at the continent-ocean transition into the structural setting imaged by the reflection seismic lines (Figures 5.2-5.7).

5.4.1 Common characteristics of conjugate margin sections: the tie-point

We identify an untypical yet similar structural style of the continent-ocean transition at both, the Mozambique and the Riiser-Larsen Sea continental margins. The continental slopes dip steeply at angles of ~6°-7° at the Mozambique margin (Figures 5.2A and 5.4) and ~5° in the Riiser-Larsen Sea (Figure 5.2B) where the depth of the top basement reflection increases from ~1s TWT to ~7s (TWT) over distances of ~50-70 km. At the foot of the continental slope, at depths of ~7 s TWT, there is a zone of highly deformed basement on both continental margins (Figure 5.2A, distance 50-70 km; Figure 5.2B, distance 160-190 km). In the deformed zone, the basement is intensely faulted over

distances of ~30 km (Figure 5.2). On Profile A (Figure 5.3A), which is oriented
subparallel to the spreading direction, the basement has been folded in an upward
direction and internal horizons are heavily deformed and dissected by faults (e.g. Figure
5.3A, distance: 50-70 km).
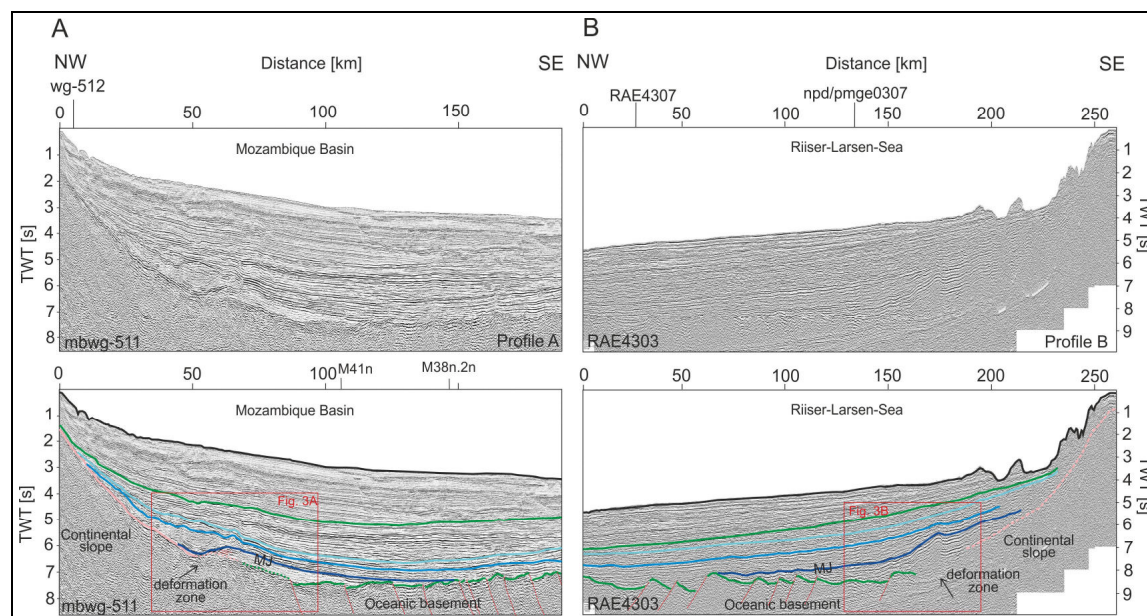
Figure 5.2: Migrated profile mbwg00-511 in the Mozambique Basin (A) and stacked profile
RAE4303 in the Riiser-Larsen Sea (B) (line locations in Figure 5.1). In the lower panels, the
stratigraphic interpretation according to Castelino et al. (2015), Leitchenkov et al. (2008) and
Mahanjane (2014) is presented. At the foot of the continental slope, at the continent-ocean
transition, a 20-30 km wide zone of deformed and fractured basement is visible. Postrift
sediments, overlying the deformation zone have been affected by the deformation. This
deformation zone is proposed as tie-point for Gondwana reconstructions.

This zone is also identified on the conjugate profile in the Riiser-Larsen Sea (Figures
5.2B and 5.3B; distance: 160-190 km) and strongly resembles the observed deformation
pattern in Figure 5.2A in the Mozambique Basin. Further northeast in the Mozambique
Basin (Figure 5.4), the basement deformation is characterized by steeply dipping normal
faults (Figure 5.4; distance 40-50 km). Faulting increases towards the SE (Figure 5.5,
distance: 50-60 km) where internal reflections have been heavily deformed and rotated.
In contrast to the area further west, which is characterized by compressional
deformation (Figure 5.2), the deformation in the SE (Figure 5.5) seems to be dominated
by extensional stress. Profile D in the Mozambique Basin (Figure 5.6) shows that the
basement is not imaged in the deformed zone (distance: 25-45 km), possibly due to the
intense faulting. Geographically, the deformed basement is visible in the eastern parts of
the basins, close to the Davie Ridge and the Gunnerus Ridge (Figure 5.8). The zone is
clearly depicted on several profiles over distances of 100-200 km in E-W direction
along the margins (Figure 5.8).

Seaward of the deformation zone along both margins, oceanic crust is interpreted that is characterized by high-amplitude, low-frequency, multi-reflector bands in depths of 7-9 s (TWT) (Figures 5.2, 5.4, 5.6 and 5.7). Locally, closely spaced diffractions are visible (Figures 5.2, 5.4, 5.6 and 5.7). Normal faults dissecting the basement with throws of ~250 ms (TWT) in the Mozambique Basin and up to ~1s (TWT) in the Riiser-Larsen Sea are observed. The faults are spaced at 5-15 km (Figure 5.2A, distance: 90-190 km; Figure 5.4, distance: 70-180 km; Figure 5.6, distance: 70-100 km) and 10-40 km (Figure 5.2B, distance: 30-110 km; Figure 5.7, distance: 0-300 km), respectively. The abundance of the faults is increasing significantly in the vicinity of the Davie Ridge (from ~15 km to 5 km) and the Gunnerus Ridge (from ~40 km to ~10 km). The observed reflection pattern and configuration of this dissected basement is typical for oceanic crust (Klimke et al., 2016).
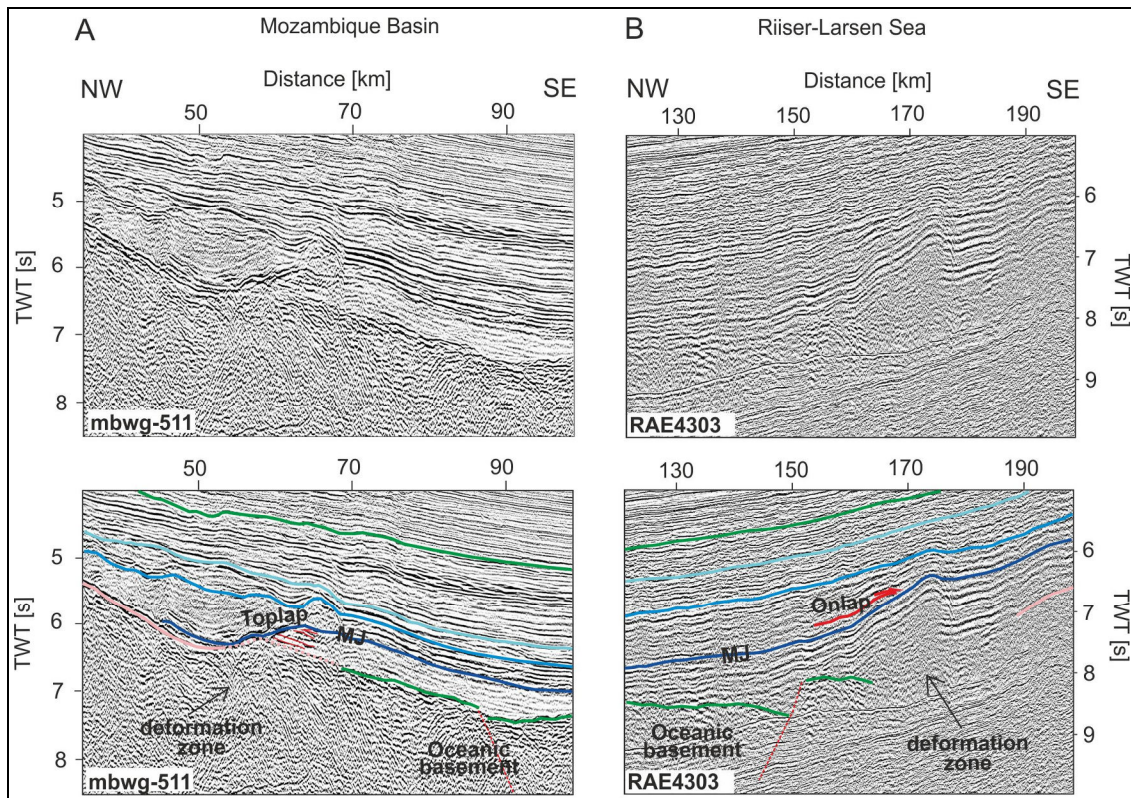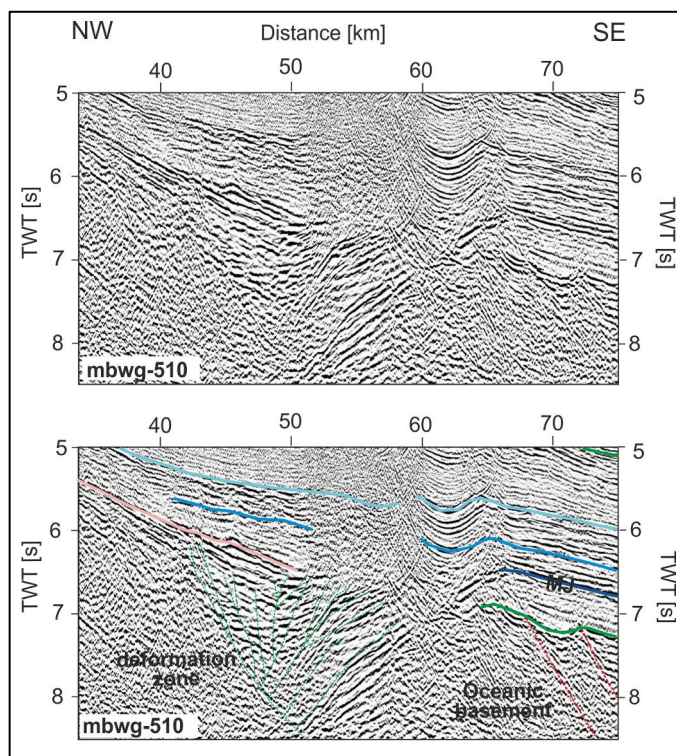

Figure 5.3: Close-up view of the zone of deformed basement in the Mozambique Basin (A) and Riiser-Larsen Sea (B) presented in Figure 5.2. The lower panels show the interpreted sections of the profiles. The basement is distinctively deformed and fractured. Overlying postrift sediments are deformed and indicate toplap (A) and onlap (B) geometries. Unconformity MJ seals the deformation.
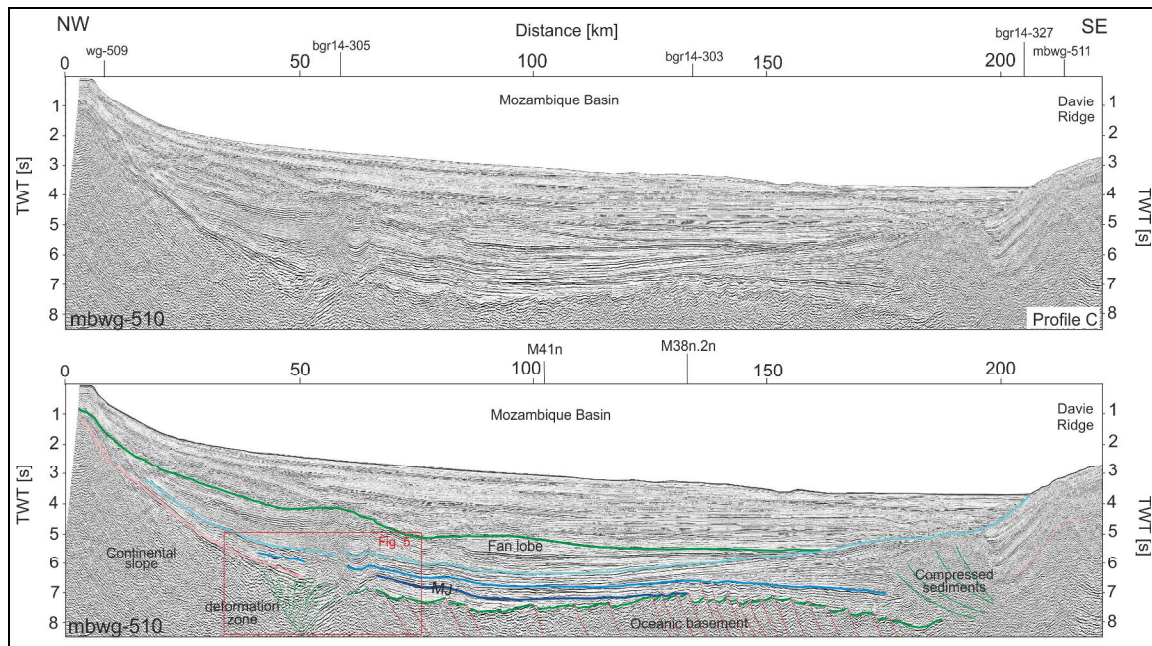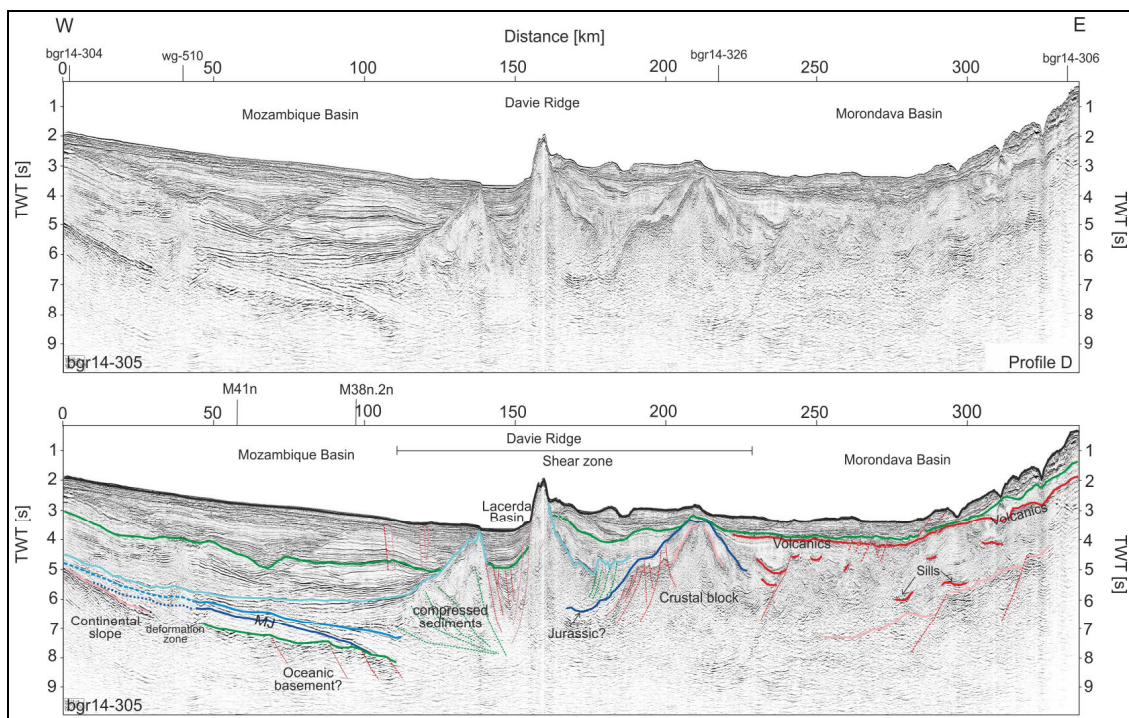
Figure 5.4: Migrated section of profile Mbwg00-510 (line location in Figure 5.1). The lower panel shows the section overlain by the stratigraphic interpretation according to Castelino et al. (2015), Franke et al. (2015) and Mahanjane (2014). The profile runs from the continental slope to the Davie Ridge offshore Madagascar. The zone of deformed basement is observed at the foot of the continental slope (distance: 40-60 km). The Davie Ridge appears as bathymetric high, rising 1 S (TWT) above the surrounding seafloor. At the foot of the western flank of Davie Ridge, a zone of deeply buried, compressed sediments is observed that might have been thrusted onto the oceanic crust during southward motion of Madagascar.

Figure 5.5: Close-up view of the zone of deformed basement in the Mozambique Basin presented in Figure 5.4. The lower panel shows the interpreted section of the profile. The basement is deformed by steeply dipping, fan-like normal faults that at depths may converge into a single, subvertical fault (green, distance: 40-60 km). The deformation is likely dominated by extensional stress.

The interpretation of oceanic crust seaward of the deformation zone is well in line with refraction seismic experiments and gravity modelling by Leinweber et al. (2013), refraction seismic experiments supported by 2D magnetic modelling of Müller and Jokat (2017) and magnetic anomaly identifications by Leinweber and Jokat (2012) and Müller and Jokat (2017) in the Mozambique Basin. According to Leinweber et al. (2013) and Müller and Jokat (2017), the continent-ocean transition at the Mozambique margin is located very close to the Zambezi coast and is characterized by high-velocity lower crustal bodies and seaward-dipping reflectors, typical for volcanic rifted margins.

Figure 5.6: Prestack migrated section of profile BGR14-305 (line location in Figure 5.1). The lower panel shows the interpreted section according to the seismostratigraphic concepts of Castelino et al. (2015), Franke et al. (2015), Klimke et al. (2016) and Mahanjane (2014). The profile runs from the continental slope offshore northern Mozambique across the Davie Ridge into the Morondava Basin offshore Madagascar. The zone of deformed basement is observed at the foot of the continental slope (distance: 30-50 km), where the basement is not imaged, which is probably due to the intense faulting of the basement. The Davie Ridge is observed in the center of the profile as a morphological expression. The shear zone including the Davie Ridge is characterized by three prominent crustal blocks, which extend over distances of ~120 km.

The position of the continent-ocean transition corresponds in our reflection seismic profiles to the area of the deformed basement (Figures 5.2, 5.4, 5.6). The profiles (Figures 5.2, 5.4 and 5.6) show that the deformed zone is about 20-30 km wide, implying that the continent-ocean transition is very abrupt. This is supported by refraction seismic experiments and gravity modelling in the Mozambique Basin (Leinweber et al., 2013, Müller and Jokat, 2017).

5.4.2 Timing of the deformation

At both conjugate margins, sedimentary successions overlying the basement have been affected by the deformational event (Figures 5.3, 5.5). Following the seismostratigraphic concept of Castelino et al. (2015), Franke et al. (2015), Leitchenkov et al. (2008) and Mahanjane (2014), the top of the deformed sediments interpreted as horizon "MJ" is of Middle Jurassic age. The sedimentary unit underlying horizon MJ is characterized by subparallel reflectors with low amplitudes. Especially at the Mozambique margin, the unit appears almost transparent which allows a clear along-margin distinction from younger, reflective deposits (e.g. Figure 5.4). Horizon MJ is visible on both margins, running from the continental slope to the abyssal plain, where it terminates against oceanic crust, which likely formed during the Jurassic Magnetic Quiet Zone (Figure 5.2A, distance: 150 km; Figure 5.2B, distance: 60 km; Figure 5.4, distance: 125 km; Figure 5.6, distance: 100 km). Extrapolating the identified magnetic anomalies (Figure 5.1; Leinweber and Jokat, 2012; Müller and Jokat, 2017) to the study area in the Mozambique Basin, the sedimentary unit below horizon MJ terminates against oceanic crust at the position of magnetic anomaly M38n.2n (~164 Ma). This confirms previous stratigraphic concepts and we propose that the deformation is Middle Jurassic in age. The deformation of the earliest, likely Middle Jurassic sediments observed at both continental margins is characterized by onlap and toplap geometries, where the MJ horizon acts as an unconformity sealing the deformation. In the Mozambique Basin, the top of the Middle Jurassic sediments has been eroded resulting in toplap structures of older sediments against the MJ horizon (Figure 5.3A; distance: 60 km). In the Riiser-Larsen Sea, the Middle Jurassic sediments have been folded upward in conjunction with the basement (Figure 5.3B; distance: 160-190 km) and subsequent, likely Late Jurassic sediments onlap the MJ horizon (Figure 5.3B, distance: 170 km).

5.4.3 Implications on the structural setting

The question now is how the deformational event identified on the conjugate seismic lines (section 4.1 and 4.2) fits into the early Gondwana dispersal scenario.

Offshore northern Mozambique (Figure 5.6), the shear zone, guiding the southward drift of Madagascar/Antarctica during Middle Jurassic and Early Cretaceous times, is visible (Figure 5.6, distance: 120-230 km). In the Mozambique Channel (Figure 5.6), the shear zone is situated about 60 km eastward of the deformed basement and is characterized by three prominent crustal blocks including the Davie Ridge. The Davie Ridge shows a morphological expression rising ~1 s above the surrounding seafloor, while its lateral extent is limited to 10-20 km (Figure 5.6, distance: 150-170 km). Dredging and coring

of Davie Ridge revealed that it is, at least locally, built up of crystalline continental basement (Bassias, 1992).
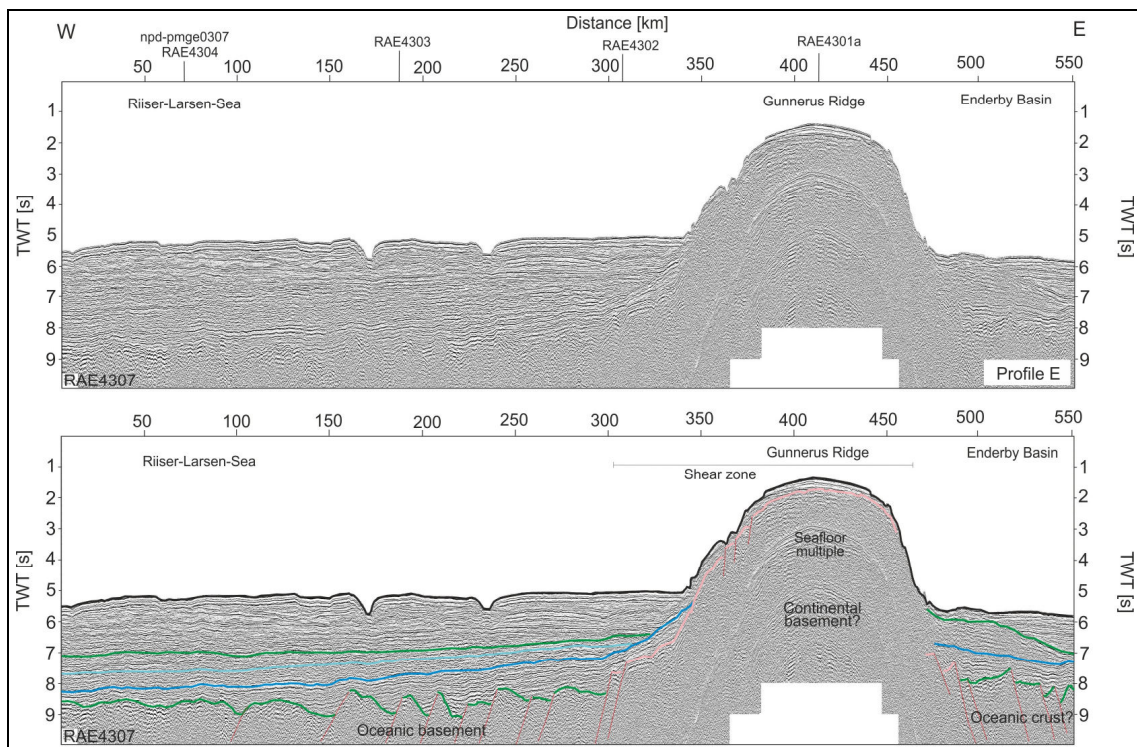
Figure 5.7: Stacked section of profile RAE4307 (line location in Figure 5.1). The lower panel shows the interpreted section of the profile with the stratigraphy according to Leitchenkov et al. (2008). The profile runs from the Riiser-Larsen Sea across the Gunnerus Ridge into the Enderby Basin. The Gunnerus Ridge rises ~4 s (TWT) above the surrounding seafloor. The transition from continental to oceanic crust along the Gunnerus Ridge is very abrupt (~30-40 km). The oceanic crust of the Riiser-Larsen Sea is dissected by normal faults. The abundance of the faults increases significantly towards the Gunnerus Ridge.

The reflection pattern of the tilted block to the west of Davie Ridge indicates a sedimentary origin, while we cannot exclude that the deeper portions are made up of basement rocks. The Davie Ridge shows a similar structural framework. The top reflection of both structures is a major unconformity that may mark the end of southward drift of Madagascar and could correspond to an Early Cretaceous (Barremian) reflector interpreted by Klimke et al. (2016) to the east of the Davie Ridge, in the West Somali Basin. Inside the tilted block, sediments have been deformed by several thrust faults dissecting the sediments and/or the basement. We consider it likely that this structure continues southward, because similarly to the west of Davie Ridge (Figure 5.4; distance: 175-200 km), deeply buried, compressed sediments are observed above the basement. The structural framework of the sediments implies deformation by transpressive forces. We suggest that the sediments have been overthrusted onto the oceanic crust of the Mozambique Basin. The crustal block to the east of Davie Ridge

(Figure 5.6, distance: 180-230 km) is covered by 0.5-1s (TWT) thick, subparallel sediments overlain by a prominent unconformity of supposedly Jurassic (?) age. The structural configuration of the deposits indicates that the crustal block, east of the Davie Ridge was uplifted prior to the formation of Davie Ridge. However, the deformation of overlying strata indicate a reactivation in the Late Cretaceous and/or Tertiary.

We observe a similar structural framework in the Riiser-Larsen Sea. There (Figure 5.7), the Gunnerus Ridge is imaged as bathymetric feature rising 4s (TWT) above the surrounding seafloor (Figure 5.7, distance: 350-460 km). Similar to the Davie Ridge, the sedimentary package located on top is very thin (~0.25 s TWT). Based on its top basement velocities of 5.8-6.1 km/s and dredged granitoid and gneissic rock samples, the Gunnerus Ridge has been ascribed a continental origin (Leitchenkov et al., 2008; Saki et al., 1987). Sediments of supposedly Late Jurassic to Recent age are onlapping the Gunnerus Ridge (Figure 5.7, distance: 350 km).

A striking observation is that at the western flanks of both, the Davie Ridge and the Gunnerus Ridge, the transition from continental to oceanic crust is very abrupt (Davie Ridge: 10-20 km; Gunnerus Ridge: ~40-50 km; Figures 5.6 and 5.7), what is well in line with the structural setting of transform margins.

5.5   Discussion

5.5.1   Landward extent of oceanic crust

The interpretation of reflection seismic profiles in the Mozambique Basin and the Riiser-Larsen Sea clearly implies a similar structural framework in both basins. Both basins show a steeply dipping continental slope with angles of 5°-7° with a zone of deformed basement situated at the foot of the continental slope. Seaward of the deformed zone lies basement with low-frequency and high-amplitude multi-reflector bands and is highly dissected by normal faults with throws of up to 1s (TWT). The abundance of the faults increases towards the Davie Ridge and the Gunnerus Ridge. The absence of typical synrift fills of the half-grabens and listric faults bounding the crustal blocks clearly excludes a continental origin of the dissected basement. Moreover, the observed reflection pattern and configuration of this dissected basement is typical for oceanic crust (Klimke et al., 2016). In the Mozambique Basin, refraction seismic experiments and gravity modelling by Leinweber et al. (2013) support this interpretation. Basement thickness at the continent-ocean transition is 3-4 km and increases seaward to ~5 km (Leinweber et al., 2013). This has been confirmed by a revised investigation of refraction seismic experiments of Müller and Jokat (2017). By extrapolating marine magnetic anomaly identifications of Leinweber and Jokat (2012) and Müller and Jokat (2017) to the location of our profiles (Figure 5.1), it is likely that the oceanic crust was formed between 166 and 160 Ma, obtained from anomalies M41n-M33n.

At both margins, magnetic anomaly M25n (~154-155 Ma) is located ~250-280 km seaward of the coast (Figure 5.1), which implies symmetric spreading between both margins. Therefore, oceanic crust older than ~155 Ma (M25n) should be present in the Riiser-Larsen Sea. A comparably wide strip of oceanic crust with ages of ~155-166 Ma fits well between magnetic anomaly M25n and the zone of deformed basement located at the base of the continental slope (chapter 4.1). This implies a considerably more southern position of the continent-ocean transition than previously anticipated (Figure 5.8). Additionally, geophysical experiments support this proposition. Gravity modelling derived crustal thicknesses of 5-6 km (Leitchenkov et al., 2008). The crustal thickness remains relatively constant west of the Gunnerus Ridge and increases from 5-6 km to 10 km only near the Astrid Ridge (Figure 16 in Leitchenkov et al., 2008). Based on these observations, we suggest to relocate the continent-ocean transition in the Riiser-Larsen Sea to the zone of deformed basement at the continental slope (Figure 5.8).
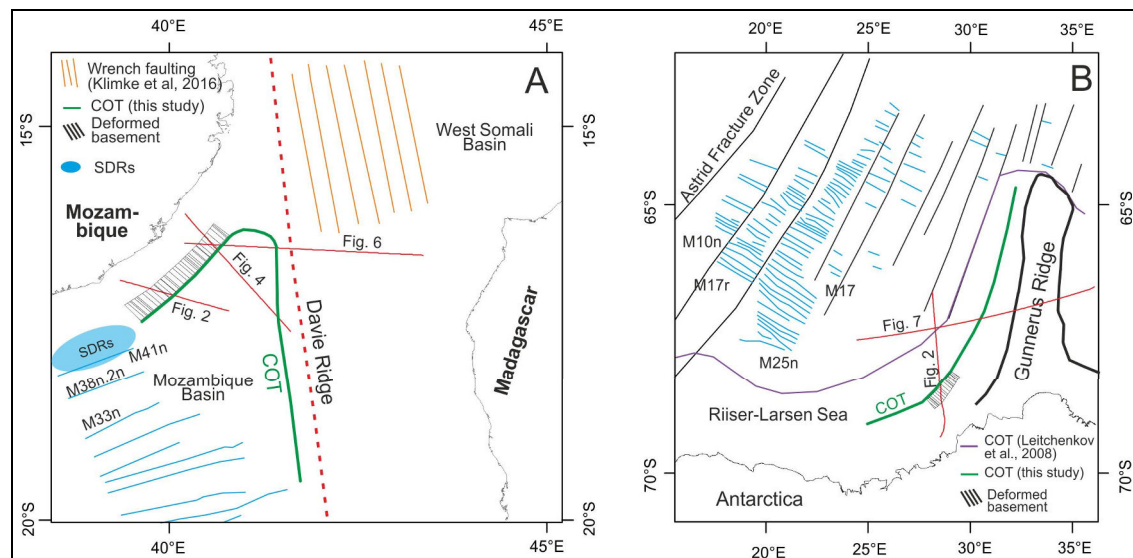
Figure 5.8: Sketch map illustrating the location of the deformed basement observed at the foot of the continental slope in the Mozambique Basin (A) and the Riiser-Larsen Sea (B). Red lines indicate the location of Profiles A to E (Figures 5.2, 5.4, 5.6 and 5.7). Blue and black lines highlight magnetic anomalies and fracture zones in the Mozambique Basin and Riiser-Larsen Sea according to Leinweber and Jokat (2012), Leitchenkov et al. (2008) and Müller and Jokat (2017). The continent-ocean transition (COT) as proposed in this study is shown in green. The continent-ocean transition according to Leitchenkov et al. (2008) in the Riiser-Larsen Sea is shown in purple. Hatched orange lines indicate wrench faulting in the West Somali Basin (Klimke et al., 2016). The location of SDRs in the Mozambique Basin is compiled from Leinweber et al. (2013) and Müller and Jokat (2017).

Along the Davie Ridge and the Gunnerus Ridge, the transition from continental to oceanic crust is very abrupt. At the western flank of the Gunnerus Ridge, the continent-ocean transition is ~40-50 km wide and at the Davie Ridge, it doesn't exceed 10-20 km. This is typical for shear margin settings, where the transition from continental to oceanic crust

typically occurs over distances of not more than 50-80 km (Bird, 2001). This confirms that the western margin of Gunnerus Ridge is a transform margin, similar to Davie Ridge. Gravity modelling of profiles crossing the Gunnerus Ridge by Leitchenkov et al. (2008) and Roeser et al. (1996) confirm the abrupt continent-ocean transition. As the abundance of normal faults increases significantly in the vicinity of the Davie Ridge and Gunnerus Ridge (Figure 5.4 and Figure 5.7), we suggest that the oceanic crust has been affected by intense shear motions during spreading.

5.5.2 Implications for Gondwana Breakup

The basement deformation at the location of the continent-ocean transition in the eastern parts of both basins certainly is unrelated to seafloor spreading. Rather, we suggest that the basement was affected by intense shearing subsequently to the initial opening of the Mozambique Basin and the Riiser-Larsen Sea. This shearing occurred likely along the Davie Ridge and the Gunnerus Ridge that in our view represent transform margins on their western flanks in the Mozambique Basin and the Riiser-Larsen Sea (Figure 5.8). The origin of the basement deformation thus could be interpreted as strike-slip faults that form positive and negative flower structures (Figure 5.3 and 5.5). Based on the reflection seismic data, the shearing processes affected basement located 60-150 km away from the transform faults (Figure 5.8). Klimke et al. (2016) observed similar structures in extended basement to the east of Davie Ridge in the West Somali Basin (Figure 5.8). The observed faults are steeply dipping wrench faults that were active during the southward movement of Madagascar along the Davie Ridge. A prominent Early Cretaceous unconformity marks the end of wrench faulting (U2) (Klimke et al., 2016).

We are confident that seaward of the deformed basement oceanic crust is found. This is based not only on the basement reflection pattern but is also confirmed by other geophysical data (seismic velocities, magnetic anomalies, gravity modelling). Thus, there was a short period of seafloor spreading preceding the wrench movements.

This confirms plate tectonic reconstructions which propose an early, NW-SE directed phase of rifting and seafloor spreading in the Mozambique Basin/Riiser-Larsen Sea (e.g. Eagles and König, 2008; Gaina et al., 2013; Reeves et al., 2016), followed by a change of spreading directions from NW-SE to N-S at M25n (~153 Ma) (Reeves et al., 2016) or M33n (~159 Ma) (Leinweber and Jokat, 2012). According to our seismo-stratigraphic concept, the change in spreading directions from NW-SE to N-S likely occurred early, at the transition from Middle to Late Jurassic, because unconformity MJ seals the deformation and terminates against oceanic crust at 164 Ma (M38n.2n; Müller and Jokat, 2017).

Westward of the study area, the Beira High (Figure 5.1) is suggested to have separated from Africa during the initial opening of the Mozambique Basin (e.g. Nguyen et al.,

2016). As significant differences in the amount of stretching are observed below the margins of Beira High, some authors propose a rift jump during the early rifting stage from the northwestern to the southeastern boundary of Beira High (e.g. Mahanjane, 2012; Müller et al., 2016).
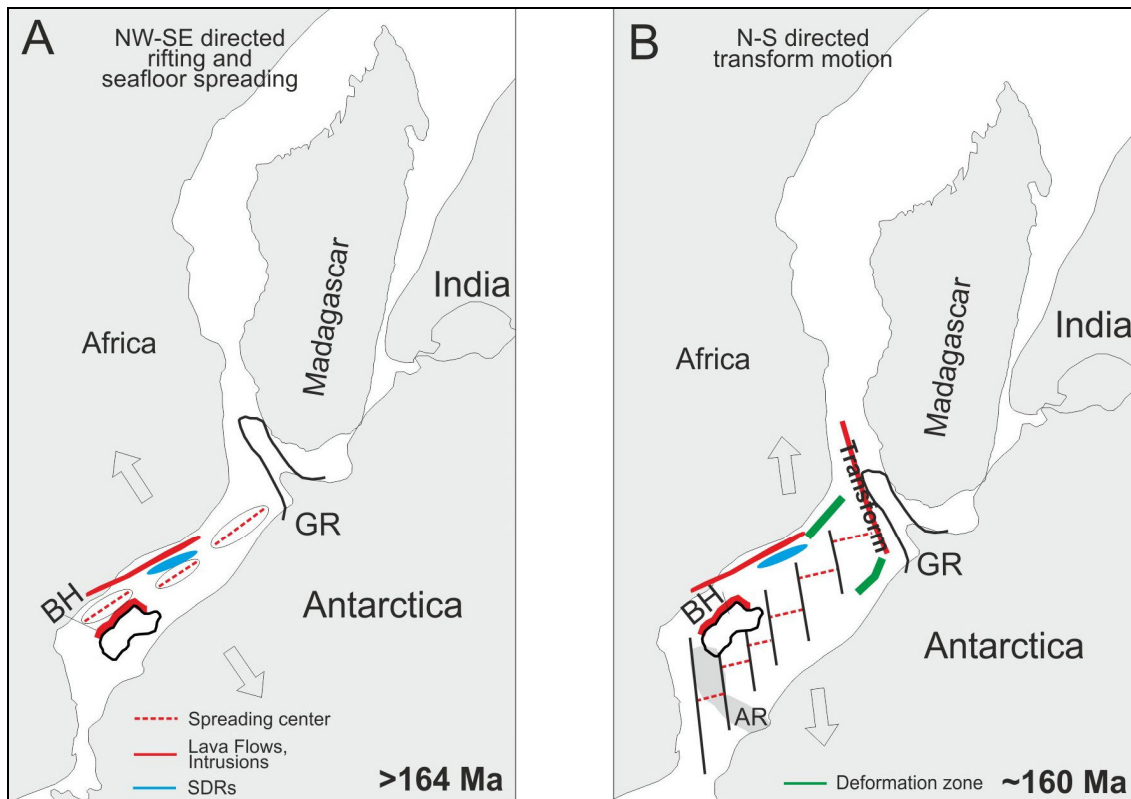
Figure 5.9: Schematic sketch of the initial opening of the Mozambique Basin/Riiser-Larsen Sea. (A) In the Middle Jurassic, NW-SE directed rifting and seafloor spreading between Africa and Antarctica initiates with the possible formation of localized spreading centers close to the present-day shoreline. (B) By the Late Jurassic, the spreading center has jumped to the south and the NW-SE extensional phase has been replaced by N-S directed seafloor spreading. At the eastern margin of the evolving Mozambique Basin/Riiser Larsen Sea Basin, a transform deformation phase, overprinting the previous continent-ocean transition, accommodates the extension. The transform fault develops along the conjugate western flanks of the Davie Ridge and the Gunnerus Ridge. The positions of Madagascar, Antarctica and India have been adopted approximately from Nguyen et al. (2016). Locations of SDRs, Lava flows and intrusions in the Mozambique Basin are taken from Mahanjane (2012) and Müller and Jokat (2017). AR= Astrid Ridge, BH= Beira High, GR= Gunnerus Ridge.

The nature of the crust situated between the Mozambique margin and Beira High remains unclear, as refraction velocities typical for oceanic crust or highly extended continental crust are observed (Müller et al., 2016). Mahanjane (2012) observes two rift phases in reflection seismic data covering the Beira High and postulates a two break-up stages concept. Our observed two-phase break-up scenario (Figure 5.9) concurs well with the proposed rift jump model (e.g. Mahanjane, 2012; Müller et al., 2016). We suggest that the "ridge jump" from the northwestern to the southern boundary of Beira High can be

associated with the change in spreading direction from NW-SE to N-S direction, initiating the strike-slip movement of Madagascar and Antarctica (Figure 5.9). This concept is in line with the reconstruction model of Leinweber and Jokat (2012) who propose a spreading center between the Beira High and Africa that jumped to the southern margin of Beira High at ~159 Ma.

Our proposed model for the initial opening of the Mozambique Basin/Riiser-Larsen Sea implies that the Gunnerus Ridge was located at the southwestern flank of Madagascar in order to be aligned with the Davie Ridge. This brings the Astrid Ridge, regardless of its crustal nature and formation age, which are still subject of discussion, to the western flank of Beira High (Figure 5.9), indicating that they could be conjugate features (Nguyen et al., 2016).

5.6   Conclusions

Based on the interpretation of reflection seismic profiles in the northeastern Mozambique Basin and the eastern Riiser-Larsen Sea, we identify a symmetric zone of deformed and faulted basement at the foot of the continental slope at both margins. The architecture and style of the observed deformation zone, which is unique at rifted margins, represents a mirror image between both conjugate margins and is proposed as a tie point for Gondwana reconstructions.

We confirm that the Gunnerus Ridge is conjugate to the Davie Ridge, offshore northern Mozambique/Madagascar. A major transform fault is interpreted at the western margin of the Gunnerus Ridge, equivalent to the Davie Ridge. The continent-ocean transition in the eastern Riiser-Larsen Sea, west of the Gunnerus Ridge, is located closer to the shoreline than was proposed in earlier studies.

Sediments overlying the basement deformation zone at the foot of the continental slope are deformed with onlap and toplap geometries, implying a post-breakup deformation phase. This indicates that a first phase of rifting and likely early seafloor spreading has been replaced by a second, transform deformation phase, overprinting the continent-ocean transition. The sedimentary horizon sealing the deformation terminates against oceanic crust at around the position of magnetic anomaly M38n.2n (164 Ma; Middle Jurassic). We consider it likely that the second phase represents the southward displacement with strike-slip movement of Madagascar and Antarctica against Africa. A first, likely NW-SE directed extensional phase may have resulted in localized seafloor spreading in the Mozambique Basin/Riiser-Larsen Sea Basin before a ridge-jump at the transition from the Middle Jurassic to the Late Jurassic may have initiated the generally N-S opening of both oceanic basins.

Chapter-specific acknowledgements

6 Synthesis and Discussion

This thesis provides new structural constraints on the early Gondwana dispersal along the East African margin. Several open questions regarding the structural architecture of the Davie Fracture Zone (section 6.1), the northward extent of the Davie Fracture Zone (section 6.2), the location of the continent-ocean transition in the Mozambique Channel (section 6.3), and the architecture of the transition from the transform margin to the volcanic rifted margin in the Mozambique Basin (section 6.4) are answered. Following the synthesis of the findings of this thesis in sections 6.1 to 6.4, section 6.5 provides a discussion about the implications of the findings on Gondwana dispersal and the southward drift of Madagascar.

6.1 Structural architecture of the Davie Fracture Zone (including the Davie Ridge)

This thesis presents a detailed structural interpretation of the Davie Fracture Zone including the Davie Ridge in the Mozambique Channel, based on a set of modern geophysical data.

From ~17 to 15-16°S, the Davie Fracture Zone is imaged as a set of three closely spaced crustal blocks including the Davie Ridge, spaced over a distance of ~100 km (Figure 5.6). The Davie Ridge in this area is characterized as prominent bathymetric feature rising ~1s (TWT) above the surrounding seafloor with a lateral extent of 10-20 km. The reflection pattern of the Davie Ridge indicates a sedimentary origin in the upper parts while the deeper parts likely are made up of basement rocks. The top reflection is a major unconformity that most likely marks the end of southward drift of Madagascar and could correspond to the Early Cretaceous (Barremian) reflector U2 interpreted in chapter 3 to the east of Davie Ridge. At the western flank of Davie Ridge, deeply buried sediments have been deformed by several thrust faults dissecting the sediments and/or the basement. This structure continues south of ~17°S (Figure 5.4), where compressed sediments most likely have been overthrusted onto the oceanic crust of the Mozambique Basin by transpressive forces.

From 15-16°S to ~11°S, strike-slip faulting occurs over distances of more than 100 km. In this area, wrench faults affecting the basement and pre-Late Cretaceous sediments (chapters 3 and 4) are visible. The wrench faults are situated at the position of former listric basement faults and mostly occur in northward alignment of the basement Davie Ridge in the south. However, the wrench faults gradually diminish northward until they die out at ~11°S. The two crustal blocks flanking the Davie Ridge have diminished in this area and the appearance of Davie Ridge as prominent basement ridge significantly decreases. From 14-16°S, the Davie Ridge is observed as bathymetric elevation at the western flank of the Lacerda Graben, where it merely rises a couple of hundreds of

milliseconds above the surrounding seafloor (Figure 3.4). From 13-14°S, it appears as rift flank of the Lacerda Graben made up of thick, well-stratified sediments (Figure 3.3 and Figure 4.4), while from 12-13°S, it completely diminishes. From 9-12°S, it is located at the eastern flank of the Kerimbas Graben and is made up of subparallel, sedimentary layers (Figure 4.3). Within both grabens, Cenozoic sediments were affected by sub-recent extensional faults that are situated at the position of former listric basement faults. This sub-recent extension corresponds to the evolution of the offshore East African Rift System (Franke et al., 2015; Mougenot et al., 1986) and increases from south to north. Franke et al. (2015) propose a southward-propagating rift zone that forms a symmetric graben in the north (Kerimbas Graben) and a half-graben (Lacerda Graben) in the south. Therefore, north of 14°S, the topography of the Davie Ridge merely results from Plio-Quaternary rift flank uplift and is most likely not connected to the southward motion of Madagascar (chapter 4). No evidence for the Davie Fracture Zone is observed north of ~10-11°S.

6.2   Continent-Ocean Transition along the Davie Ridge

The most striking result is the absence of normal oceanic crust to the east of the Davie Ridge, north of Madagascar (chapter 3). Instead, a succession of rotated basement blocks, bounded by listric faults, is observed (Figure 3.5). The basement has been affected by two phases of deformation. The first phase resulted in the generation of NE-dipping basement fault blocks bounded by listric faults and the second corresponds to wrench faulting that probably correlates to the southward drift of Madagascar. The preceding extensional deformation took place prior to the formation of the first oceanic crust in the West Somali Basin. Normal oceanic crust in the West Somali Basin is observed to the NE of the area of the stretched basement, at ~13°S, and is characterized by highly reflective multi-reflector bands showing only minor internal deformation (Figure 5.8). The reflection pattern is typical for oceanic crust (chapter 3) and resembles seismic images of Mid/Late Jurassic oceanic crust in the northern part of the West Somali Basin (Coffin and Rabinowitz, 1988).

In contrast to earlier studies, it can now be confirmed that the Davie Fracture Zone does not delineate the continent-ocean transition in the West Somali Basin to the north of Madagascar. Moreover, between 15-16°S and ~11°S, the Davie Fracture Zone is not characterized as a major single transform fault. Wrench faulting occurs within a more than 100 km wide zone east of Davie Ridge (Figure 5.10).

Unlike in the West Somali Basin, an abrupt transition from continental to oceanic crust is observed in the Mozambique Basin, where the Davie Fracture Zone is observed as a set of three prominent crustal blocks (chapter 5). The transition occurs over distances of not more than 10-20 km, as is typical for sheared margins (Figure 5.8). At the continent-ocean transition in this area, deeply buried, compressed sediments are visible that most

likely have been overthrusted onto oceanic crust by transpressive forces during southward drift of Madagascar (Figure 5.4).

6.3   Northward extent of the Davie Fracture Zone

Reflection seismic data do not imply evidence for the continuation of the Davie Fracture Zone offshore Tanzania and Kenya (chapter 4). Only small-scale basement highs are observed on the seismic profiles along the Tanzanian margin, which, however, are not present on every profile. A marginal ridge, typically observed at transform margins, is missing (Figure 4.5). Offshore Kenya, the Walu Ridge, which in the literature (e.g. Coffin and Rabinowitz, 1987; Rabinowitz, 1971) is proposed as continuation of the basement Davie Ridge, is identified as a Late Cretaceous inversion structure, unrelated to the southward drift of Madagascar (Figure 4.6). The reflector, sealing the deformation of the Walu Ridge, is of Turonian or Cenomanian to Albian (~100 Ma) age and therefore postdates the cessation of southward drift of Madagascar by approximately 20-30 Ma. The ridge most likely results from a previously existing Early Cretaceous rift basin in prolongation of the Anza rift (Figure 4.1).

6.4   Transition from the transform margin to the volcanic rifted margin in the Mozambique Basin/Riiser-Larsen Sea

In the Mozambique Basin/Riiser-Larsen Sea, near the Davie Ridge and the Gunnerus Ridge, a zone of deformed and fractured basement is observed (chapter 5; Figure 5.8). This zone is located at the foot of the continental slope at both margins in the area of the continent-ocean transition (Figure 5.2). Sediments overlying the deformation zone are deformed with toplap and onlap geometries, implying a post-breakup deformation phase (Figure 5.2). This indicates that a first phase of likely NW-SE directed rifting and early seafloor spreading has been replaced by a second, N-S directed transform deformation phase, overprinting the continent-ocean transition (Figure 5.9). It is most likely that the second phase represents the southward displacement of Madagascar and Antarctica against Africa. It can now be confirmed that, similar to the Davie Ridge, the western margin of the Gunnerus Ridge is a major transform fault where the transition from continental to oceanic crust occurs over a distance of 40-50 km, typical for sheared margins. The Gunnerus Ridge is conjugate to the Davie Fracture Zone, guiding the southward drift of Madagascar and Antarctica relative to Africa.

## 6.5   Implications on Gondwana dispersal and the southward movement of Madagascar

The results of this thesis yield important new information and insights on Madagascar´s pre-breakup position and its southward movement in the Mesozoic. There is no evidence for the presence of the Davie Fracture Zone and the typical transform margin

setting, commonly proposed in the literature (chapter 1), offshore northern Mozambique, Tanzania and Kenya (chapter 3 and 4). A typical transform margin is observed south of ~15°S, where an abrupt transition from continental to oceanic crust of the Mozambique Basin occurs (chapter 5). A striking result of this thesis is the identification of two deformation phases in the West Somali Basin and Mozambique Basin/Riiser-Larsen Sea, close to the Davie Ridge and the Gunnerus Ridge, respectively (chapters 3 and 5). The first deformation phase is associated with NW-SE directed rifting and seafloor spreading, while the second transform deformation phase likely correlates with the southward drift of Madagascar. These results question most plate kinematic reconstructions, which model a straight, southward displacement of Madagascar along the Davie Fracture Zone and imply that the Davie Fracture Zone represents the continent-ocean boundary at the western edge of the West Somali Basin (e.g. Coffin and Rabinowitz, 1987; Davis et al., 2016; Gaina et al., 2015; Reeves, 2014).

In this thesis, a new concept for the opening of the West Somali Basin is presented, that does not invoke a 1000 km transform fault at the western edge of the West Somali Basin (chapter 4). It is suggested that the West Somali Basin opened by initially oblique SW-propagating rifting and seafloor spreading (Figure 4.7). The propagator would come close to the Tanzanian coast, where it would join with the Davie Fracture Zone, at ~11°S. Once this connection was established, N-S to NNW-SSE-trending rifting and seafloor spreading in both the West Somali Basin and Mozambique Basin/Riiser-Larsen Sea could have initiated. In the Mozambique Basin/Riiser-Larsen Sea, a change from NW-SE-directed rifting and early seafloor spreading to N-S directed transform motion is observed as a post-breakup deformation phase overprinting the continent-ocean transition, close to the Davie Ridge and western flank of Gunnerus Ridge (chapter 5), indicating that they are conjugate features. The opening scenario presented in this thesis complies with the results of recent reflection seismic surveys offshore Tanzania that could indicate the presence of oceanic crust located inbound of the commonly proposed location of the Davie Fracture Zone (e.g. Sauter et al., 2016).

The oblique opening scenario of the West Somali Basin presented in this thesis implies that Madagascar was oriented in Gondwana in a N-S oriented alignment. This is in agreement with recent reconstruction models of e.g. Gaina et al. (2013, 2015) (Figure 1.5). An important new aspect of this concept is the more southerly pre-breakup position of Madagascar in Gondwana. Opening of the West Somali Basin by oblique rifting and early seafloor spreading implies that there is no need for a counterclockwise rotation of Madagascar subsequent to breakup (Figure 4.7) as is implicit in reconstruction models by, e.g. Davis et al. (2016), Leinweber and Jokat (2012), Phethean et al. (2016) and Reeves (2014) (Figure 1.5).

Some recently published reconstruction models (e.g. Phethean et al., 2016; Reeves et al., 2016) imply that the Davie Fracture Zone off northern Mozambique, Tanzania and Kenya could represent an ocean-ocean fracture zone and that the continent-ocean transition is located west of the commonly proposed Davie Fracture Zone (Figure 6.1).
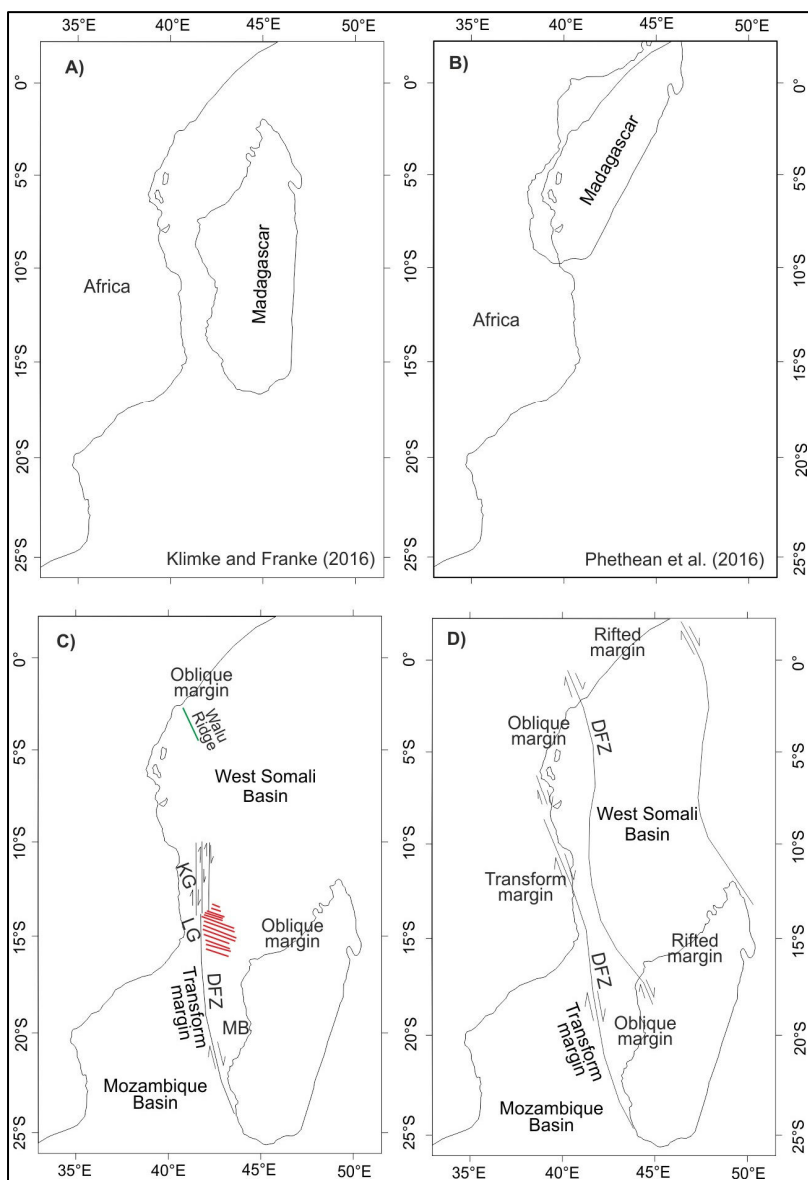
Figure 6.1: Schematic sketch illustrating the pre-breakup position of Madagascar according to (A) Klimke and Franke (2016) (chapter 4) and (B) Phethean et al. (2016). The lower panels show the corresponding structural setting according to (C) Klimke and Franke (2016) and (D) Phethean et al. (2016). Red hatched lines mark the location of the stretched basement identified in the reflection seismic profiles. DFZ= Davie Fracture Zone; MB= Morondava Basin; KG= Kerimbas Graben, LG= Lacerda Graben.

However, reflection seismic profiles available in this thesis do not give evidence for a major ocean-ocean fracture zone at the western edge of the West Somali Basin, neither off Tanzania and Kenya nor off northern Mozambique (chapters 3 and 4). Moreover, the identification of deeply buried rift structures in the Kerimbas and Lacerda Grabens (chapter 4; Franke et al., 2015) provides strong evidence that these basins are situated in the continental domain.

In contrast to the model presented in this thesis (Klimke and Franke, 2016), nearly all reconstruction models, including the recent reconstruction models of Phethean et al. (2016) and Reeves et al. (2016), presume that the West Somali Basin is continuously underlain by oceanic crust. In this thesis, it is shown that the basement in a wide area to the east of Davie Ridge, to the north of Madagascar, does not consist of normal oceanic crust (chapter 3), which also makes the presence of a major ocean-ocean fracture zone, as proposed by Phethean et al. (2016) (Figure 6.1), in this area unlikely. The stretched basement identified to the east of Davie Ridge (Figure 6.1) is interpreted as highly-stretched basement deformed with strike-slip faults (chapter 3). The oblique opening scenario presented in this thesis takes these observations into account (chapter 4).

In fact, the crustal nature of the West Somali Basin has not been conclusively determined until today and the continuous presence of oceanic crust in the West Somali Basin has been questioned by other detailed studies (e.g. Talwani, 1962; Lort et al., 1979). The area south of the Comoros islands, which includes the region where the stretched basement is observed, has been suggested to consist of continental basement by Lort et al. (1979). Moreover, there is no general consensus regarding the age of the oldest oceanic crust in the West Somali Basin, where recent magnetic anomaly interpretations range from M41n (~166 Ma, Gaina et al., 2015) to M24Bn (~152 Ma; Davis et al., 2016). Magnetic signatures in the West Somali Basin are weak and ambiguous (Lort et al., 1979), suggesting that oceanic crust may have formed during the Jurassic Magnetic Quiet Zone (Coffin and Rabinowitz, 1987; Rabinowitz et al., 1983).

Similarly, the crustal nature of the offshore Morondava Basin, located to the west of Madagascar, remains uncertain as no evidence from drillings or deep wide-angle seismic experiments is available. Reflection seismic profiles used in this thesis imply that the basin has been significantly affected by Late Cretaceous volcanism, widely masking basement reflections (chapters 3 and 5). Implicit in the here presented opening scenario is that the offshore Morondava Basin is not made up of normal oceanic crust, generated by steady-state seafloor spreading. This may also be indicated by the identification of stretched basement east of Davie Ridge, northwest of Madagascar (chapter 3). In contrast, Phethean et al. (2016), similar to Reeves et al. (2016), presume that the offshore Morondava Basin consists of oceanic basement (Figure 6.1). They align Madagascar in NE-SW direction in Gondwana with Madagascar´s southern tip close to southern Tanzania and model an initial phase of NW-SE directed rifting and seafloor spreading, leading to the generation of oceanic crust in the Morondava Basin. Marine magnetic anomalies supporting an oceanic origin have not been identified until today. Much effort appears to be necessary to derive a conclusive interpretation of Gondwana breakup in the east. However, it seems clear, that most of the published reconstruction models are difficult to match with the new data and results presented in this thesis.

7   Outlook

The results of this thesis provide important new information on several aspects regarding Madagascar´s paleoposition prior to Gondwana dispersal and its southward drift subsequent to Gondwana breakup. The geophysical dataset used in this thesis is of excellent quality regarding the resolution of the deeply buried basement structures in the Mozambique Channel and the structural architecture of the Davie Fracture Zone. However, for the surrounding areas, e.g. the Tanzanian, Kenyan, north Madagascan and Somalian continental margins, additional high-resolution geophysical datasets are needed in order to satisfactorily interpret the structural architecture of the margins and to determine the location of the continent-ocean transition. An improved understanding of these continental margins is essential for the development of a conclusive opening model of the West Somali Basin. Especially the north Madagascan and Somali continental margins remain considerably underexplored. Refraction seismic data are of special importance for the determination of the continent-ocean transition along the margins, as they provide information on crustal velocities and thicknesses. In combination with gravity data, gravity modelling should be carried out in order to verify results of the refraction data. Additional geophysical data covering the West Somali Basin and the offshore Morondava Basin are needed to determine its crustal nature and, for the West Somali Basin, to verify available marine magnetic anomaly interpretations. Deep offshore drillings at the continental margins as well as in the deepwater areas would give important constraints for the stratigraphic and structural interpretation of the areas. The results gained in this thesis should be included into plate reconstruction models. Finally, the new important findings may be used by the hydrocarbon exploration industry to predict potential source and reservoir rocks and to improve heat flow and maturity models.

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Acknowledgements

Thesis/project organization and funding

Curriculum Vitae

JENNIFER KLIMKE

Date of birth	14.03.1987 in Lehrte
Nationality	German

WORK EXPERIENCE

10/2017- present	University of Hamburg, Hamburg, Germany
Position held	Research Scientist in the Department of Earth Sciences, Institute of Geology
Responsibilities	Processing and interpretation of marine reflection seismic data with Vista® and Petrel®. Integration of borehole logs. Integration of data into GIS and plate reconstruction models. Presentation and publication of the results.
01/2014-02/2017	Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany
Position held	Research Scientist in the "Geology of the Energy Resources" Group
Responsibilities	Processing and interpretation of marine reflection seismic data with ProMAX 2D and GeoFrame®. Interpretation of magnetic and gravity data. Integration of data into GIS and plate reconstruction models. Presentation and publication of the results.
02/2014-04/2014	Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany
Position held	Research Scientist in the "Geology of the Energy Resources" Group during Research Cruise SO231 with RV Sonne in the Mozambique Channel
Responsibilities	Working shifts on processing of marine reflection seismic data and marine mammal watching. Interpretation of seismic data and help in installing the outboard equipment.
06/2012-12/2013	Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany
Position held	Research Scientist in the Marine Research Group
Responsibilities	Re-Processing and interpretation of marine reflection seismic data in the Mediterranean south of Cyprus and the Baffin Bay with ProMAX 2D and GeoFrame®.

Integration of data into GIS and plate reconstruction models. Presentation and publication of the results.

02/2010 - 08/2011	Leibniz-Institute for Applied Geophysics (LIAG), Hannover, Germany
Position Held	Student Research Assistant in Section 1 "Seismics – Gravimetry – Magnetics"
Responsibilities	Processing of reflection seismic data. Fieldwork on the island of Borkum and measurement of groundwater conductivity and groundwater table. Integration of data into ArcGIS. Compilation of conductivity maps of the island of Borkum.

EDUCATION

01/2014-08/2017	Gottfried Wilhelm Leibniz University, Hannover, Germany and Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany. Doctoral candidate
Degree	Ph.D. in Natural Sciences (Dr. rer. nat.)
Focal points	Ph.D. thesis used ProMAX 2D, GeoFrame®, ArcGIS for processing and interpretation of marine geophysical data in the Mozambique Channel.

10/2009 – 03/2012	Gottfried Wilhelm Leibniz University, Hannover, Germany
Degree	Master of Science Geosciences (M.Sc.)
Focal points	Master thesis used GoCAD® and ArcGIS to compile a geological-geophysical three-dimensional model of the Quakenbrück Basin in Lower Saxony. It is shown that the use of airborne electromagnetic methods immensely improve the three-dimensional models and help identify zones of saline groundwater. Major classes include Soil Protection, Hydrogeology, Geophysics, Sedimentation Systems, Basin Analysis, Quaternary Geology and Structural Geology.

10/2006 - 09/2009	Gottfried Wilhelm Leibniz University, Hannover, Germany
Degree	Bachelor of Science Geosciences (B.Sc.)
Focal points	Bachelor thesis used ProMAX 2D to examine the importance of the reflection seismic acquisition parameters on the structural image of the underground. Major classes include Earth dynamics, Paleontology, Structural Geology, Geochemistry, Petrology, Mineralogy, Quaternary Geology, and Sedimentology.

LANGUAGES

Languages	German	native
	English	full professional proficiency
	French, Spanish, Turkish	basic knowledge

List of Publications

Publications in peer-reviewed journals

Presented in this thesis

Klimke, J., Franke, D., Mahanjane, E.S., and Leitchenkov, G., submitted. Tie-points for Gondwana reconstructions from a structural interpretation of the Mozambique Basin, East Africa, and the Riiser-Larsen Sea, Antarctica, 2017.

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Other Publications

Klimke, J., and Ehrhardt, A., 2014. Impact and implications of the Afro-Eurasian collision south of Cyprus from reflection seismic data. Tectonophysics 626, 105-119, https://doi.org/10.1016/j.tecto.2014.04.002.

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Conference abstracts

Klimke, J., and Franke, D., 2015. Identification of hyper-extended crust east of Davie Ridge in the Mozambique Channel, DGG-Jahrestagung 2015, Hannover, Germany.

Klimke, J., and Franke, D., 2015. Identification of hyper-extended crust east of Davie Ridge in the Mozambique Channel, EGU General Assembly 2015, Vienna, Austria.

Klimke, J., and Ehrhardt, A., 2015. The Afro-Eurasian collision south of Cyprus – new implications from reflection seismic data, DGG-Jahrestagung 2015, Hannover, Germany.

Klimke, J., and Ehrhardt, A., 2013. Westward extension of the Levant Basin to the Eratosthenes Seamount and the Cyprus Arc – no evidence for strike-slip motion, EGU General Assembly 2013, Vienna, Austria.

Klimke, J., and Ehrhardt, A., 2013. Das Levantebecken im Einfluss von Kollision und Subduktion, DGG-Jahrestagung 2013, Leipzig, Germany.

Klimke, J., Ertl., G., Elbracht, J., Wiederhold, H., and Winsemann, J., 2012. Erstellung eines geologisch-geophysikalischen 3D-Modells für das Quakenbrücker Becken in Niedersachsen, DGG-Jahrestagung 2012, Hamburg, Germany.

Klimke, J., Ertl, G., Wiederhold, H. Elbracht, J., and Winsemann, J., 2012. Saline groundwater in the Quakenbrück Basin verified by airborne geophysics, 22nd Salt Water Intrusion Meeting (SWIM), Armacao dos Buzios, Brazil.

Master thesis

Klimke, J., 2011. Erstellung eines geologisch-geophysikalischen Untergrundmodells für den Bereich des pleistozänen Quakenbrücker Beckens in Niedersachsen, Master Thesis, Gottfried Wilhelm Leibniz University Hannover, Hannover, Germany, 105 pp.

Bachelor thesis

Klimke, J., 2009. Einfluss der Datenakquisitionsgeometrie auf die seismische Strukturabbildung des Untergrundes, Bachelor Thesis, Gottfried Wilhelm Leibniz University Hannover, Hannover, Germany.