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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 East Gondwana dispersal are poorly constrained, and there is debate about conjugate geologic structures and the timing and directions of the rifting and earliest seafloor spreading phases. We present a combined structural interpretation of multichannel reflection seismic profiles from offshore of 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 close to the continent–ocean transition, the basement is intensely deformed and fractured, a structural style very untypical for rifted continental margins. Sediments overlying the fractured basement are deformed and reveal toplap and onlap geometries, indicating a post-breakup deformation phase. We propose this unique deformation zone as a tie point for Gondwana reconstructions. Accordingly, we interpret the western flank of Gunnerus Ridge, Antarctica as a transform margin similar to the Davie Ridge offshore of Madagascar, implying that they are conjugate features. As the continental slope deformation is post-rift, we propose a two-phase opening scenario. A first phase of rifting and early seafloor spreading, likely in NW–SE direction, was subsequently replaced by a N–S-directed transform deformation phase overprinting the continent–ocean transition. From previously identified magnetic chrons and the sediment stratigraphy, this change in the spreading directions from NW–SE to N–S is suggested to have occurred by the late Middle Jurassic. 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 pre-rift 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 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 the immediate vicinity. In the Mozambique Basin, the transition from the SW–NE-trending rifted margin to the N–S-trending transform margin along the

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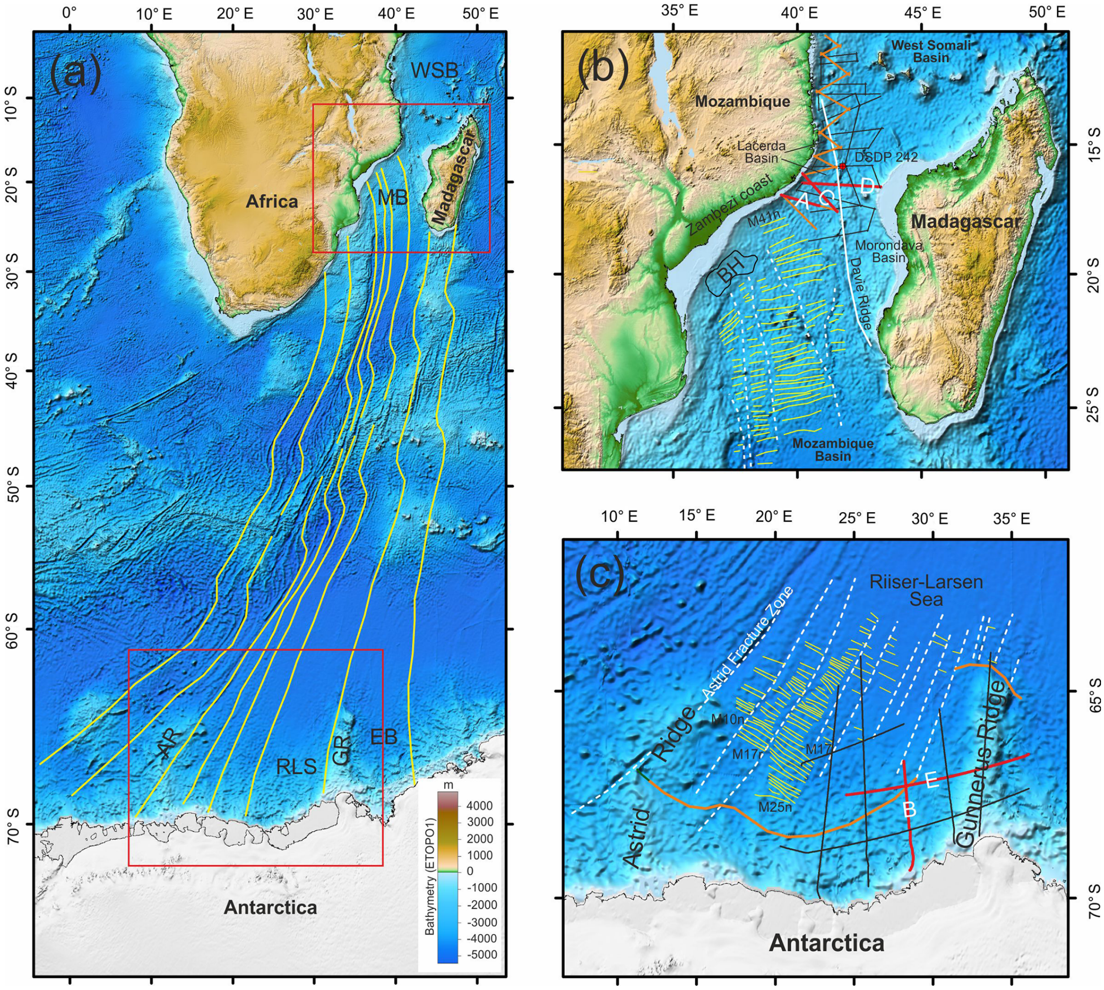

Figure 1. Bathymetric map of the Africa–Antarctic corridor, the Mozambique Basin and the Riiser-Larsen Sea (ETOPO1 1 arcmin global relief model; Amante and Eakins, 2009). **(a)** The yellow flow lines indicate the motion between Africa and Antarctica according to Eagles and König (2008). Red boxes indicate 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)** Black and orange 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 the Beira High is from Mahanjane (2012). Magnetic isochrons (yellow lines) and oceanic fracture zones (dashed white lines) are compiled from Leinweber and Jokat (2012) and Müller and Jokat (2017). The location of Davie Ridge is marked with a solid white line. BH: Beira High. **(c)** 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 isochrons (yellow) and fracture zones (dashed 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 a thick orange line.

Davie Ridge (Fig. 1) remains poorly studied. Existing studies focus mostly on the sedimentary infill of the Mozambique Basin (e.g., Castelino et al., 2015; Mahanjane, 2014; Salman and Abdula, 1995) or 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 new and previously published multichannel reflection seismic profiles from different datasets. We concentrate on offshore Mozambique (East Africa) in the vicinity of the Davie Ridge and the conjugate Riiser-Larsen Sea (Antarctica) at the transition from the rifted margin to the Gunnerus Ridge (Fig. 1) and compare the structural configuration of the basement and the earliest post-rift sediments.

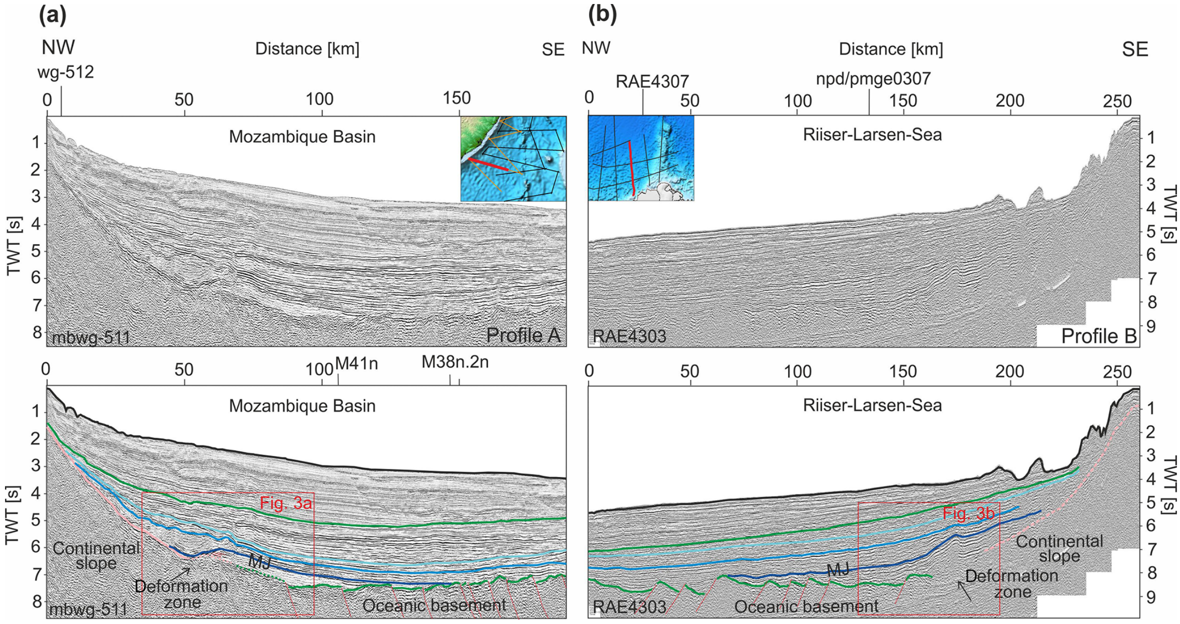

Figure 2. Migrated profile Mbwg00-511 in the Mozambique Basin **(a)** and stacked profile RAE4303 in the Riiser-Larsen Sea **(b)** (line locations in inset maps and Fig. 1). In the lower panels, the stratigraphic interpretation according to Castelino et al. (2015), Leitchenkov et al. (2008) and Mahanjane (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. Post-rift sediments overlying the deformation zone have been affected by the deformation. This deformation zone is proposed as a tie point for Gondwana reconstructions.

The main outcome of this study is the identification of a zone of deformed and faulted basement at the foot of the continental slope at both margins. The sediments overlying the deformation zone are deformed, revealing a post-breakup deformation phase. We provide evidence that these unique structures can serve as a tie point for Gondwana reconstructions. This leads to a two-phase opening scenario for the conjugate Mozambique Basin and Riiser-Larsen Sea.

1.1 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). It is generally accepted that the breakup of Gondwana along the East African margin 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; Reeves et al., 2016). While earlier studies proposed that the Mozambique Basin and West Somali Basin opened in a generally N–S direction, more recent plate tectonic reconstructions argue for an almost simultaneous opening of both basins in the NW–SE direction (e.g., Gaina et al., 2013; Reeves et al., 2016). There is also debate about the timing and directions of the earliest rifting and spreading phases. A change in the spreading direction has been suggested to have occurred at ∼ 159 Ma (Leinweber and Jokat, 2012), ∼ 153 Ma (Reeves et al., 2016) or ∼ 150 Ma (Phethean et al., 2016).

Oceanic crust generated by seafloor spreading between Africa and Antarctica has been dated by the identification of marine magnetic anomalies. Recent studies, using new geophysical data, tentatively identify M41n (∼ 165 Ma; Leinweber and Jokat, 2012) or M38n.2n (∼ 164 Ma; Müller and Jokat, 2017; magnetic polarity timescale of Ogg, 2012) as the oldest magnetic anomaly in the Mozambique Basin. This makes the Mozambique Basin and the Riiser-Larsen Sea considerably older than proposed 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). There is general agreement that 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).

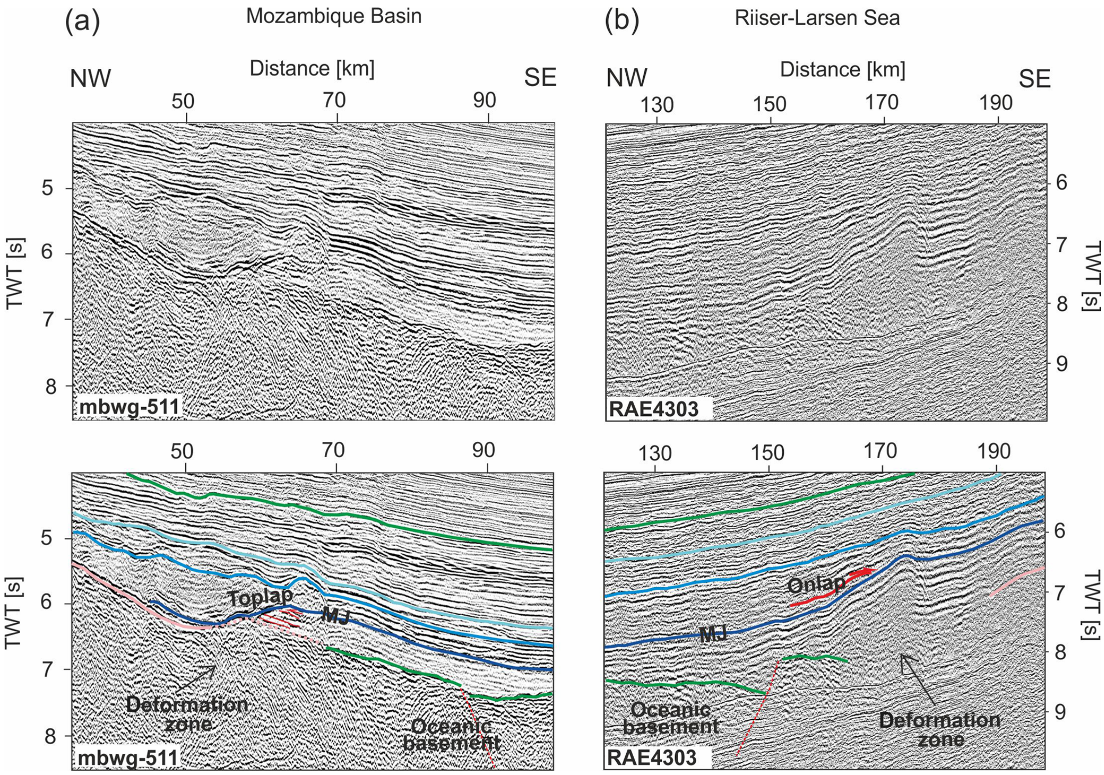

Figure 3. Close-up view of the zone of deformed basement in the Mozambique Basin **(a)** and Riiser-Larsen Sea **(b)** presented in Fig. 2. The lower panels show the interpreted sections of the profiles. The basement is distinctively deformed and faulted. Overlying post-rift sediments are deformed and indicate toplap **(a)** and onlap **(b)** geometries. Unconformity MJ, with an inferred age at the transition from the Middle to Late Jurassic, seals the deformation. Blue sedimentary horizons indicate Late Jurassic and Middle Cretaceous strata; the green horizon near the top is Late Cretaceous.

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

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 and Antarctica with respect to Africa. This transform is thought to have been active from the late Middle Jurassic ($\sim$ 160–165 Ma) to the Early Cretaceous ($\sim$ 125–135 Ma; e.g., Coffin and Rabinowitz, 1987; Segoufin and Patriat, 1980). Although the presence of a transform continental margin and its expression, the Davie Ridge, has been questioned in the West Somali Basin (Klimke and Franke, 2016), offshore of west Madagascar this structure is obvious. The Gunnerus Ridge in the Riiser-Larsen Sea may be the prolongation of the shear zone offshore of 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 $km\,s^{-1}$ 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). Both structural interpretation (Mahanjane, 2012) and seismic velocities derived from refraction seismic data (Müller et al., 2016) indicate that the 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.

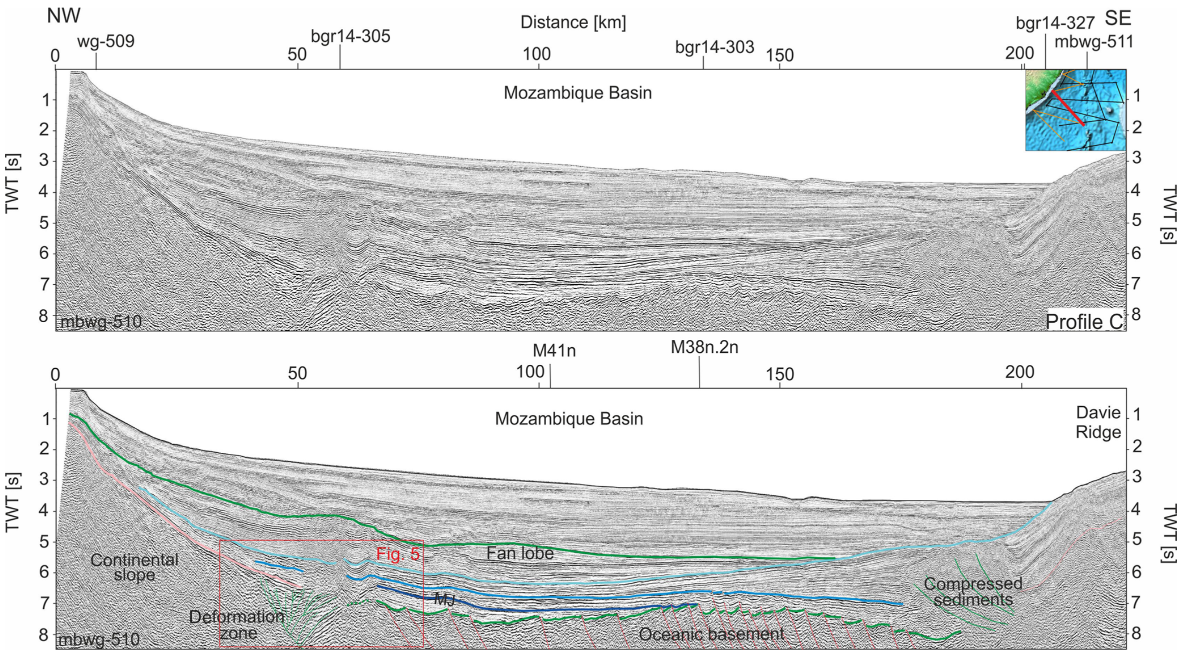

Figure 4. Migrated section of profile Mbwg00-510 (line location in inset map and Fig. 1). The lower panel shows the section overlain by the stratigraphic interpretation according to Castelino et al. (2015), Franke et al. (2015) and Mahanjane (2014). The profile runs from the continental slope to the Davie Ridge offshore of 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.

2 Materials and methods

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 a yet unpublished profile striking E–W, crossing the Mozambique Basin into the Morondava Basin offshore of 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 has recently been presented by Mahanjane (2014). Here, we present one previously published profile (Mahanjane, 2014) with a focus on the continental slope and additionally show one previously unpublished profile of this dataset. Our interpretation of the sedimentary successions is based on 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 the Polar Marine Geosurvey Expedition during a survey with the R/V *Akademik Alexander Karpinsky* in 1998. For a detailed description of the equipment used, 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).

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 (Figs. 2 and 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, 7 and 8) are oriented in the E–W direction, crossing the Davie Ridge and Gunnerus Ridge, respectively.

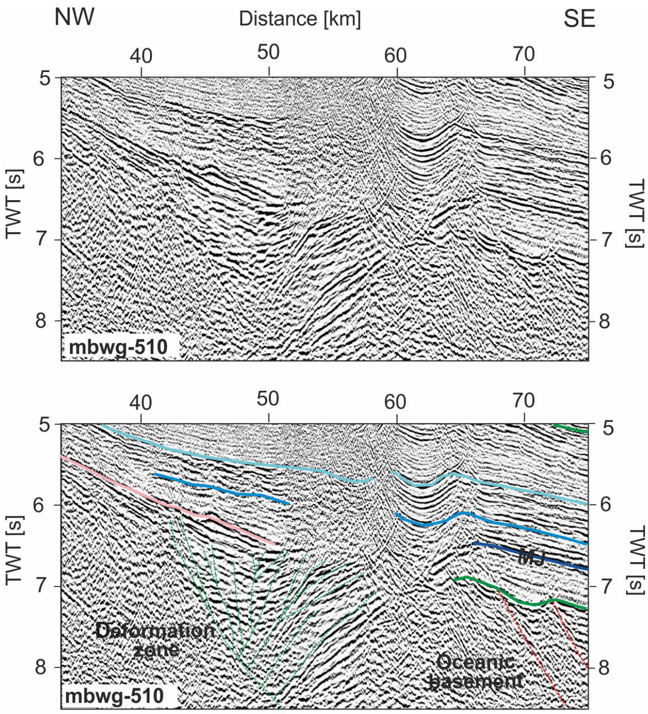

Figure 5. Close-up view of the zone of deformed basement in the Mozambique Basin presented in Fig. 4. The lower panel shows the interpreted section of the profile. The basement is deformed by steeply dipping, fan-like normal faults that at depths converge into a single, subvertical fault (green, profile distance: 40–60 km). The overall geometry of the deformation resembles a negative flower structure. Unconformity MJ has an inferred age at the transition from the Middle to Late Jurassic and the blue sedimentary horizons indicate Late Jurassic and Middle Cretaceous strata.

3 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 (Fig. 2a) and ∼ 5° in the Riiser-Larsen Sea (Fig. 2b). The top basement reflection is clearly imaged below the slopes and increases in depth from ∼ 1 s (TWT) to ∼ 7 s (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 continental basement on both continental margins (Fig. 2a, offset range: 50–70 km; Fig. 2b, offset range: 160–190 km). In the deformed zone, the basement is intensely faulted over distances of about 30 km (Fig. 2). On Profile A (Fig. 3a), the basement is uplifted by apparent high-angle reverse faulting and the sedimentary cover is folded at the tip of the main fault strands. Internal horizons are heavily deformed and dissected by faults (Fig. 3a; offset range: 50–70 km). The unconformity MJ seals the deformation, which according to our seismostratigraphic concept has an age of the transition from the Middle to the Late Jurassic. The sedimentary unit underlying horizon MJ is characterized by subparallel reflectors with low amplitudes. The seismic transparency of this unit allows for a clear along-margin distinction from younger, reflective deposits (Fig. 2).

The same kind of deformation is identified on the conjugate continental slope in the Riiser-Larsen Sea (Figs. 2b and 3b, offset range: 160–190 km). Again, the basement is dissected by high-angle faults at the foot of the continental slope. A similar package of post-rift sediments is affected by folding to form a gentle anticline, altogether resembling the observed deformation pattern in the Mozambique Basin (Figs. 2a and 3a). The overall geometries resemble positive flower structures developed along strike-slip faults (e.g., Harding, 1985, 1990; Sylvester, 1988; Figs. 2 and 3).

Further northeast in the Mozambique Basin (Fig. 4), the basement deformation is characterized by steep and very closely spaced faults (Fig. 4, offset range: 40–50 km). Faulting increases towards the SE (Fig. 5, offset range: 50–60 km) where internal reflections have been heavily deformed and rotated to form gentle synclines. In contrast to the area further west at the continental slope of the Mozambique margin, which is characterized by compressional deformation (Fig. 2), the horizontal component of motion across the faults in the SE (Fig. 5) is extensional, and the overall geometry resembles negative flower structures (Harding, 1985, 1990; Sylvester, 1988). Profile D in the Mozambique Basin (Fig. 6) shows that the basement is transparent in the deformed zone (profile distance: 25–45 km), possibly due to intense faulting.

Seaward of the deformation zone along both continental 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, 7 and 8). Locally, closely spaced diffractions are distinct (Figs. 2, 4, 6, 7 and 8), both features being 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 modeling by Leinweber et al. (2013), refraction seismic experiments supported by the 2-D magnetic modeling of Müller and Jokat (2017) and magnetic anomaly identifications by Leinweber and Jokat (2012) and Müller and Jokat (2017) in the Mozambique Basin. Normal faults dissecting the oceanic crust with throws of ∼ 250 ms (TWT) in the Mozambique Basin (Figs. 2a and 4) and up to ∼ 1 s (TWT) in the Riiser-Larsen Sea (Figs. 2b, 7 and 8) are distinct. The faults are spaced at 5–15 km (Fig. 2a, offset range: 90–190 km; Fig. 4, offset range: 70–180 km; Fig. 6, offset range: 70–100 km) and 10–40 km (Fig. 2b, offset range: 30–110 km; Fig. 7, offset range: 0–300 km), respectively. The abundance of the faults increases significantly in the vicinity of the Davie Ridge (from ∼ 15 to 5 km) and the Gunnerus Ridge (from ∼ 40 to ∼ 10 km).

At both margins, unconformity MJ, which seals the deformation, terminates seawards against oceanic crust, which likely formed during the Jurassic Magnetic Quiet Zone (Mid-

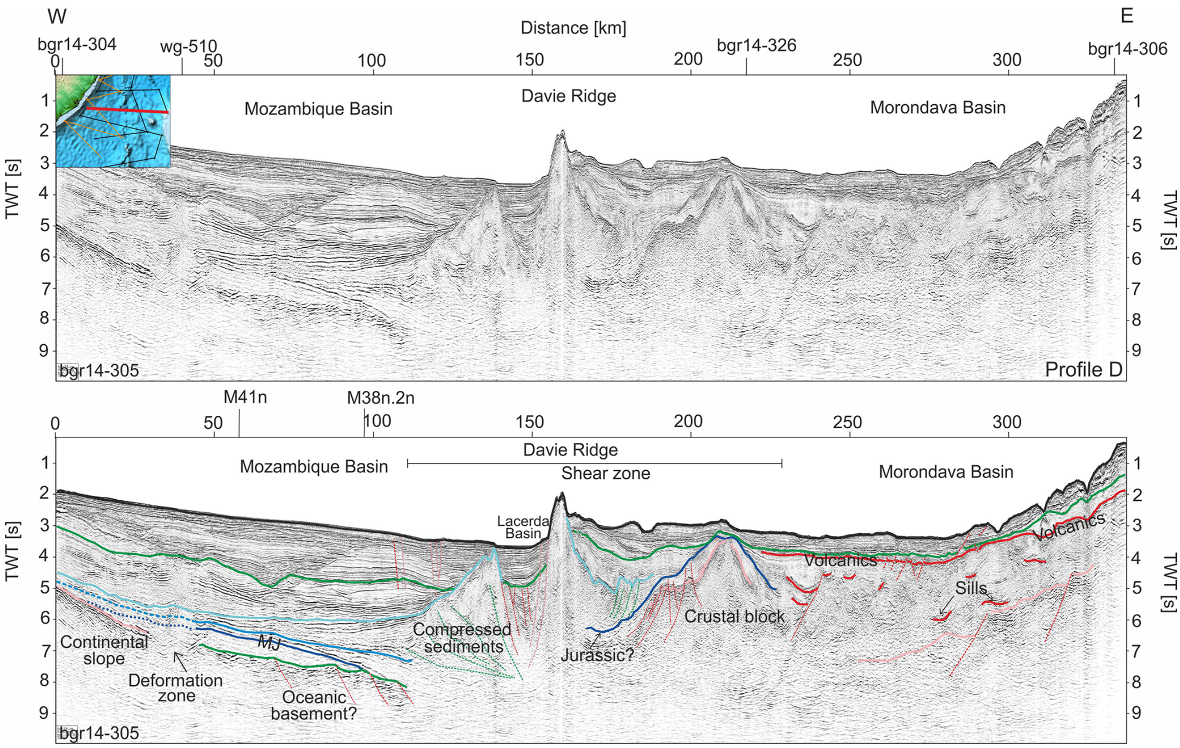

Figure 6. Pre-stack migrated section of profile BGR14-305 (line location in inset map and in Fig. 1). The lower panel shows the interpreted section according to the seismostratigraphic concepts of Castelino et al. (2015), Franke et al. (2015), Klimke et al. (2016) and Mahanjane (2014). The profile runs from the continental slope offshore of northern Mozambique across the Davie Ridge into the Morondava Basin offshore of Madagascar. The zone of deformed basement is observed at the foot of the continental slope (offset range: 30–50 km) where the basement is not imaged, which is probably due to the intense faulting of the basement. The Davie Ridge shows a clear morphological expression in the center of the profile. The shear zone, however, is much wider and, including the Davie Ridge, it is characterized by three prominent crustal blocks. Overall, the deformation zone extends over ∼ 120 km perpendicular to the shear movement. The westernmost block consists of deeply buried, compressed sediments that might have been thrusted onto the oceanic crust during southward motion of Madagascar.

dle to Late Jurassic). An extrapolation of identified magnetic anomalies (Figs. 1 and 9; Leinweber and Jokat, 2012; Müller and Jokat, 2017) to the NE Mozambique Basin (Fig. 9) indicates that the sedimentary unit below horizon MJ terminates against oceanic crust at approximately the position of magnetic anomaly M38n.2n (∼ 164 Ma). The extrapolation of the magnetic anomalies was done by noting the distance of magnetic anomaly M38n from the continent–ocean transition in the Mozambique Basin (Fig. 9). This is well in line with our stratigraphic concept and we propose that the deformation is Middle Jurassic in age and was finished at the transition from the Middle to Late Jurassic. The deformation of the earliest, likely Middle Jurassic sediments observed at both continental margins is characterized by onlap and toplap geometries in which 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, offset: 60 km). In the Riiser-Larsen Sea, the Middle Jurassic sediments have been folded upward in conjunction with the basement (Fig. 3b, offset range: 160–190 km), and subsequent, likely Late Jurassic sediments onlap the MJ horizon (Fig. 3b, profile distance: 170 km). 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, which are typical for volcanic rifted margins.

This previously identified position of the continent–ocean transition corresponds in our reflection seismic profiles to the area of the deformed basement (Figs. 2, 4, 6). Geographically, the deformed basement zone is distinct in the eastern parts of the oceanic basins close to the Davie Ridge and the Gunnerus Ridge (Fig. 9). The zone is clearly depicted on several profiles over distances of 100–200 km in the E–W direction along the margins (Fig. 9).

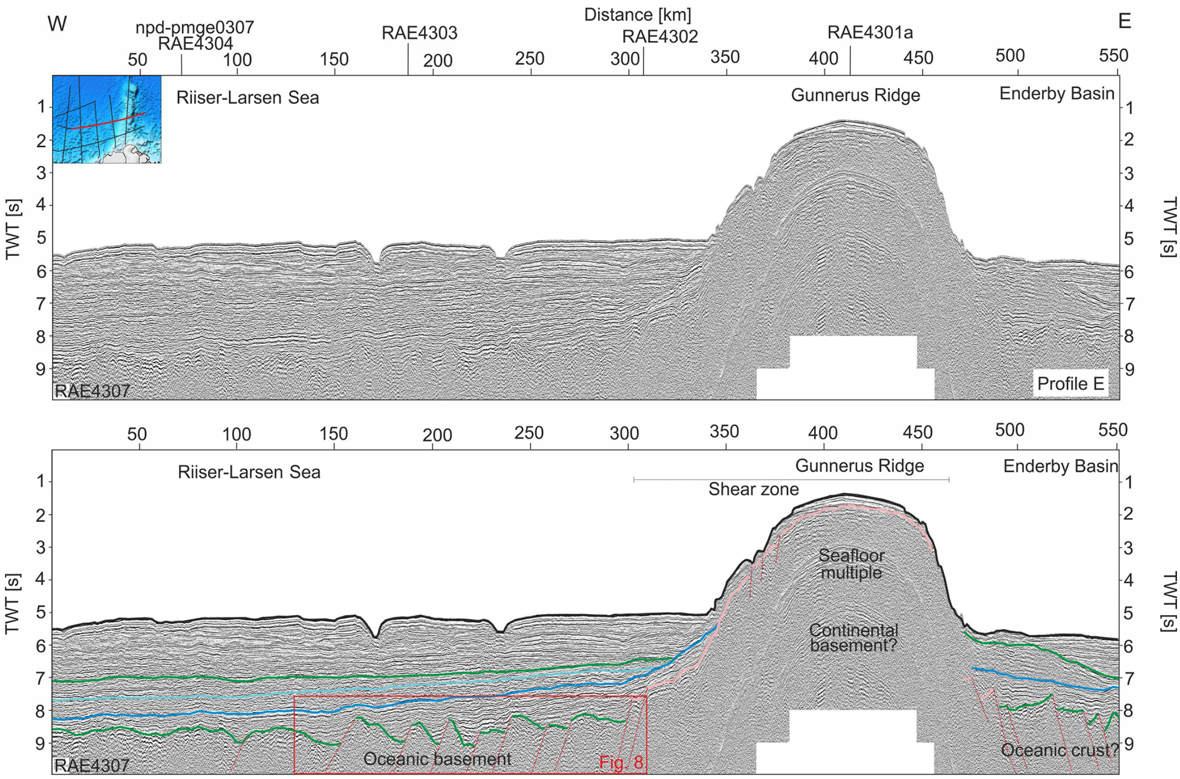

Figure 7. Stacked section of profile RAE4307 (line location in inset map and in Fig. 1). The lower panel shows the stratigraphic interpretation according to Leitchenkov et al. (2008). The profile runs from the Riiser-Larsen Sea across the Gunnerus Ridge into the Enderby Basin. The Gunnerus Ridge rises ∼ 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.

4 Discussion

4.1 Landward extent of oceanic crust

Both the Mozambique Basin and the Riiser-Larsen Sea 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 oceanic crust is interpreted, which is highly dissected by normal faults. The abundance of the faults, with throws of up to 1 s (TWT), increases towards the Davie Ridge and the Gunnerus Ridge.

At both margins, magnetic anomaly M25n (∼ 154–155 Ma) is located ∼ 250–280 km seaward of the coast (Fig. 1), which implies symmetric spreading. If the interpretation of magnetic anomaly M38n.2n (∼ 164 Ma; Müller and Jokat, 2017) is correct, oceanic crust older than ∼ 155 Ma (M25n) should also be found in the Riiser-Larsen Sea. A comparably wide strip of oceanic crust with ages of ∼ 155–166 Ma fits well in the area between magnetic anomaly M25n and the zone of deformed basement at the base of the continental slope identified here (Sect. 4). This implies a considerably more southern position of the continent–ocean transition than previously anticipated for the Riiser-Larsen Sea (Fig. 9). Gravity-modeling-derived crustal thicknesses of 5–6 km (Leitchenkov et al., 2008) are in accordance with this concept. The crustal thickness remains relatively constant west of the Gunnerus Ridge and increases from 5–6 to 10 km only near the Astrid Ridge (Fig. 16 in Leitchenkov et al., 2008). Based on these observations, we suggest relocating the continent–ocean transition in the Riiser-Larsen Sea to the zone of deformed basement at the continental slope (Fig. 9).

Along the Davie Ridge and the Gunnerus Ridge, the transition from continental to oceanic crust is abrupt. At the western flank of the Gunnerus Ridge, the continent–ocean transition is ∼ 40–50 km wide, and at the Davie Ridge it does not exceed 10–20 km. This is typical for transform continental margin settings in which the transition from continental to oceanic crust occurs over distances of not more than 50–80 km (e.g., Bird, 2001). The gravity modeling of profiles crossing the Gunnerus Ridge by Leitchenkov et al. (2008) and Roeser et al. (1996) confirm the abrupt continent–ocean transition. Thus, we propose that the western margin of Gunnerus Ridge is a transform margin similar to Davie Ridge. As the abundance of normal faults increases significantly in the vicinity of the Davie Ridge and Gunnerus Ridge (Figs. 4

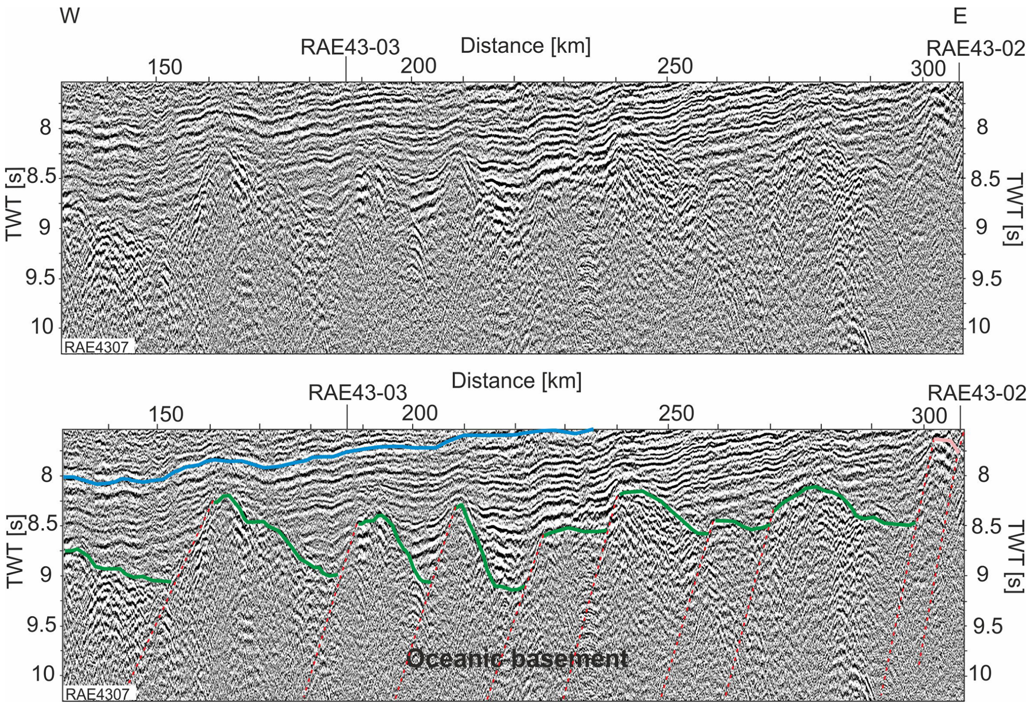

Figure 8. Close-up view of the faulted oceanic basement presented in Fig. 7 in the Riiser-Larsen Sea close to the Gunnerus Ridge. The lower panel shows the interpreted section of the profile.

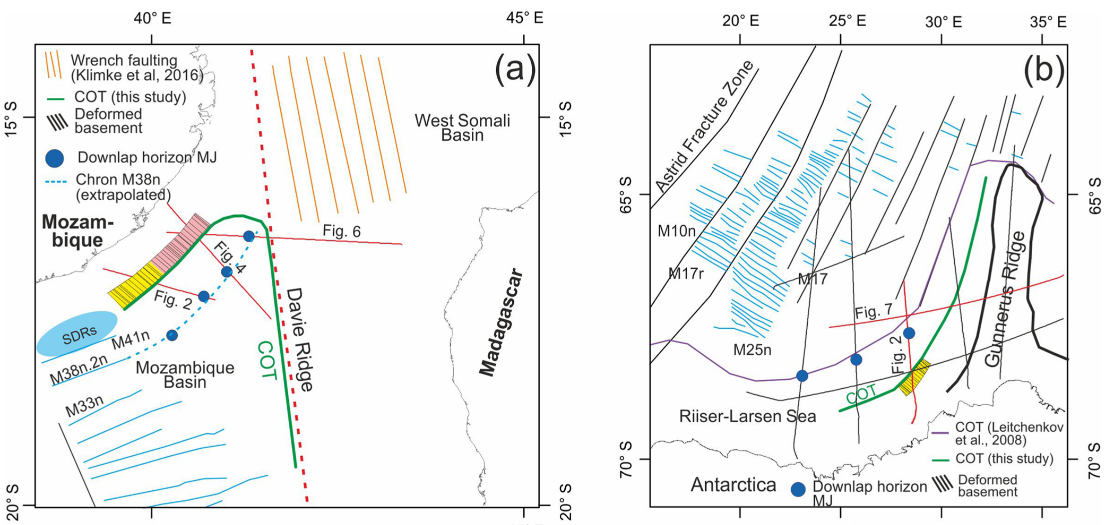

Figure 9. Sketch map illustrating the location of the deformed basement observed at the foot of the continental slope in the Mozambique Basin **(a)** and the Riiser-Larsen Sea **(b)**. Solid lines indicate the location of Profiles A to E (Figs. 2, 4, 6 and 7). Blue and black lines highlight magnetic 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. Orange lines indicate wrench faulting in the West Somali Basin (Klimke et al., 2016). Blue dots mark onlap locations of horizon MJ against oceanic basement. The dashed blue line marks the extrapolation of magnetic chron M38n (Müller and Jokat, 2017) to the study area in the Mozambique Basin. The extrapolation was done by noting the distance of magnetic chron M38n from the continent–ocean transition. Yellow and rose hatched areas mark the location of transpressional (yellow) and transtensional (rose) deformation. The location of Davie Ridge is marked with a thick dashed red line. The location of SDRs in the Mozambique Basin is compiled from Leinweber et al. (2013) and Müller and Jokat (2017).

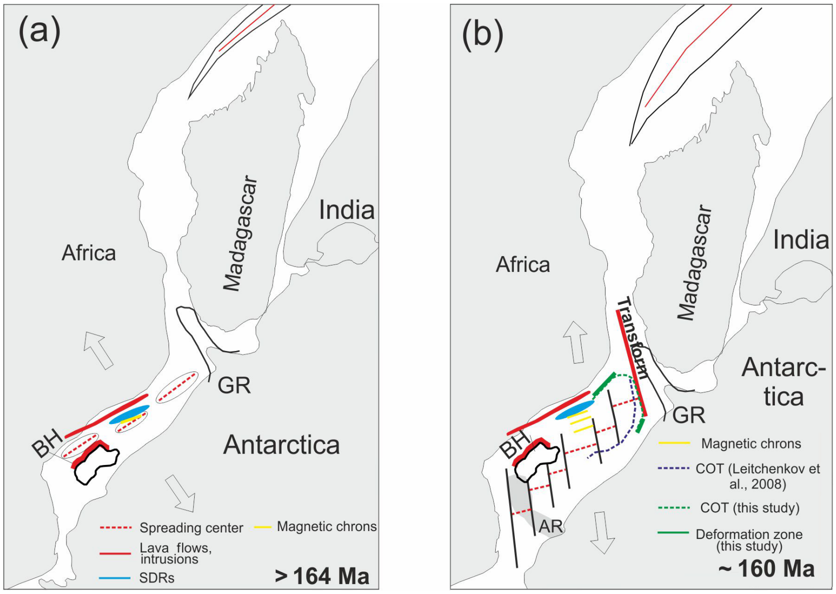

Figure 10. Schematic sketch of the initial opening of the Mozambique Basin and the Riiser-Larsen Sea. **(a)** In the Middle Jurassic, NW–SE-directed rifting and seafloor spreading between Africa and Antarctica initiates with the possible formation of localized spreading centers close to the present-day 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 and the 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 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). Magnetic chrons taken from Leinweber and Jokat (2012) and Müller and Jokat (2017). The thick green lines mark the basement deformation zone presented in this study. The dashed green line marks the continent–ocean transition (COT) of this study. The dashed purple line is the continent–ocean transition (COT) of Leitchenkov et al. (2008). SW-propagating, NW–SE-oriented oblique rifting and seafloor spreading between Madagascar and Africa according to Klimke and Franke (2016). AR: Astrid Ridge, BH: Beira High, GR: Gunnerus Ridge.

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

4.2 Implications for Gondwana breakup

As the origin of the distinct basement deformation at the continent–ocean transition in the eastern parts of both the Mozambique Basin and the Riiser-Larsen Sea, we propose intense strike-slip shearing. From the reflection seismic data, we interpret oceanic crust just seaward of the deformed basement. Thus, there was a short period of seafloor spreading preceding the N–S-directed strike-slip movement. From the orientation, this is in agreement with plate tectonic reconstructions, which propose an early and NW–SE-directed phase of rifting and seafloor spreading in the Mozambique Basin and the Riiser-Larsen Sea (e.g., Eagles and König, 2008; Gaina et al., 2013; Reeves et al., 2016), followed by a change in spreading directions from NW–SE to N–S. According to our seismostratigraphic concept, the change in spreading directions from NW–SE to N–S likely occurred in the late Middle Jurassic shortly before the formation of the sealing unconformity dated at the transition from Middle to Late Jurassic. At the latter time, seafloor spreading likely formed such a wide oceanic domain that strike-slip movements no longer affected the rifted continental margins in Mozambique and Antarctica. A change in the elongation of the early mid-oceanic ridge corresponding to the proposed variation in the spreading direction has so far not been reported. This may be difficult to identify as this early oceanic basement has been intensively deformed by subsequent shear movements. The major portion of shearing certainly occurred along the Davie Ridge and the Gunnerus Ridge, which in our view represent transform margins on their western flanks in the Mozambique Basin and the Riiser-Larsen Sea (Fig. 9). However, the reflection seismic data reveal that the shearing processes affected oceanic crust located as far as 200 km away from the main transform faults (Fig. 9), also indicating a longer-lasting process. Klimke et al. (2016) observed similar structures in extended basement to the east of Davie Ridge in the West Somali Basin (Fig. 9). The observed faults are steeply dipping wrench faults that were active during the southward movement of Madagascar along the Davie Ridge. Here, a prominent unconformity of inferred Early Cretaceous age marks the end of wrench deformation (Klimke et al., 2016).

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 the Beira High, some authors propose a rift jump during the early rifting stage from the northwestern to the southeastern edge of the Beira High (e.g., Mahanjane, 2012; Müller et al., 2016). Mahanjane (2012) observes two rift phases in reflection seismic data covering the Beira High and postulates a two-breakup-stage concept. Our observed two-phase breakup scenario (Fig. 10) 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 edge of the Beira High is associated with the change in spreading direction from the NW–SE to N–S direction, initiating the strike-slip movement of Madagascar and Antarctica (Fig. 10). However, the structure of the eastern margin of the Beira High remains elusive, and the nature of this continent–ocean transition is unclear.

Our proposed model for the initial opening of the Mozambique Basin and the 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, to the western flank of the Beira High (Fig. 10), indicating that they are conjugate features (Nguyen et al., 2016).

5 Conclusions

1. In reflection seismic profiles, we identify a symmetric zone of deformed and faulted basement at the foot of the continental slope at the continental margins of the northeastern Mozambique Basin and the conjugate eastern Riiser-Larsen Sea.

2. 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. Strike-slip shearing is proposed as the origin of the deformed continental slope.

3. Sediments overlying the basement deformation zone at the foot of the continental slope are deformed with onlap and toplap geometries, indicating a post-breakup deformation phase. For the unconformity sealing the strike-slip deformation we estimate an age at about the transition from the Middle to Late Jurassic. The structural configuration indicates a first phase of rifting and early seafloor spreading that has been subsequently overprinted by late Middle Jurassic strike-slip deformation and the formation of a transform boundary at the expense of the original continent–ocean transition.

4. From the structural configuration, the Gunnerus Ridge in Antarctica is conjugate to the Davie Ridge offshore of Mozambique and Madagascar. A major transform fault is proposed at the western margin of the Gunnerus Ridge similar to the Davie Ridge. Strike-slip deformation affected not only the rims of Davie and Gunnerus Ridge, but also the adjacent oceanic crust up to a distance of 200 km from the main transform fault. In the eastern Riiser-Larsen Sea, oceanic crust likely extends further south than previously proposed.

5. In the breakup scenario proposed here, a first and likely NW–SE-directed extensional phase resulted in localized seafloor spreading in the Mozambique Basin and the Riiser-Larsen Sea basin in the Middle Jurassic. A second late Middle Jurassic phase, likely in association with a ridge jump, initiated the generally N–S opening of the oceanic basin. The second phase represents the southward displacement of East Gondwana, with strike-slip movement of Madagascar and Antarctica against Africa and the development of transform margins along Gunnerus Ridge and Davie Ridge.

Data availability. All reflection seismic profiles of the BGR14 dataset can be accessed via Geo-Seas (http://www.geo-seas.eu). The reflection seismic dataset (RAE43) located in the Riiser-Larsen Sea has been made available through the Antarctic Seismic Data Library System (SDLS) and can be accessed via http://sdls.ogs.trieste.it/ (Antarctic Seismic Data Library System, 1998). Two profiles of the Mbwg00 dataset located in the Mozambique Channel are commercial seismic lines, the original data from which cannot be made available.

Competing interests. The authors declare that they have no conflict of interest.

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