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

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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.

1. INTRODUCTION

The Mozambique Basin off East Africa and the conjugate Riiser-Larsen Sea off Antarctica (Fig. 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. 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 passive margin to the N-S trending transform margin along the Davie Ridge (Fig. 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) (Fig. 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 (Fig. 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 (Fig. 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.

2. TECTONIC AND GEOLOGICAL SETTING

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 approx. 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 (Fig. 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).

2.2 ENIGMATIC CRUSTAL BLOCKS IN THE MOZAMBIQUE BASIN AND 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 (Fig. 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). (Fig. 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 (Fig. 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 (Fig. 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.

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 (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 1) using as a basis the stratigraphic framework of Leitchenkov et al. (2008).

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 (Fig. 1) and thus cover parts of two conjugate margins resulting from the separation of Antarctica from

Africa. Two profiles (Fig. 2 and Fig. 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 (Fig. 4 and Fig. 5) trends NW-SE and runs from the Mozambique margin towards the Davie Ridge, while Profiles D and E (Figs. 6 and 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 Sect. 4.3, we integrate the deformational event as identified at the continent-ocean transition into the structural setting imaged by the reflection seismic lines (Figs. 2-7).

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 (Figs. 2A and 4) and ~5° in the Riiser-Larsen Sea (Fig. 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 distinct zone of highly deformed basement on both continental margins (Fig. 2A, distance 50-70 km; Fig. 2B, distance 160-190 km). In the deformed zone, the basement is intensely faulted over distances of ~30 km (Fig. 2). On Profile A (Fig. 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. Fig. 3A, distance: 50-70 km). This zone is also identified on the conjugate profile in the Riiser-Larsen Sea (Figs. 2B and 3B; distance: 160-190 km) and strongly resembles the observed deformation pattern in Fig. 2A in the Mozambique Basin. Further northeast in the Mozambique Basin (Fig. 4), the basement deformation is characterized by steeply dipping normal faults (Fig. 4; distance 40-50 km). Faulting increases towards the SE (Fig. 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 (Fig. 2), the deformation in the SE (Fig. 5) seems to be dominated by extensional stress. Profile D in the Mozambique Basin (Fig. 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 distinct in the eastern parts of the basins, close to the Davie Ridge and the Gunnerus Ridge (Fig. 8). The zone is clearly depicted on several profiles over distances of 100-200 km in E-W direction along the margins (Fig. 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) (Figs. 2, 4, 6 and 7). Locally, closely spaced diffractions are distinct (Figs. 2, 4, 6 and 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 distinct. The faults are spaced at 5-15 km (Fig. 2A, distance: 90-190 km; Fig. 4, distance: 70-180 km; Fig. 6, distance: 70-100 km) and 10-40 km (Fig. 2B, distance: 30-110 km; Fig. 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). 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.

The position of the continent-ocean transition corresponds in our reflection seismic profiles to the area of the deformed basement (Figs. 2, 4, 6). The profiles (Figs. 2, 4 and 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).

4.2 TIMING OF THE DEFORMATION

At both conjugate margins, sedimentary successions overlying the basement have been affected by the deformational event (Figs. 3, 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. Fig. 4). Horizon MJ is distinct 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 (Fig. 2A, distance: 150 km; Fig. 2B, distance: 60 km; Fig. 4, distance: 125 km; Fig. 6, distance: 100 km). Extrapolating the identified magnetic anomalies (Fig. 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 (Fig. 3A; distance: 60 km). In the Riiser-Larsen Sea, the Middle Jurassic sediments have been folded upward in conjunction with the basement (Fig. 3B; distance: 160-190 km) and subsequent, likely Late Jurassic sediments onlap the MJ horizon (Fig. 3B, distance: 170 km).

4.3 IMPLICATIONS ON THE STRUCTURAL SETTING

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

Offshore northern Mozambique (Fig. 6), the shear zone, guiding the southward drift of Madagascar/Antarctica during Middle Jurassic and Early Cretaceous times, is distinct (Fig. 6, distance: 120-230 km). In the Mozambique Channel (Fig. 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 (Fig. 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). 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 (Fig. 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 (Fig. 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 (Fig. 7), the Gunnerus Ridge is imaged as bathymetric feature rising 4s (TWT) above the surrounding seafloor (Fig. 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 (Fig. 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; Figs. 6 and 7), what is well in line with the structural setting of transform margins.

5. DISCUSSION

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 (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 8).

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 (Fig. 4 and Fig. 7), we suggest that the oceanic crust has been affected by intense shear motions during spreading.

5.2 IMPLICATIONS FOR GONDWANA BREAKUP

The distinct 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 (Fig. 8). The origin of the basement deformation thus could be interpreted as strike-slip faults that form positive and negative flower structures (Fig. 3 and Fig. 5). Based on the reflection seismic data, the shearing processes affected basement located 60-150 km away from the transform faults (Fig. 8). Klimke et al. (2016) observed similar structures in extended basement to the east of Davie Ridge in the West Somali Basin (Fig. 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 distinct 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 (Fig. 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). 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 (Fig. 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 (Fig. 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 (Fig. 9), indicating that they could be conjugate features (Nguyen et al., 2016).

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.

DATA AVAILABILITY

All reflection seismic profiles of the bgr14 dataset can be accessed via the principal author. The reflection seismic dataset (RAE43) located in the Riiser-Larsen Sea has been made available through Antarctic Seismic Data Library System (SDLS) and can be accessed via http://sdls.ogs.trieste.it/. Two profiles of the Mbwg00 dataset located in the Mozambique Channel are commercial seismic lines, original data of which cannot be made available.

COMPETING INTERESTS

The authors declare that they have no conflict of interest.

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REFERENCES

Amante, C. and Eakins, B.W., 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24, National Geophysical Data Center, NOAA. doi:10.7289/V5C8276M [11.02.2016].

Bassias, Y., 1992. Petrological and geochemical investigation of rocks from the Davie fracture zone (Mozambique Channel) and some tectonic implications: Journal of African Earth Sciences (and the Middle East), v. 15, no. 3–4, p. 321-339.

Bergh, H.W., 1987. Underlying fracture zone nature of Adtrid Ridge off Antarctica´s Queen Maud Land. Journal of Geophysical Research 92 (B1), 475-484.

Bergh, H.W., 1977. Mesozoic sea floor off Dronning Maud Land, Antarctica. Nature 269, 686-687.

Bird, D., 2001. Shear margins: Continent-ocean transform and fracture zone boundaries: The Leading Edge, 150-159.

Castelino, J.A., Reichert, C., Klingelhoefer, F. and Aslanian, D., 2015. Mesozoic and Early Cenozoic sediment influx and morphology of the Mozambique Basin. Marine and Petroleum Geology 66, 890-905.

Coffin, M.F., and Rabinowitz, P.D., 1987. Reconstruction of Madagascar and Africa: Evidence from the Davie Fracture Zone and Western Somali Basin. Journal of Geophysical Research: Solid Earth 92, 9385-9406.

Cox, K.G., 1992. Karoo igneous activity, and the early stages of the break-up of Gondwanaland. From: Storey, B.C., Alabaster, T. and Pankhurst, R.j. (eds), 1992. Magmatism and the Causes of Continental Break-up. Geological Society Special Publication 68, 137-148.

Davis, J.K., Lawver, L.A., Norton, I.O. and Gahagan, L.M., 2016. New Somali Basin magnetic anomalies and a plate model for the early Indian Ocean. Gondwana Research 34, 16-28.

Eagles, G., and König, M., 2008. A model of plate kinematics in Gondwana breakup. Geophysical Journal International 173, 703-717.

Franke, D., Jokat, W., Ladage, S., Stollhofen, H., Klimke, J., Lutz, R., Mahanjane, E.S., Ehrhardt, A. and Schreckenberger, B., 2015. The offshore East African Rift System: Structural framework at the toe of a juvenile rift. Tectonics 34, 2086-2104, doi:10.1002/2015TC003922.

Gaina, C., Van Hinsbergen, D.J.J. and Spakman, W., 2015. Tectonic interactions between India and Arabia since the Jurassic reconstructed from marine geophysics, ophiolite geology, and seismic tomography. Tectonics 34, 875-906.

Gaina, C., Torsvik, T.H., van Hinsbergen, D.J.J., Medvedev, S., Werner, S.C., and Labails, C., 2013. The African Plate: A history of oceanic crust accretion and subduction since the Jurassic. Tectonophysics 604, 4-25.

Hinz, K., Neben, S., Gouseva, Y.B. and Kudryavtsev, G.A., 2004. A Compilation of Geophysical Data from the Lazarev Sea and the Riiser-Larsen Sea, Antarctica. Marine Geophysical Researches 25, 233-245.

Jokat, W., Boebel, T., König, M. and Meyer, U., 2003. Timing and geometry of early Gondwana breakup. Journal of Geophysical Research 108 (B9), 2428.

Klimke, J., Franke, D., Gaedicke, C., Schreckenberger, B., Schnabel, M., Stollhofen, H., Rose, J. and Chaheire, M., 2016. How to identify oceanic crust – evidence for a complex break-up in the Mozambique Channel, off East Africa, Tectonophysics 693, Part B, 436-452, http://dx.doi.org/10.1016/j.tecto.2015.10.012.

Klimke, J. and Franke, D., 2016. Gondwana breakup: no evidence for a Davie Fracture Zone offshore northern Mozambique, Tanzania and kenya. Terra Nova 28, 233-244.

Leinweber, V.T. and Jokat, W., 2012. The Jurassic history of the Africa-Antarctica corridor – new constraints from magnetic data on the conjugate continental margins. Tectonophysics 530-531, 87-101.

Leinweber, V.T., Klingelhoefer, F., Neben, S., Reichert, C., Aslanian, D., Matias, L., Heyde, I., Schreckenberger, B. and Jokat, W., 2013. The crustal structure of the Central Mozambique continental margin – Wide-angle seismic, gravity and magnetic study in the Mozambique Channel, Eastern Africa. Tectonophysics 599, 170-196.

Leitchenkov, G., Guseva, J., Gandyukhin, V., Grikurov, G., Kristoffersen, Y., Sand, M., Golynsky, A and Aleshkova, N., 2008. Crustal structure and tectonic provinces of the

Riiser-Larsen Sea area (East Antarctica): results of geophysical studies. Marine Geophysical Research 29, 135-158.

Mahanjane, E.S., 2012. A geotectonic history of the northern Mozambique Basin including the Beira High – A contribution for the understanding of its development. Marine and Petroleum Geology 36, 1-12.

Mahanjane, E.S., 2014. The Davie Ridge and adjacent basins in the offshore Mozambique Margin – A new insights for the hydrocarbon potential. Marine and Petroleum Geology 57, 561-571.

Marks, K.M. and Tikku, A.A., 2001. Cretaceous reconstructions of East Antarctica, Africa and Madagascar. Earth and Planetary Science Letters 186, 479-495.

Martin, A.K. and Hartnady, C.J.H., 1986. Plate tectonic development of the South West Indian Ocean: A revised reconstruction of East Antarctica and Africa. Journal of Geophysical Research 91 (B5), 4767-4786.

Müller, C.O. and Jokat, W., 2017. Geophysical evidence for the crustal variation and distribution of magmatism along the central coast of Mozambique, Tectonophysics 712-713, 684-713.

Müller, C.O., Jokat, W. and Schreckenberger, B., 2016. The crustal structure of Beira High, central Mozambique – Combined investigation of wide-angle seismic and potential field data. Tectonophysics 683, 233-254.

Nguyen, L.C., Hall, S.A., Bird, D.E. and Ball, P.J., 2016. Reconstruction of the East Africa and Antarctica continental margins. Journal of Geophysical Research: Solid Earth 121, 4156-4179.

Phethean, J.J.J., Kalnins, L.M., van Hunen, J., Biffi, P.G., Davies, R.J. and McCaffrey, K.J.W., 2016. Madagascar´s escape from Africa: A high-resolution plate reconstruction for the Western Somali Basin and implications for supercontinent dispersal. Geochemistry, Geophysics, Geosystems 17, 5036-5055.

Rabinowitz, P.D., Coffin, M.F., and Flavey, D., 1983. The separation of Madagascar and Africa. Science 220, 67-69.

Reeves, C.V., Teasdale, J.P. and Mahanjane, E.S., 2016. Insight into the Eastern Margin of Africa from a new tectonic model of the Indian Ocean. From: Nemcok, M., Rybár, S., Sinha, S.T., Hermeston, S.A. and Ledvényiová, L. (eds). Transform margins: Development, Controls and Petroleum Systems. Geological Society, London, Special Publications 431.

Reeves, C., 2014. The position of Madagascar within Gondwana and its movements during Gondwana dispersal. Journal of African Earth Sciences 94, 45-57.

Roeser, H.A., Fritsch, J. and Hinz, K., 1996. The development of the crust of Dronning Maud Land, East Antarctica. From: Storey, B.C., King, E.C. and Livermore, R.A. (eds), 1996. Weddell Sea Tectonics and Gondwana Break-up. Geological Society Special Publication 108, 243-264.

Saki, T., Tamura, Y., Tokuhashi, S., Kodato, T., Mizukoshi, I. and Amano, H., 1987. Preliminary report of geological and geophysical surveys off Dronning Maud Land, East Antarctica. Proceedings of the Nat Inst Polar Res (NIPR) Symposium: Ant. Geoscience 1, 23-40, Tokio.

Salman, G. and Abdula, I., 1995. Development of the Mozambique and Ruvuma sedimentary basins, offshore Mozambique. Sedimentary Geology 96 (1–2), 7-41.

Segoufin, J., 1978. Anomalies magnétiques mésozoiques dans le bassin de Mozambique. C. R. Acad. Sci. D 287, 109-112.

Segoufin, J., and Patriat, P., 1980. Existence d'anomalies mesozoiques dans le bassin de Somalie. Implications pour les relations Afrique-Antarctique-Madagascar. C.R. Acad. Sci. Paris 291, 85-88.

Simpson, E.S.W., Sclater, J.G., Parsons, B., Norton, I., Meinke, L., 1979. Mesozoic magnetic lineations in the Mozambique Basin. Earth Planet. Sci. Lett. 43, 260–264.

Smith, A.G. and Hallam, A., 1970. The fit of the Southern Continents. Nature 225, 139-144.

Torsvik, T.H., and Cocks, L.R.M., 2013. Gondwana from top to base in space and time. Gondwana Research 24, 999-1030.

White, R.S., McKenzie, D. and O´Nions, R.K., 1992. Oceanic crustal thickness from seismic measurements and rare earth element inversions. Journal of Geophysical Research 97 (B13), 19683-19715.

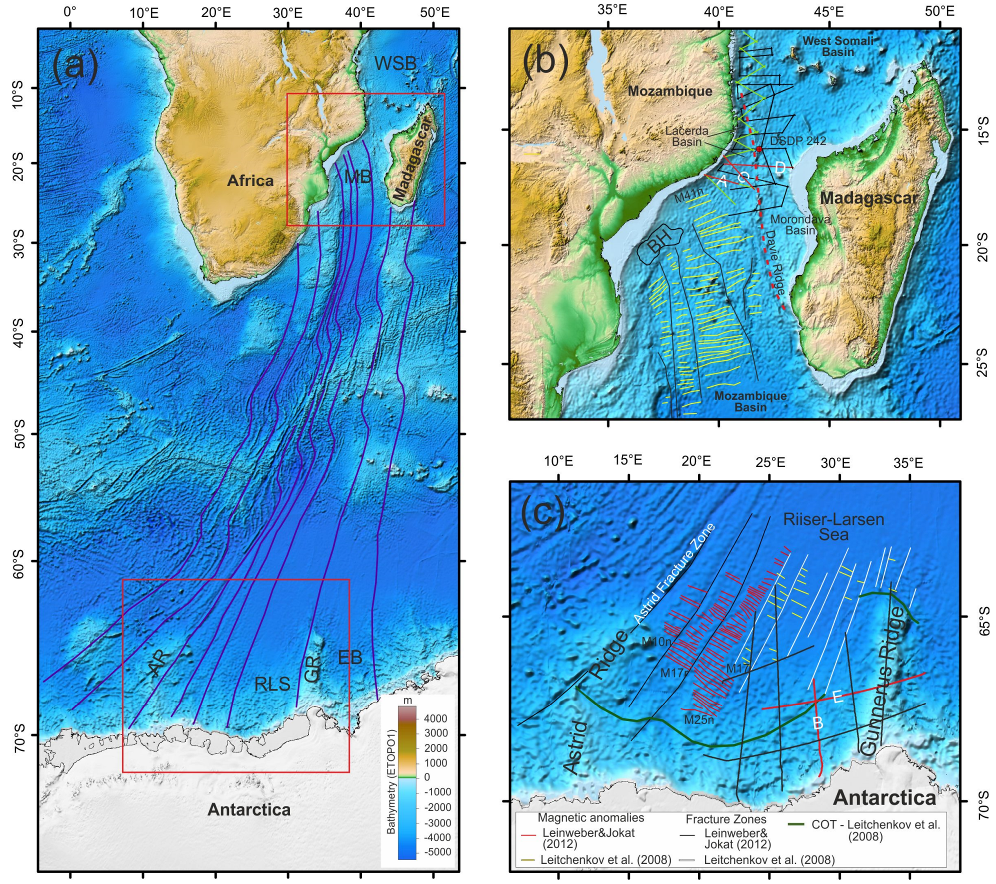

FIGURE 1: A) Bathymetric map of the Africa-Antarctic corridor. The purple flow lines indicate the motion between Africa and Antarctica according to Eagles and König (2008). Red boxes indicate the study area in the Mozambique Basin and the Riiser-Larsen Sea. AR= Astrid Ridge, EB= Enderby Basin, GR= Gunnerus 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 (Figs. 2A, 4 and 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 (Figs. 2B and 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.

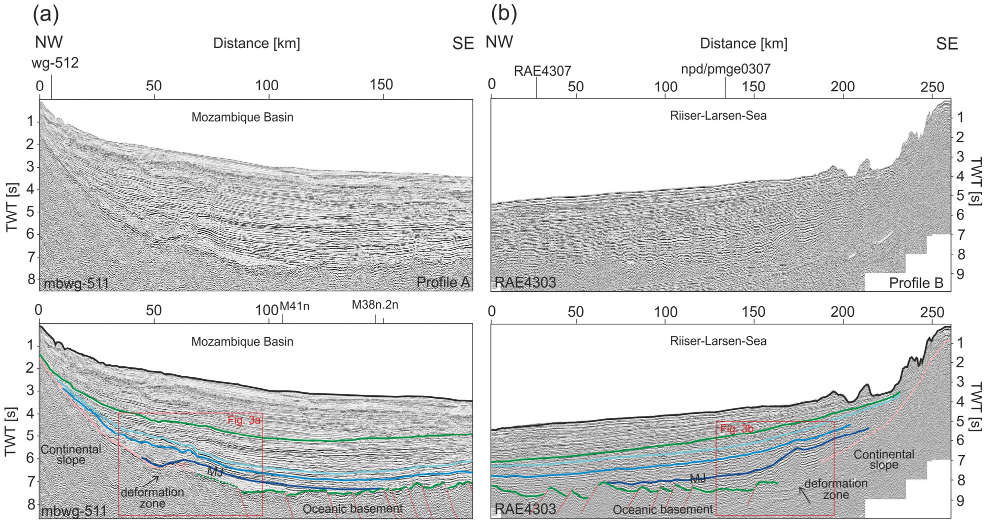

FIGURE 2: Migrated profile Mbwg00-511 in the Mozambique Basin (A) and stacked profile RAE4303 in the Riiser-Larsen Sea (B) (line locations in Fig. 1). In the lower panels, the stratigraphic interpretation according to Castelino et al. (2015), Leitchenkov et al. (2008) and Mahanjane (2014) is presented. At the foot of the continental slope, at the continent-ocean transition, a 20-30 km wide zone of deformed and fractured basement is distinct. Postrift sediments, overlying the deformation zone have been affected by the deformation. This deformation zone is proposed as tie-point for Gondwana reconstructions.

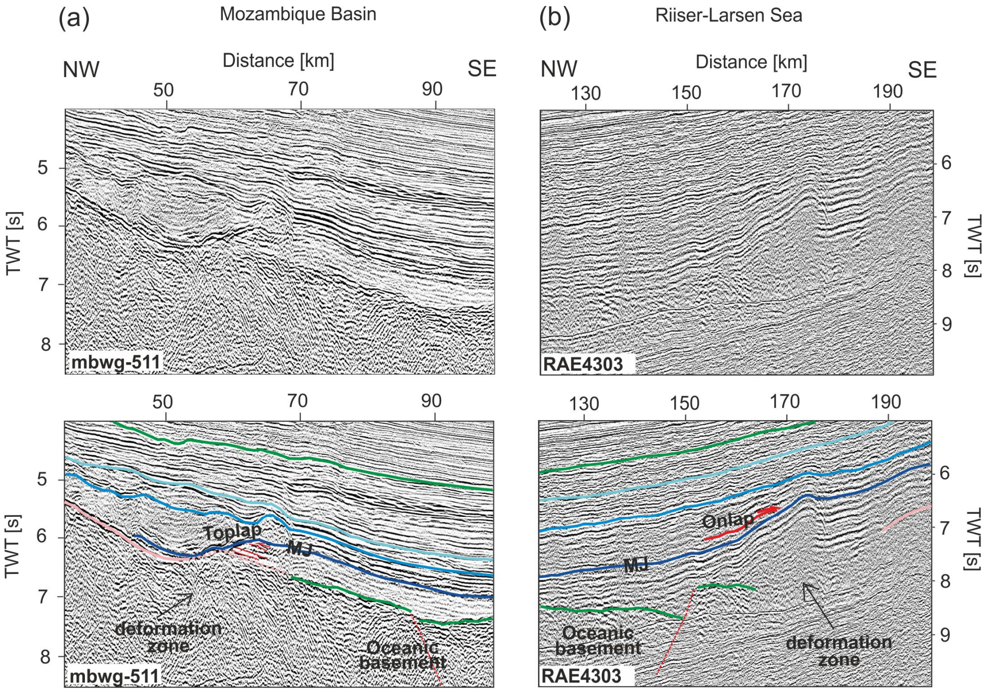

FIGURE 3: Close-up view of the zone of deformed basement in the Mozambique Basin (A) and Riiser-Larsen Sea (B) presented in Fig. 2. The lower panels show the interpreted sections of the profiles. The basement is distinctively deformed and fractured. Overlying postrift sediments are deformed and indicate toplap (A) and onlap (B) geometries. Unconformity MJ seals the deformation.

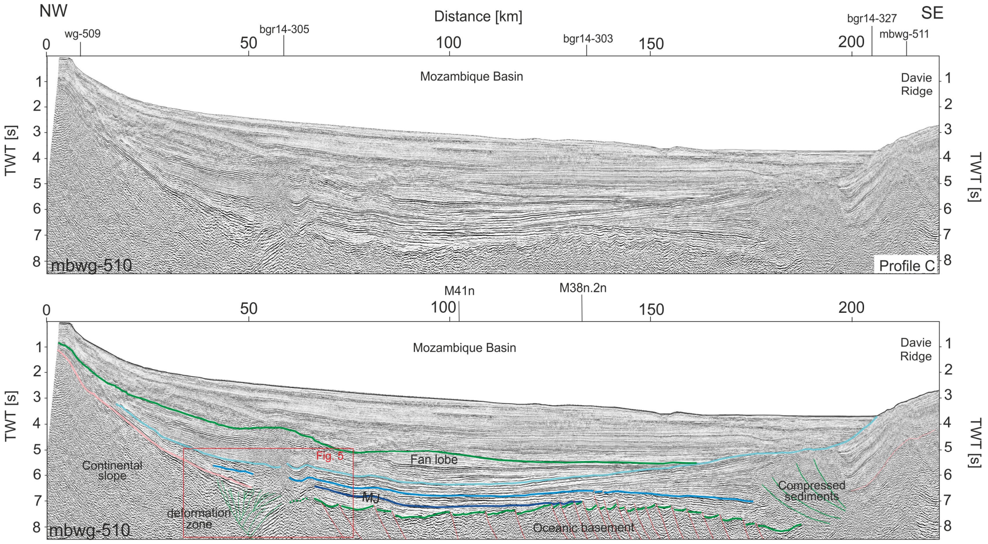

FIGURE 4: Migrated section of profile Mbwg00-510 (line location in Fig. 1). The lower panel shows the section overlain by the stratigraphic interpretation according to Castelino et al. (2015), Franke et al. (2015) and Mahanjane (2014). The profile runs from the continental slope to the Davie Ridge offshore Madagascar. The zone of deformed basement is observed at the foot of the continental slope. 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.

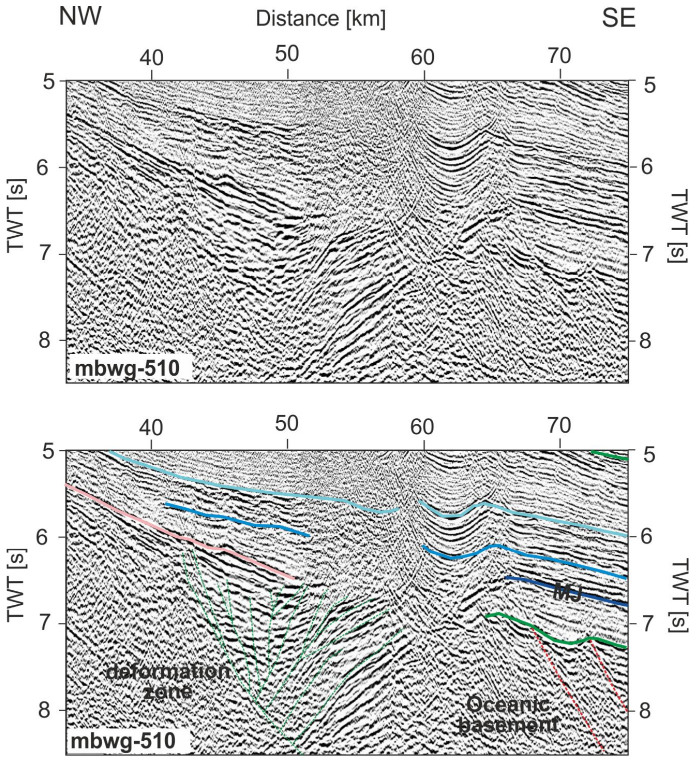

FIGURE 5: Close-up view of the zone of deformed basement in the Mozambique Basin presented in Fig. 4. The lower panel shows the interpreted section of the profile. The basement is deformed by steeply dipping, fan-like normal faults that at depths may converge into a single, subvertical fault (green, distance: 40-60 km). The deformation is likely dominated by extensional stress.

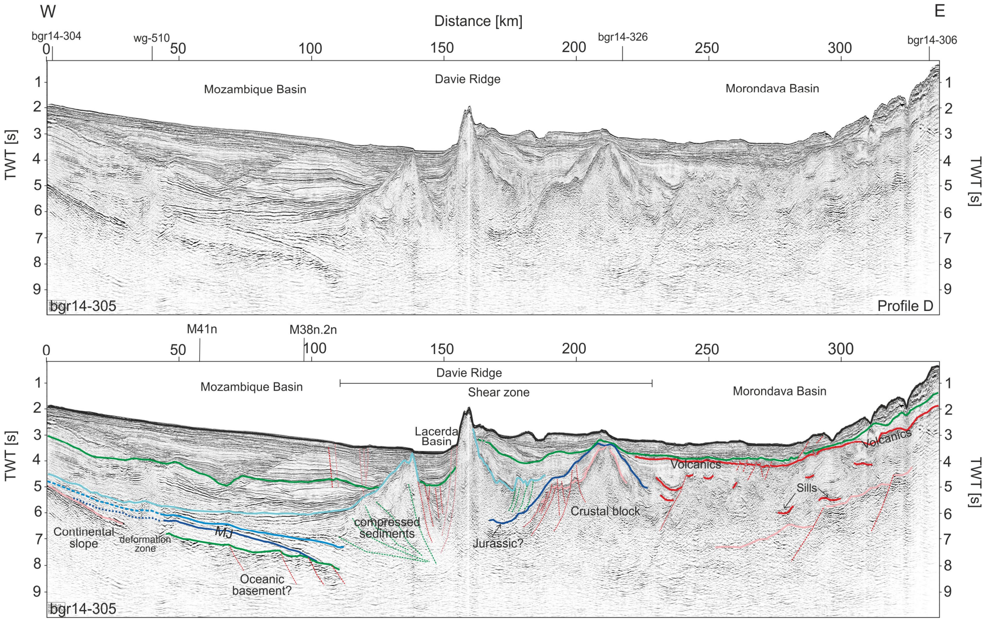

FIGURE 6: Pre-stack migrated section of profile BGR14-305 (line location in Fig. 1). The lower panel shows the interpreted section according to the seismostratigraphic concepts of Castelino et al. (2015), Franke et al. (2015), Klimke et al. (2016) and Mahanjane (2014). The profile runs from the continental 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.

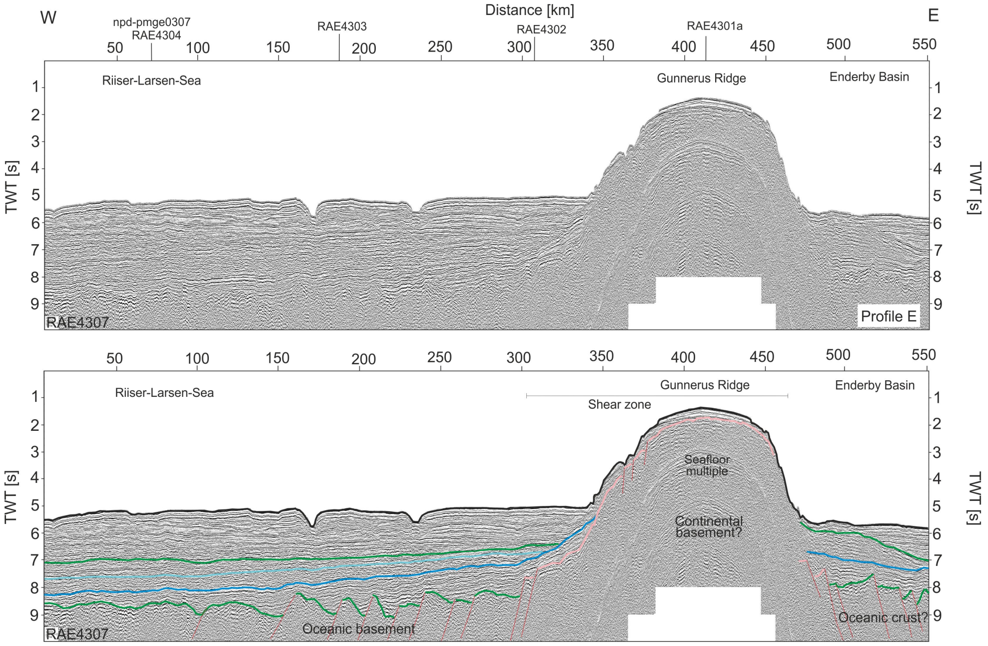

FIGURE 7: Stacked section of profile RAE4307 (line location in Fig. 1). The lower panel shows the interpreted section of the profile with the stratigraphy according to Leitchenkov et al. (2008). The profile runs from the Riiser-Larsen Sea across the Gunnerus Ridge into the Enderby Basin. The Gunnerus 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.

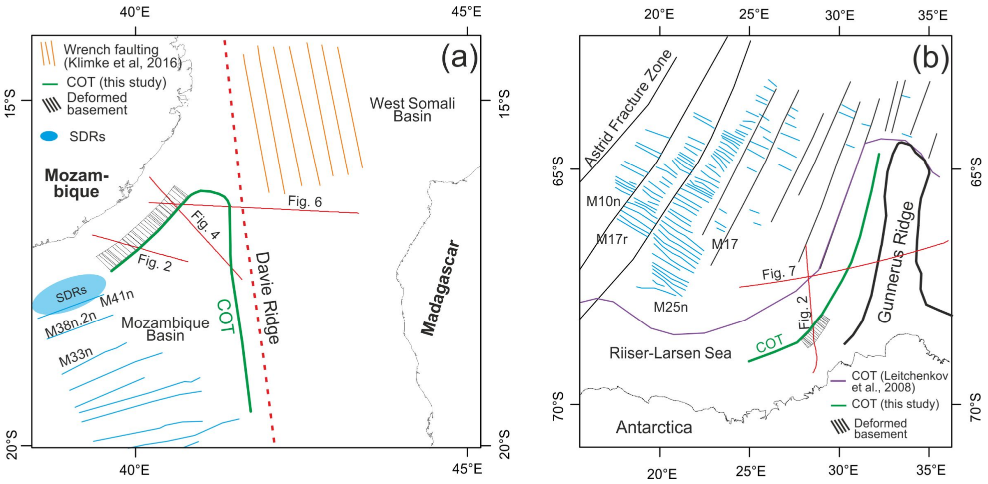

FIGURE 8: Sketch map illustrating the location of the deformed basement observed at the foot of the continental slope in the Mozambique Basin (A) and the Riiser-Larsen Sea (B). Red lines indicate the location of Profiles A to E (Figs. 2, 4, 6 and 7). Blue and black lines highlight magnetic anomalies 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).

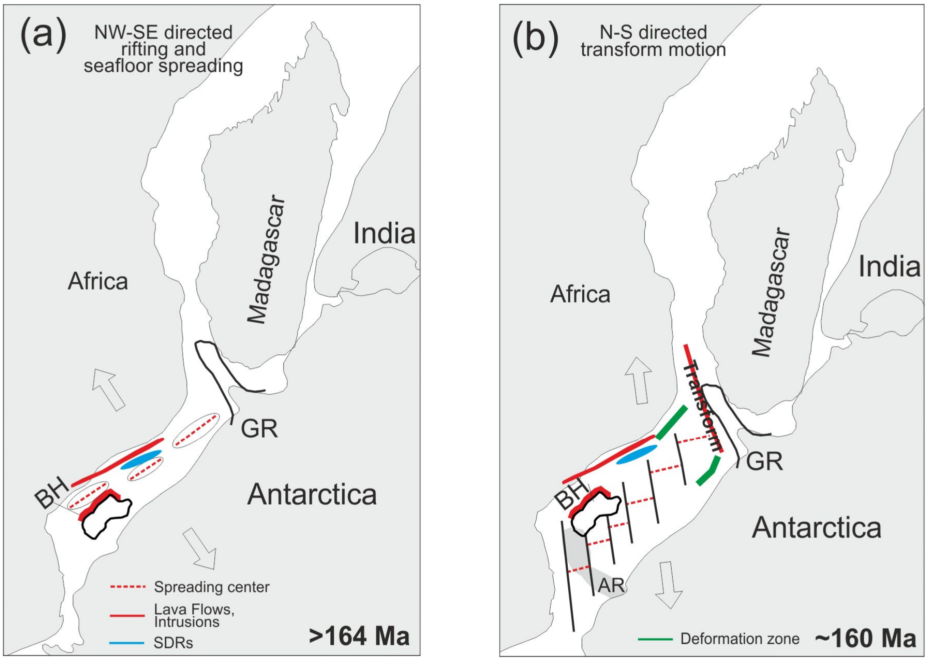

FIGURE 9: Schematic sketch of the initial opening of the Mozambique Basin/Riiser-Larsen Sea. A) In the Middle Jurassic, NW-SE directed rifting and seafloor spreading between Africa and Antarctica initiates with the possible formation of localized spreading centers close to the present-day shoreline. 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 oriented 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.