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

Jennifer Klimke[1,*], Dieter Franke[1], Estevão Stefane Mahanjane[2] and German Leitchenkov[3, 4]

[1]Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, 30655 Hannover, Germany

[2]Institute National Petroleum (INP), Av. Fernão Magalhaes N. 34, 2nd Floor, PO Box 4724, Maputo, Mozambique

[3]All-Russia Research Institute for Geology and Mineral Resources of the World Ocean, 1 Angliysky Ave, St. Petersburg 190121, Russia

[4]St.-Petersburg State University, 13B Universitetskaya Emb., St. Petersburg, 199034, Russia

*Corresponding author now at: University of Hamburg, Bundesstraße 55, 20146 Hamburg; Tel.: +49 40 42838 9466; Jennifer.Klimke@uni-hamburg.de; Jennifer.Klimke@gmx.net

ABSTRACT

Movements within early East Gondwana dispersal are poorly constrained and there is uncertainty about the position of the continent-ocean transition and the timing and directions of the rifting and earliest seafloor spreading phases. Here, 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 the Davie Ridge offshore 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 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 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. In the Mozambique Basin, the transition from the SW-NE trending rifted margin to the N-S trending transform margin along the 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 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 new and 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). We compare the structural configuration of the basement and the earliest postrift sediments.

The main outcome of this study is 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, revealing 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). It is generally accepted that 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

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. The change of 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. A recent study, using new geophysical data, tentatively identifies 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/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).

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).

2.2 ENIGMATIC CRUSTAL BLOCKS IN THE MOZAMBIQUE BASIN AND 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/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 (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). 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 a yet unpublished 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 has recently been presented by Mahanjane (2014). Here, we present one previously published profile (Mahanjane, 2014) with the focus on the continental slope and additionally show one previously unpublished profile of this dataset. For the interpretation of the sedimentary successions, we base 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 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, 7 and 8) are oriented in E-W direction, crossing the Davie Ridge and Gunnerus Ridge, respectively.

In the following, we present a structural interpretation of the continent-ocean transition at both continental margins (section 4.1) (Figs. 2-8), with a special emphasis on the timing of the deformation observed at the foot of the continental slope (section 4.2). Finally, we discuss implications on opening scenarios for the Mozambique Basin/Riiser-Larsen Sea (section 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 (Figs. 2A and 4) and ~5° in the Riiser-Larsen Sea (Fig. 2B). The top basement reflection is clearly imaged below the slopes and increases in depth 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 about 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). The same kind of deformation is identified on the conjugate continental slope in the Riiser-Larsen Sea (Figs. 2B and 3B; distance: 160-190 km). Again, the basement is dissected by faults and has been folded at the foot of the continental slope. A similar package of post-rift sediments is included in the folds, altogether resembling the observed deformation pattern in the Mozambique Basin (Figs. 2A and 3A). The origin of the basement deformation is interpreted as strike-slip faults that form positive flower structures (Fig. 2 and Fig. 3).

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 at the continental slope of the Mozambique margin, which is characterized by compressional deformation (Fig. 2), the deformation in the SE (Fig. 5) seems to be dominated by extensional stress, forming negative flower structures. Profile D in the Mozambique Basin (Fig. 6) shows that the basement is transparent in the deformed zone (distance: 25-45 km), possibly due to intense faulting.

Geographically, the deformed basement zone is distinct in the eastern parts of the 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 E-W direction along the margins (Fig. 9).

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, 7 and 8). Locally, closely spaced diffractions are distinct (Figs. 2, 4, 6 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 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. Normal faults dissecting the oceanic crust with throws of ~250 ms (TWT) in the Mozambique Basin (Fig. 2A, 4) and up to ~1s (TWT) in the Riiser-Larsen Sea (Fig. 2B, 7 and 8) 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).

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.

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).

4.2 TIMING OF THE DEFORMATION

At both conjugate margins, sedimentary successions overlying the basement have been affected by the deformational event (Figs. 2 and 3). According to our seismostratigraphic concept, the top of the deformed sediments (horizon "MJ") is of Middle Jurassic age. The sedimentary unit underlying horizon MJ is characterized by subparallel reflectors with low amplitudes. The seismic transparency of this unit allows a clear along-margin distinction from younger, reflective deposits (e.g. Fig. 4). At both margins, Horizon MJ is terminating seawards against oceanic crust, which likely formed during the Jurassic Magnetic Quiet Zone (Middle to the Late Jurassic) (Fig. 2A, distance: 150 km; Fig. 2B, distance: 60 km; Fig. 4, distance: 125 km; Fig. 6, distance: 100 km). An extrapolation of identified magnetic anomalies (Figs. 1 and 9; Leinweber and Jokat, 2012; Müller and Jokat, 2017) to the study area in the Mozambique Basin (Fig. 9), indicates that the sedimentary unit below horizon MJ terminates against oceanic crust at 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. 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).

5. DISCUSSION

5.1 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 1s (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. 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 (section 4.1). This implies a considerably more southern position of the continent-ocean transition than previously anticipated for the Riiser-Larsen Sea (Fig. 9). 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. 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 shear margin settings, where the transition from continental to oceanic crust typically occurs over distances of not more than 50-80 km (e.g. Bird, 2001). Gravity modelling 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 (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

As origin of The distinct basement deformation at the continent-ocean transition in the eastern parts of both, Mozambique Basin and the Riiser-Larsen Sea we propose intense shearing. We are confident that seaward of the deformed basement oceanic crust is found. Thus, there was a short period of seafloor spreading preceding the wrenching. Shear movements affected a basement that was formed by rifting, breakup and early 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. 9). Based on the reflection seismic data, the shearing processes affected oceanic crust located as far as 100-200 km away from the main transform faults (Fig. 9). 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 faulting (U2) (Klimke et al., 2016).

With this scenario, we confirm 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. According to our seismostratigraphic concept, the change in spreading directions from NW-SE to N-S likely occurred early, at the transition from Middle to Late Jurassic. This age is derived from the seaward termination against oceanic crust at 164 Ma (M38n.2n; Müller and Jokat, 2017) of the unconformity MJ sealing the deformation.

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). 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. 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 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. 10). 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, to the western flank of Beira High (Fig. 10), indicating that they could be conjugate features (Nguyen et al., 2016).

6. CONCLUSIONS

In reflection seismic profiles we identify a symmetric zone of deformed and faulted basement at the foot of the continental slope at the margins of the northeastern Mozambique Basin and the conjugate eastern Riiser-Larsen Sea. 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 interpret strike-slip deformation as the origin of the deformed continental slope. 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. This indicates that a first phase of rifting and early seafloor spreading has been subsequently 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).

From the structural configuration, the Gunnerus Ridge is conjugate to the Davie Ridge, offshore Mozambique/Madagascar. A major transform fault is interpreted at the western margin of the Gunnerus Ridge, similar to the Davie Ridge. However, strike-slip deformation affected not only the rims of Davie and Gunnerus Ridge but also the adjacent oceanic crust. Faults, dissecting the top oceanic crust reflection are distinct with decreasing amplitude up to a distance of 100-200 km from the main transform fault.

The location of the continent-ocean transition along the Gunnerus Ridge indicates that the oceanic crust in the eastern Riiser-Larsen Sea extends further south than previously anticipated. The continent-ocean transition in Antarctica is likely located closer to the shoreline than proposed in earlier studies.

In the here proposed breakup scenario, a first, likely NW-SE directed extensional phase resulted in localized seafloor spreading in the Mozambique Basin/Riiser-Larsen Sea Basin before 164 Ma. Likely a ridge-jump at the transition from the Middle Jurassic to the Late Jurassic initiated the generally N-S opening of both oceanic basins. 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 Dieter Franke. 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.

ACKNOWLEDGEMENTS

The German Ministry for Research and Education (BMBF) funded the cruise SO231 and supported the study through grant 03G0231A. BGR staff is thanked for helping in data acquisition and processing. We thank the National Petroleum Institute of Mozambique for allowing publication of two seismic profiles of the Mbwg00 dataset. The reflection seismic dataset (RAE43) located in the Riiser-Larsen Sea has been made available through Antarctic Seismic Data Library System (SDLS).

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].

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 Pertroleum 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.

Ogg, J.G., 2012. Geomagnetic polarity time scale. In: Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G. (Eds.). The Geologic Time Scale 2012. Elsevier, pp. 731-791.

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.

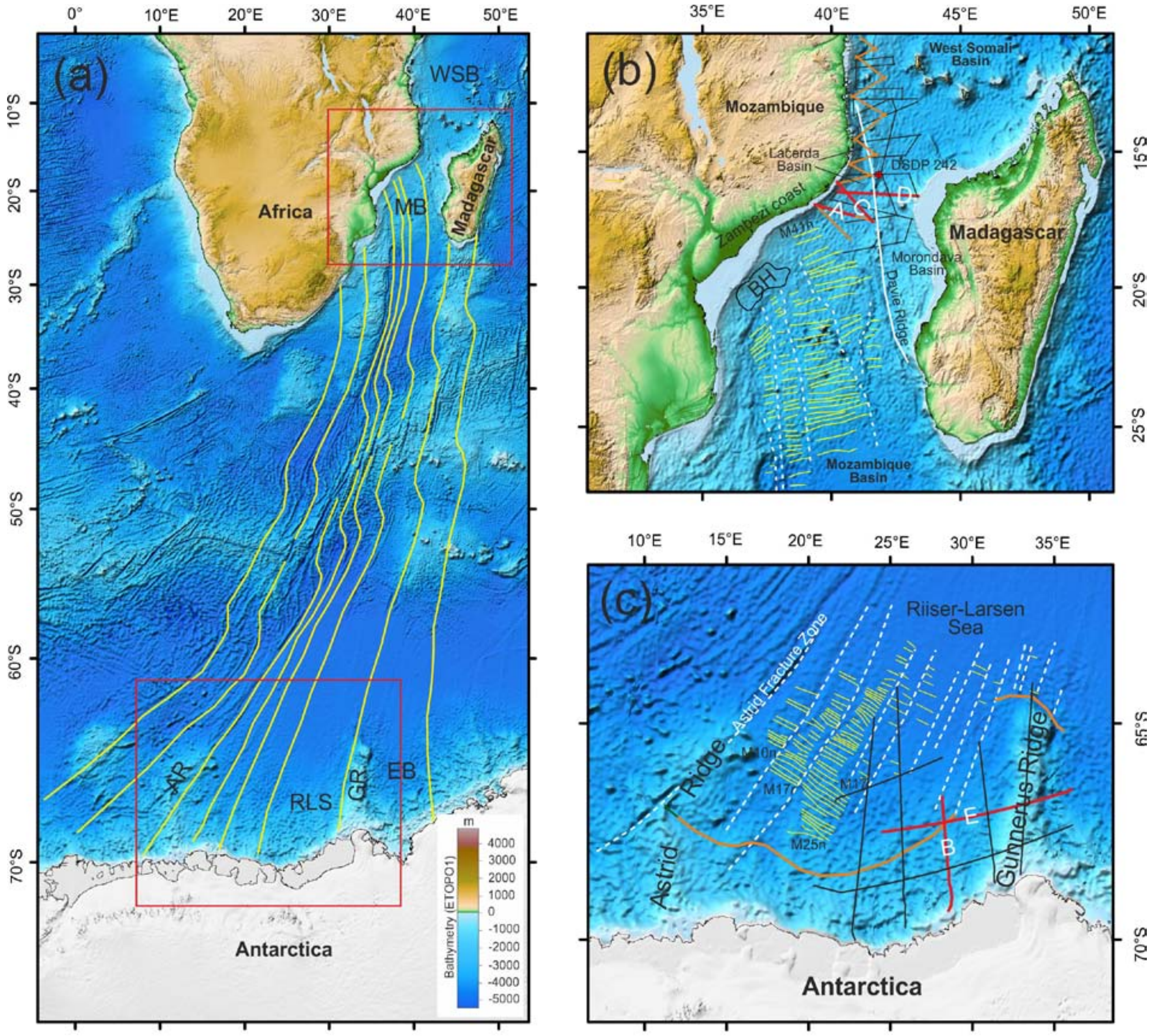

FIGURE 1: Bathymetric map of the Africa-Antarctic corridor, the Mozambique Basin and the Riiser-Larsen Sea (ETOPO1 1 arc-minute global relief model; Amante and Eakins, 2009) A). The yellow flow lines indicate the motion between Africa and Antarctica according to Eagles and König (2008). Red boxes indicate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

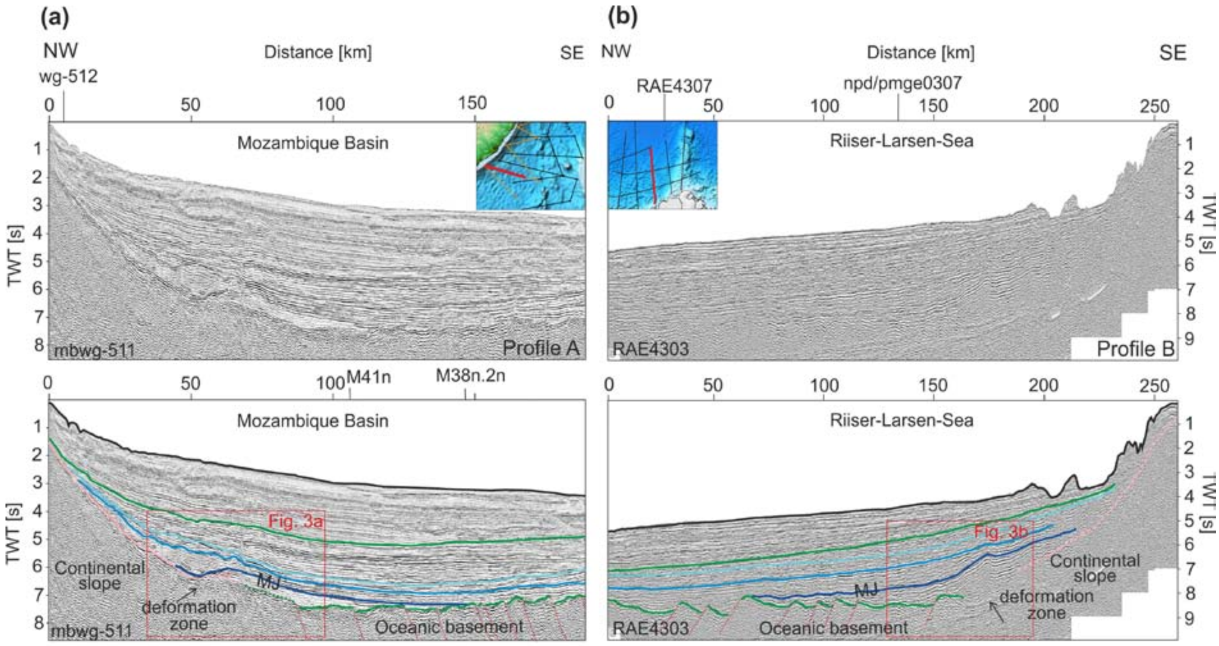

FIGURE 2: Migrated profile Mbwg00-511 in the Mozambique Basin (A) and stacked profile RAE4303 in the Riiser-Larsen Sea (B) (line locations in inset maps and Fig. 1). In the lower panels, the stratigraphic interpretation according to Castelino et al. (2015), Leitchenkov et al. (2008) and Mahanjane (2014) 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. Postrift sediments, overlying the deformation zone have been affected by the deformation. This deformation zone is proposed as tie-point for Gondwana reconstructions.

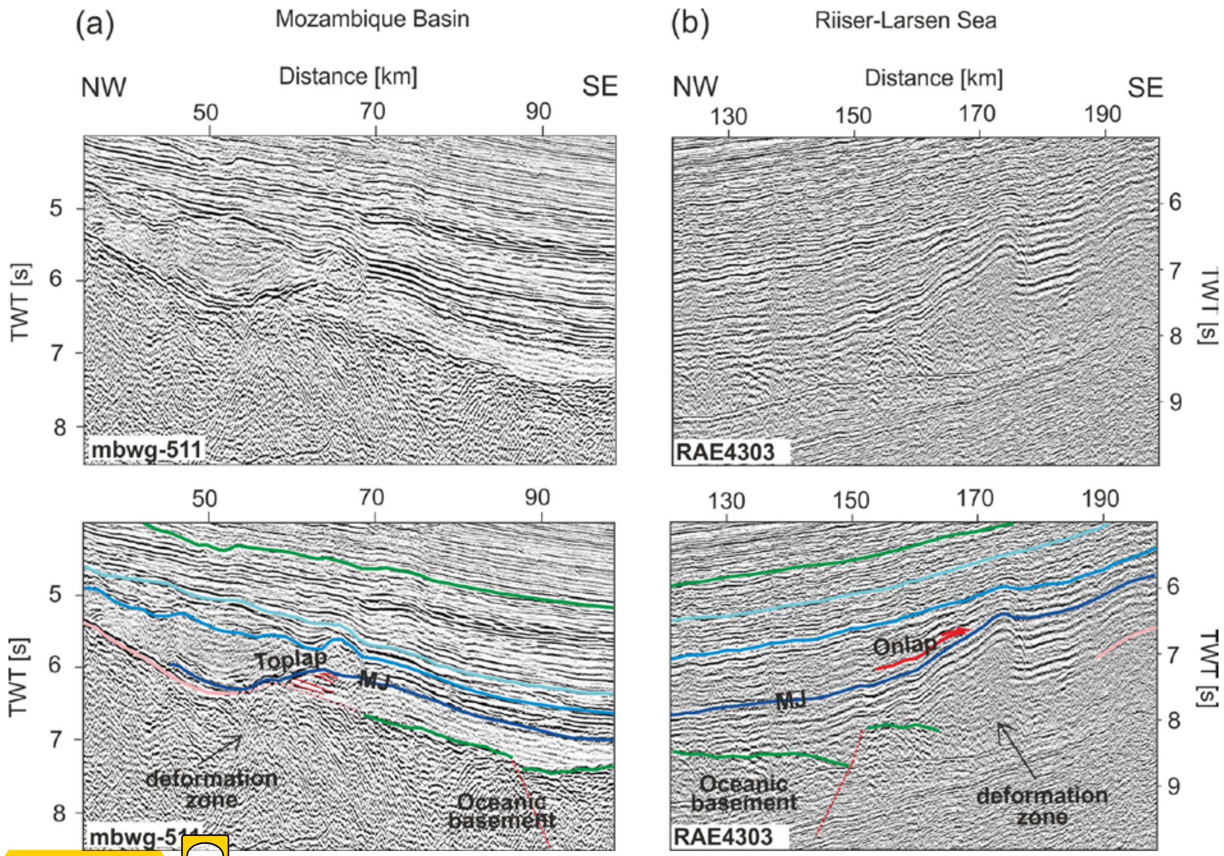

FIGURE 3: Close-up view of the zone of deformed basement in the Mozambique Basin (A) and Riiser-Larsen Sea (B) presented in Fig. 2. The lower panels show the interpreted sections of the profiles. The basement is distinctively deformed and fractured. Overlying postrift sediments are deformed and indicate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

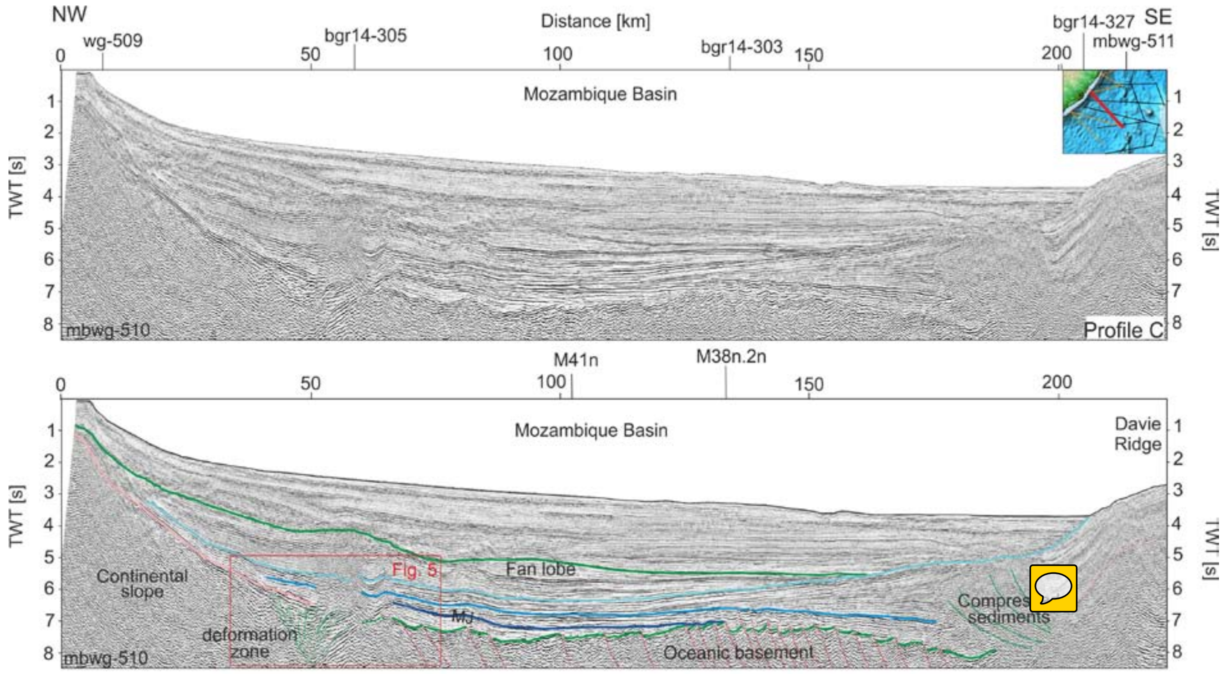

FIGURE 4: Migrated section of profile Mbwg00-510 (line location in inset map and Fig. 1). The lower panel shows the section overlain by the stratigraphic interpretation according to Castelino et al. (2015), Franke et al. (2015) and Mahanjane (2014). The profile runs from the continental slope to the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

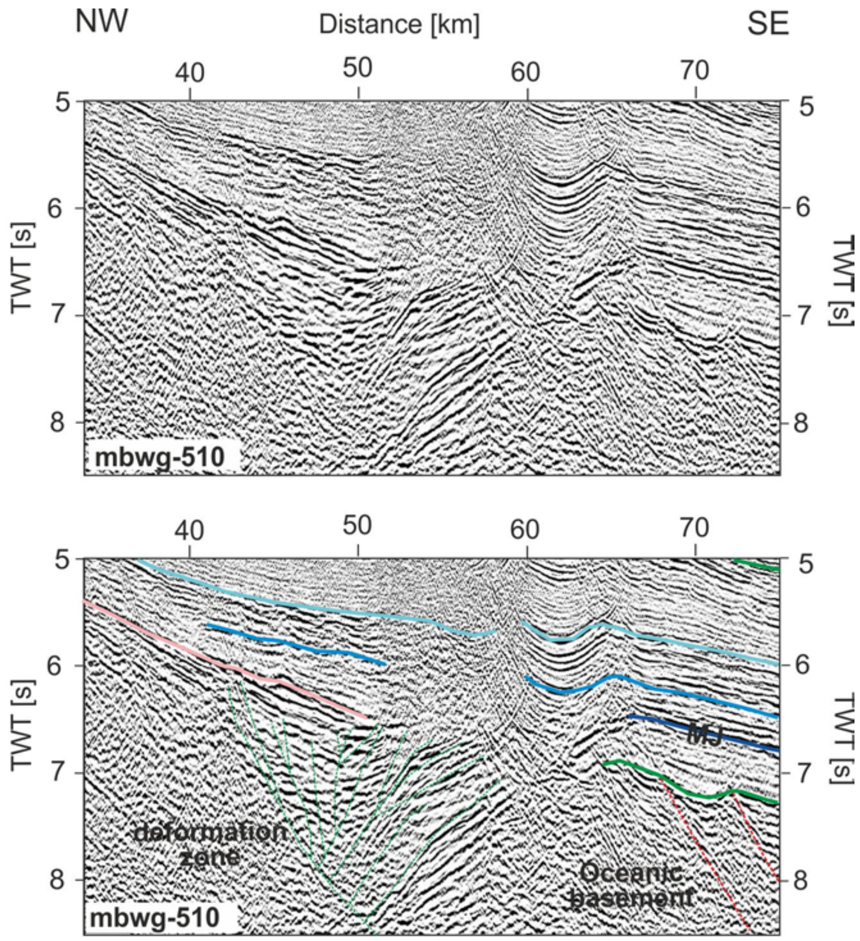

FIGURE 5: Close-up view of the zone of deformed basement in the Mozambique Basin presented in Fig. 4. The lower panel shows the interpreted section of the profile. The basement is deformed by steeply dipping, fan-like normal faults that at depths may converge into a single, subvertical fault (green,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

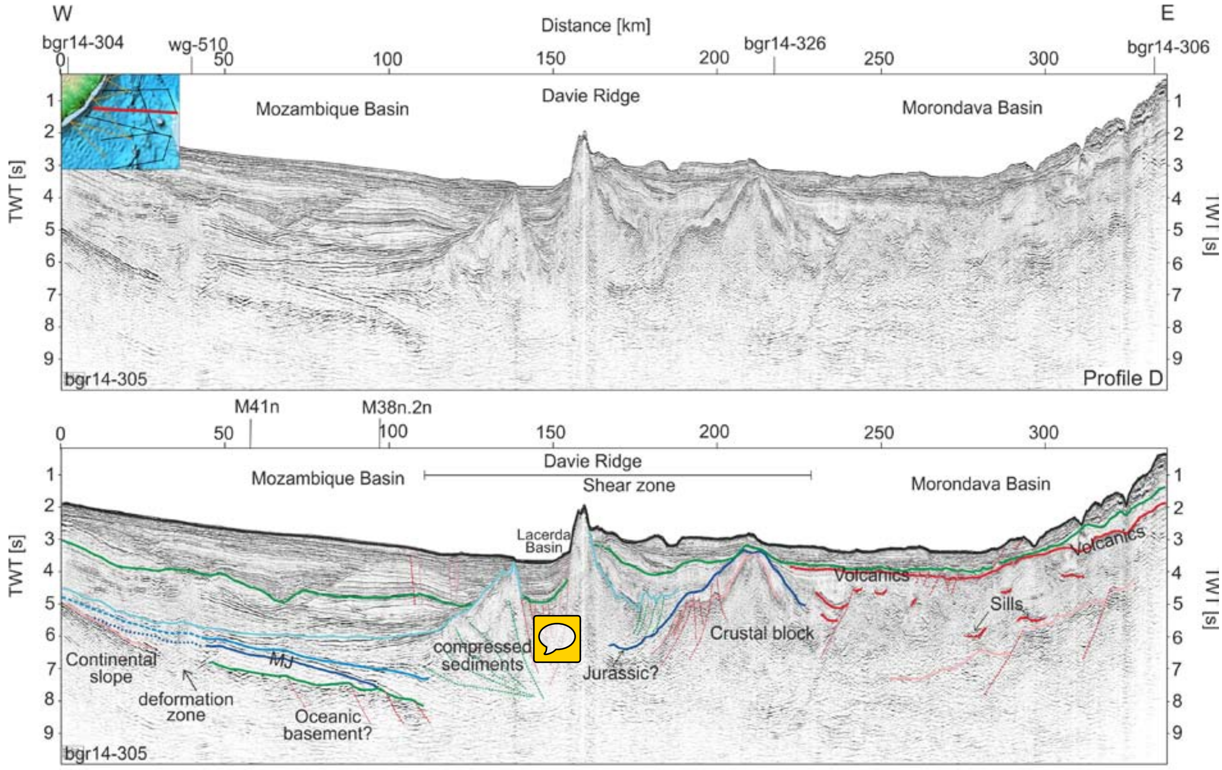

FIGURE 6: Pre-stack migrated section of profile BGR14-305 (line location in inset map and in Fig. 1). The lower panel shows the interpreted section according to the seismostratigraphic concepts of Castelino et al. (2015), Franke et al. (2015), Klimke et al. (2016) and Mahanjane (2014). The profile runs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

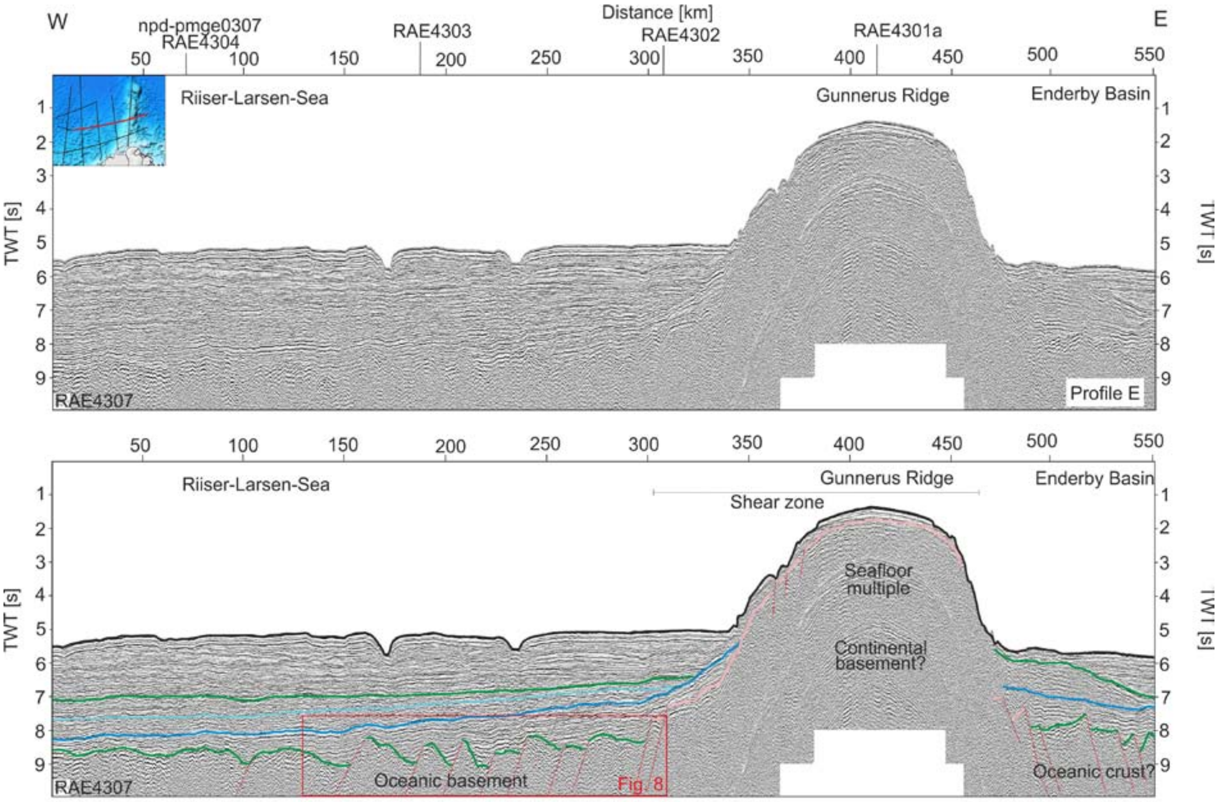

FIGURE 7: Stacked section of profile RAE4307 (line location in inset map and in Fig. 1). The lower panel shows the interpreted section of the profile with the stratigraphy according to Leitchenkov et al. (2008). The profile runs from the Riiser-Larsen Sea across the Gunnerus Ridge into the Enderby Basin.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

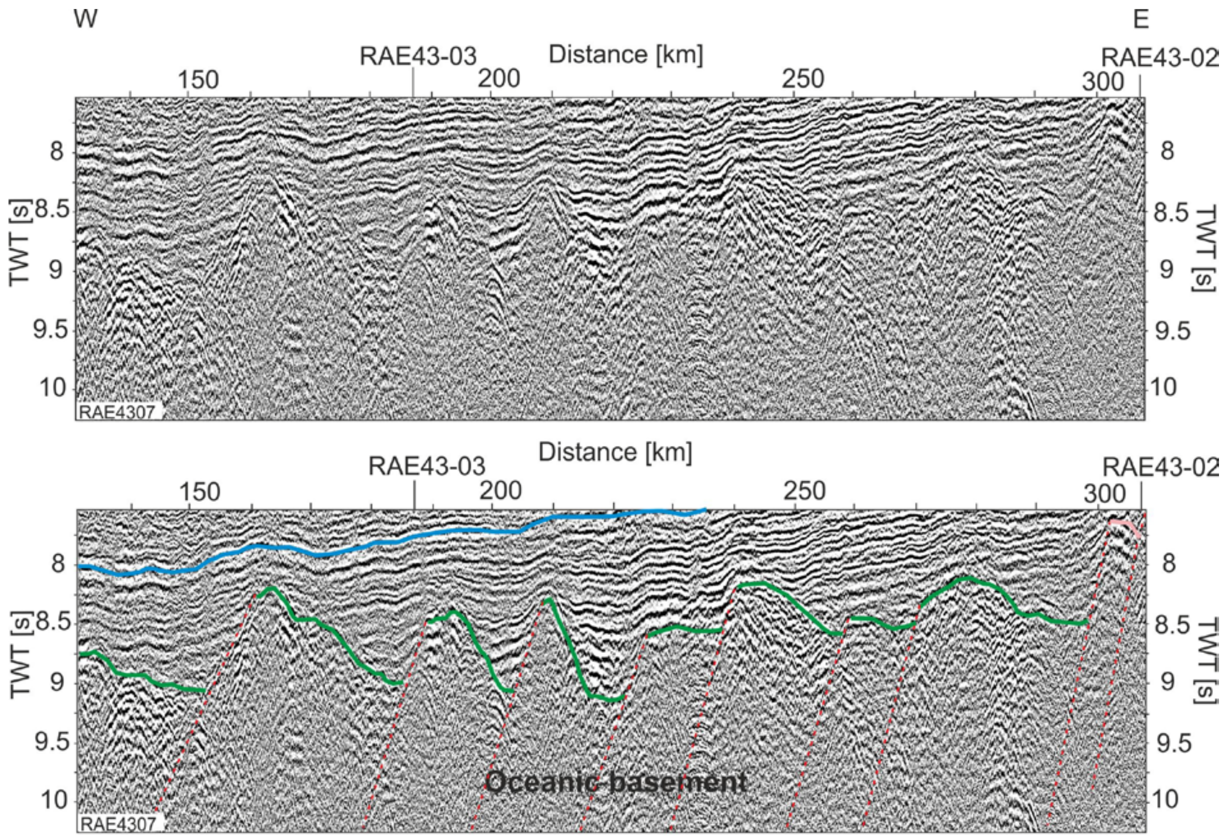

FIGURE 8: Closeup view of the faulted oceanic basement presented in Fig. 7 in the Riiser-Larser, Sea, close to the Gunnerus Ridge. The lower panel shows the interpreted section of the profile.

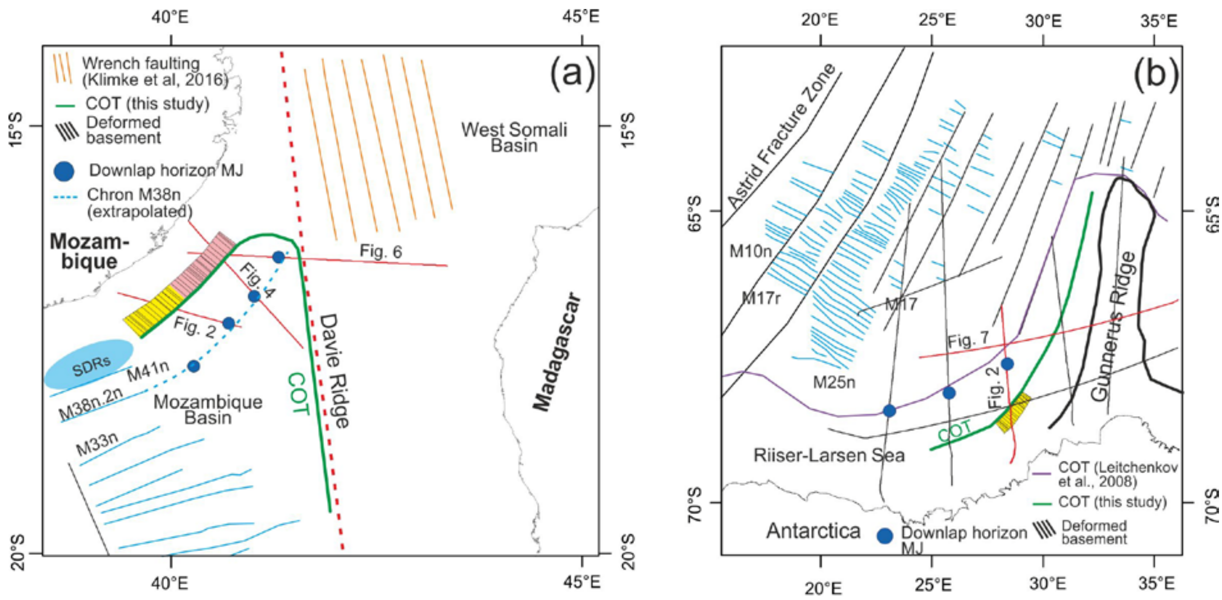

FIGURE 9: Sketch map illustrating the location of the deformed basement observed at the foot of the continental slope in the Mozambique Basin (A) and the Riiser-Larsen Sea (B). Solid Red lines indicate the location of Profiles A to E (Figs. 2, 4, 6 and 7). Blue and black

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. 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. 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 thick dashed red line. The location of SDRs in the Mozambique Basin is compiled from Leinweber et al. (2013) and Müller and Jokat (2017).

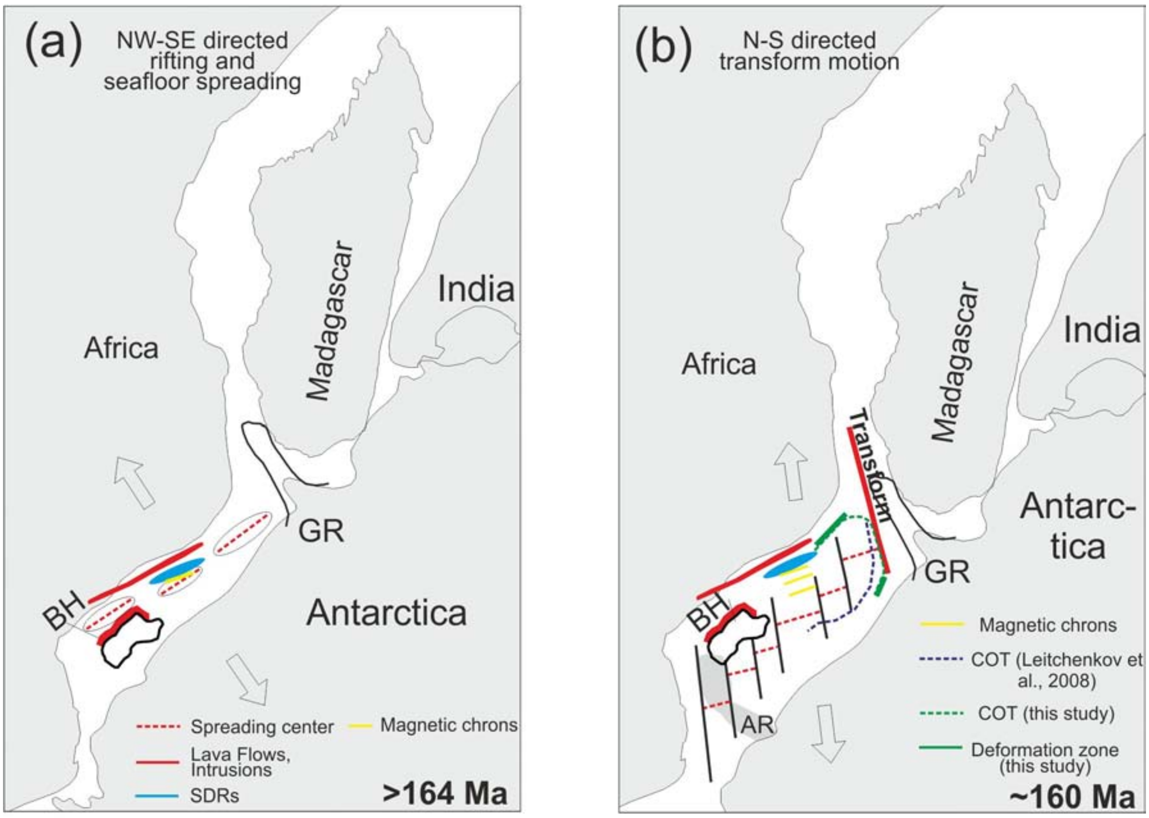

FIGURE 10: Schematic sketch of the initial opening of the Mozambique Basin/Riiser-Larsen Sea. A) In the Middle Jurassic, NW-SE directed rifting and seafloor spreading between Africa

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 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). Thick green lines mark the basement deformation zone presented in this study. Dashed green line marks the continent-ocean transition (COT) of this study. Dashed purple line is the continent-ocean transition (COT) of Leitchenkov et al. (2008). AR= Astrid Ridge, BH= Beira High, GR= Gunnerus Ridge.