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Crustal variability along the rifted/sheared East African margin: a review

Maren Vormann[1] · Wilfried Jokat[1,2]

Abstract

The East African margin between the Somali Basin in the north and the Natal Basin in the south formed as a result of the Jurassic/Cretaceous dispersal of Gondwana. While the initial movements between East and West Gondwana left (oblique) rifted margins behind, the subsequent southward drift of East Gondwana from 157 Ma onwards created a major shear zone, the Davie Fracture Zone (DFZ), along East Africa. To document the structural variability of the DFZ, several deep seismic lines were acquired off northern Mozambique. The profiles clearly indicate the structural changes along the shear zone from an elevated continental block in the south (14°–20°S) to non-elevated basement covered by up to 6-km-thick sediments in the north (9°–13°S). Here, we compile the geological/geophysical knowledge of five profiles along East Africa and interpret them in the context of one of the latest kinematic reconstructions. A pre-rift position of the detached continental sliver of the Davie Ridge between Tanzania/Kenya and southeastern Madagascar fits to this kinematic reconstruction without general changes of the rotation poles.

Keywords Davie Ridge · Davie Fracture Zone · Gondwana breakup · Kinematic reconstruction · Continental fragment

Introduction

The breakup of Gondwana commenced around 182 Ma ago with massive emplacement of flood basalts and subsequent rifting in the Mozambique Basin (Müller and Jokat 2019). No such massive volcanism has been reported further north

Highlights
• The northern Mozambican margin is an atypical transform margin.
• The continent ocean transition does not always coincide with the Davie Fracture Zone.
• The Davie Ridge is separated into a sedimentary northern and a continental southern part.
• A refined kinematic reconstruction, which includes the continental fragment of the Davie Ridge, is discussed.

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along the northern Mozambican, Tanzanian, Kenyan and Somali margins (Mortimer et al. 2020). Here, the rifting and subsequent separation of Madagascar from East Africa were mainly magma poor. A variety of reconstructions present Madagascar as part of East Gondwana (Antarctica, India, Australia) (Heirtzler and Burroughs 1971; Reeves et al. 2002, 2016; Jokat et al. 2003; Leinweber and Jokat 2012; Reeves 2014; Davis et al. 2016; Phethean et al. 2016; Tuck-Martin et al. 2018; Müller and Jokat 2019). In these reconstructions, Madagascar has various pre-rift positions and rotations north of Kenya and Tanzania, which were part of West Gondwana (Africa, South America). The initial direction of rifting and drifting of East from West Gondwana between 182 and 157 Ma (GTS2012, Ogg 2012) was mainly perpendicular to the present-day coastline off central Mozambique and Somalia, and oblique to the coasts of northern Mozambique, Tanzania and Kenya (Müller and Jokat 2019). This was the case until approximately 157 Ma (M26r, Müller and Jokat 2019). Then, between 157 and 144 Ma (M26r-M28n), the spreading direction, in present-day African coordinates, between East and West Gondwana changed to N-S (Phethean et al. 2016; Müller and Jokat 2019). Initial movements between Greater India (India and Madagascar) and East Antarctica began about 136 Ma as well as the separation of Australia from East Gondwana (M14r, Reeves 2018).

Madagascar, whilst still connected to India, reached its final position with respect to Africa at some point in Early Cretaceous times (M9n-M1n, Eagles and König 2008; Davis et al. 2016; Tuck-Martin et al. 2018; Müller and Jokat 2019). The latter movement created a large fracture zone and/or transform system in the Somali Basin and the Mozambique Channel, known as the Davie Fracture Zone (DFZ) or Davie Transform System (DTS) (Bunce and Molnar 1977; Davis et al. 2016; Sinha et al. 2019).

Today, the Mozambique Channel separates Madagascar from the African continent between 12° and 25°S. Here, the most prominent topographic feature is the Davie Ridge (DR) running parallel to the southeastern branch of the East African Rift System along the DFZ (Chorowicz 2005). Mascle et al. (1987) proposed that the DR consists of three different parts: a northern part between 9° and 13°S with a steep western flank, a middle section of numerous seamounts between 13° and 17°S and a southern part between 17° and 20°S in the Mozambique Basin. Recent investigations classified the southern and middle parts of the DR to have a continental origin, while the northern part is a sedimentary build-up (Franke et al. 2015; Klimke et al. 2016; Vormann et al. 2020; Vormann and Jokat in review). This is supported by dredge samples analysed by Bassias (1992). At the transition at 13°S, the DR is not physiographically present, but slightly further south, it seems to turn towards the continent. Several sedimentary basins are observed along the western flank of the DR, such as the Kerimbas Basin in the north and the Lacerda Basin in the south. Along the margin of East Africa, a gravity low is observed, which is mostly connected with the transform margin (Mascle et al. 1987). Regional kinematic models for the East African margin suffer from the poor knowledge of the location and shape of the transition between continental and oceanic crust, especially along northern Mozambique, which might be used to better constrain the movement of Madagascar. In the absence of such knowledge, questions remain: Did Madagascar's drift away from Africa follow a path close to the present-day African coast, or even inland of it? Does the topographic expression of the DFZ reliably indicate its crustal affinity and, if yes, how? Can continental crust be confirmed by seismic refraction data under the DR? If so, where was the DR continental sliver situated before Gondwana breakup? How does the crustal fabric change in comparison with that of the rifted margin of central Mozambique?

These questions have partly been addressed in several publications. Here, we review their findings by displaying the five crustal transects in a consistent way. For this, we focus on the crustal variability of the DR along central and northern Mozambique and compare the results to knowledge gained from other geophysical data.

Crustal structure off Northern Mozambique—similarities/differences

In 2007 and 2014, seismic refraction data were acquired in the Mozambique Channel during three scientific expeditions (AISTEK II, MOCOM and PAGE-FOUR cruises). The five seismic refraction lines reviewed here all cross the DFZ. Four of them are east-west oriented and the fifth runs NNE-SSW. Together, they reveal crustal information along more than 1400 km of the East African coast between 11°S and 20°S (Figs. 1 and 2; Leinweber et al. 2013; Müller and Jokat 2017; Vormann et al. 2020; Vormann and Jokat in review). The profiles are labelled A to E from north to south.

In all seismic refraction profiles (Fig. 2), we observe a sedimentary cover up to 6 km thick, with sedimentary velocities reaching values of up to 4.7 km/s just above the acoustic basement, which are typical for this region (Lort et al. 1979; Müller et al. 2016; Müller and Jokat 2017). Crustal velocities along our five lines start at around 5.5 km/s in the southern part, are around 5.1 km/s in the north and increase up to 7.0 km/s in the lower crust (Leinweber et al. 2013; Müller and Jokat 2017; Vormann et al. 2020; Vormann and Jokat in review), as is typical for the Central Mozambican margin (Leinweber et al. 2013; Müller et al. 2016; Müller and Jokat 2017).

Along the 182-km-long northern profile A (AWI-20140150, Vormann and Jokat in review), the DR forms the eastern margin of the Kerimbas Basin (KB, Fig. 2). Some basement elevations are observed beneath the Kerimbas Basin, but there is no distinct basement topography beneath the DR. No steep deepening of the Mohorovičić discontinuity (Moho) is visible in the west of the DR (Fig. 2). The velocity gradient matches to an interpretation of highly stretched continental crust (Christensen and Mooney 1995) and intruded continental crust (Sibuet et al. 2016), both of which are typical for a continent-ocean transition zone (COT) (Vormann and Jokat in review). Here, the DFZ is located below the Kerimbas Basin. East of the DR, the basement and Moho are both flat-lying. The crustal thickness (7 km) and the velocity-depth distribution match those of the old oceanic crust as observed south of this line (White et al. 1992; Leinweber et al. 2013; Müller et al. 2016; Vormann et al. 2020).

Along the second profile, B, at 13°S (AWI-20140130, Vormann and Jokat in review), the seafloor and basement have no elevation in the area of the expected DR (Fig. 2). The western end of the profile represents the COT and shows a steep decrease in crustal thickness seawards, as constrained by gravity modelling. The velocity gradient within the COT matches that of stretched continental crust (Christensen and Mooney 1995). The onset of up to 6.5-km-thick oceanic crust lies to the west of a crustal bulge (CB, Fig. 2), a rather unusual structure that is probably connected to underplated material feeding
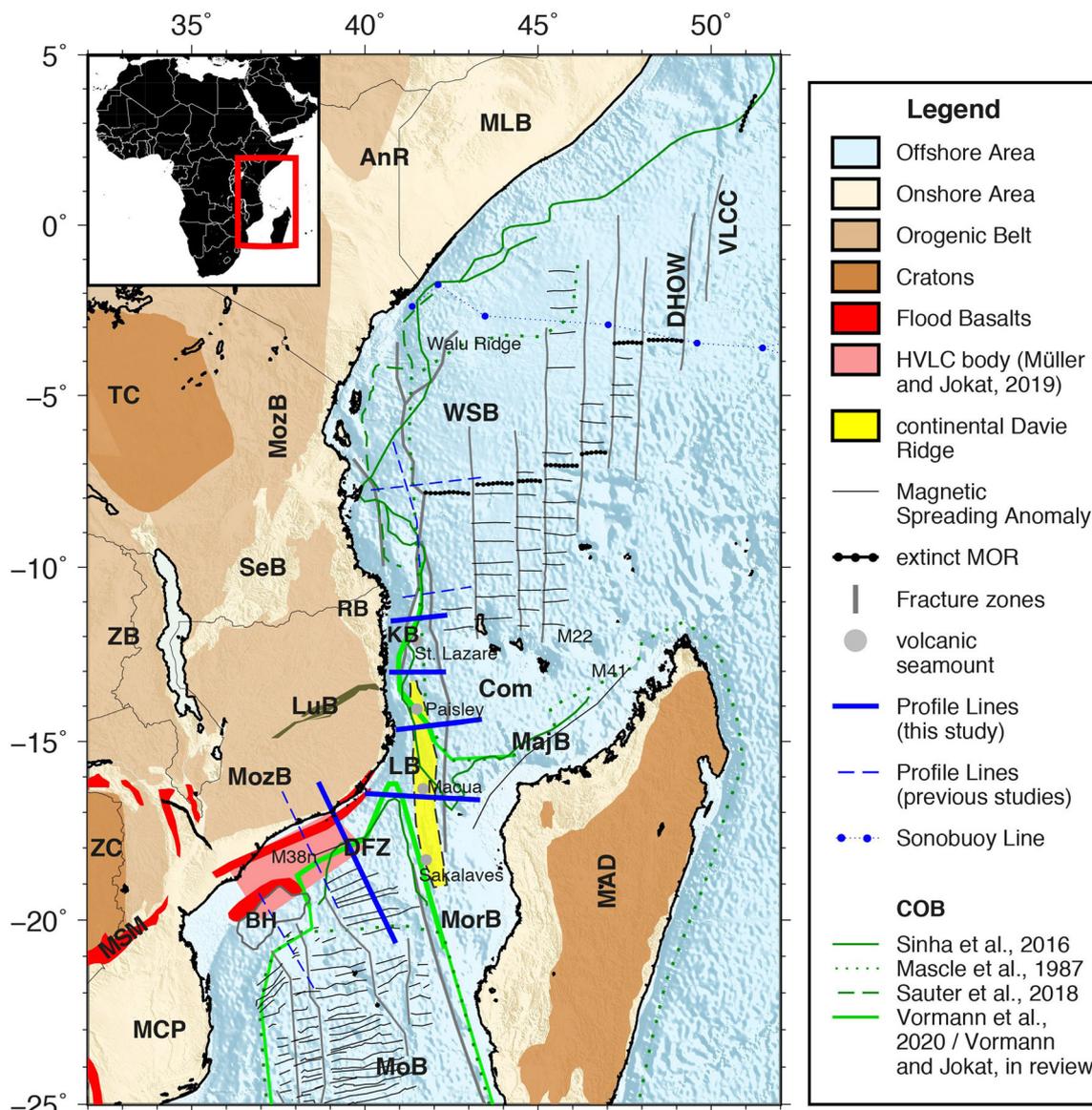
Fig. 1 Overview of the geologic structures in East Africa, the earthquake distribution and the postulated minor plates according to Stamps et al. (2008). Abbreviations: Anza Rift (AnR), Beira High (BH), Comores (Com), Davie Fracture Zone (DFZ), Kerimbas Basin (KB), Lacerda Basin (LB), Lurio Belt (LuB), Madagascar (MAD), Mandava-Lugh Basin (MLB), Majunga Basin (MajB), Mozambique Basin (MoB), Mozambique Coastal Plains (MCP), Morondava Basin (MorB), Mozambique Belt (MozB), Monotake-Sabi-Monokline (MSM), Rovuma Basin (RB), Selous Basin (SeB), West Somali Basin (WSB), Tanzania Craton (TC), Zambesi Belt (ZB), Zambesi Craton (ZC)

neo-volcanism at Paisley Seamount (Vormann and Jokat in review). The true extent of the observed underplating cannot be determined from a single profile. Thus, its regional relevance remains speculative. Recent volcanism is also observed further south at the Sakalaves seamount (Courgeon et al. 2018). The DFZ is interpreted to be located over the area of underplated material and to be situated in oceanic crust.

Further south, profile C at 14.5°S (AWI-20140100, Vormann et al. 2020) reveals the DR as a basement elevation covered by thin (2 km) sediments. Close to the Mozambican coast in the west, the data show a crustal thickness of 15 km, which continuously decreases towards the DR. The DFZ is

suggested to lie east of DR, in thinned (5.5 km thick) oceanic crust. The presence of oceanic crust (7.1 km) is well characterized by its typical thickness and velocity gradient (White et al. 1992; Vormann et al. 2020).

The three northern profiles (A-C) do not reveal crustal characteristics that would be typical of a purely sheared margin, such as a steep decrease in crustal thickness and/ or a narrow COT (Bird 2001). The margin, in contrast, shows a variable and complex crustal structure, with different COT geometries and a fracture zone that is partially located in oceanic crust. This may be explained by an initially oblique phase of separation of the northern

Fig. 2 Compilation of the interpretations of 5 seismic refraction profiles along the northern Mozambican margin. Profile A: 182 km with 20 OBS/OBH (Vormann and Jokat., in review), profile B: 178 km with 20 OBS/OBH (Vormann and Jokat., in review), profile C: 270 km with 24 OBS/OBH (Vormann et al. 2020), profile D: 356 km with 22 OBS/OBH (Vormann et al. 2020), profile E: 500 km with 35 OBS (Leinweber et al. 2013; Müller and Jokat 2017). Bathymetry is shown in blue. Abbreviations are: CB-crustal bulge (underplated material), cont-continental crust, COT-continent ocean transition zone, DR-Davie Ridge, HVLC-high velocity lower crust, KB-Kerimbas Basin, oc-oceanic crust
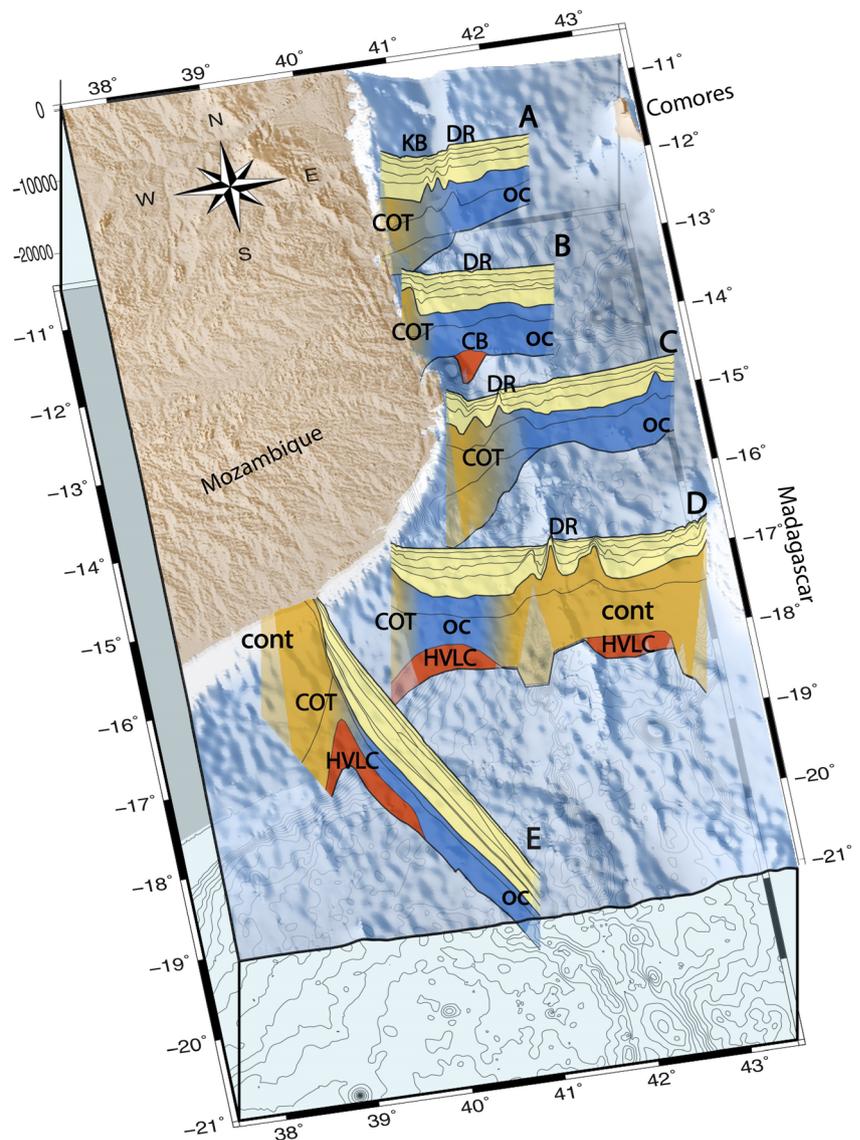
Mozambican, Tanzanian, and Kenyan margins from their conjugates during the Jurassic. NNW-SSE-oriented extension of continental crust and formation of early oceanic crust preceded a change in the direction of divergence between East and West Gondwana to N-S between 157 and 144 Ma, leading to the formation of a major shear zone, the Davie Fracture Zone (DFZ). This evolution is responsible for the present-day crustal variability along the East African margins.

The fourth profile, D, at 16.5°S shows strong crustal variations. At its western part off Mozambique (AWI-20140050, Vormann et al. 2020), a thin body of high velocity lower crust (HVLC) is observed beneath the COT (Fig. 2). Eastwards, only a small corridor of oceanic crust (70 km) is found before the western margin of the DR for which a continental origin is encountered. In the centre of the line, the DFZ is observed to coincide with

the DR and two additional buried ridges. The velocity distribution is similar to that of stretched continental crust, as observed in continental fragments such as the Beira High (Müller et al. 2016). The crustal thickness and velocity distribution further east do not support the presence of oceanic crust towards the northwestern Madagascan margin. Instead, the crust is interpreted as stretched continental crust that may be underlain by a thin HVLC (120 km wide, 2.5 km thick), consistent with the presence of magmatic intrusions in the sediments off Madagascar (Klimke et al. 2016).

The southernmost profile, E (AWI-20070201, Leinweber et al. 2013, Müller and Jokat 2017), between 16° and 20°S, is oriented NNW. It describes the transition from Jurassic oceanic crust off Central Mozambique to the onshore continental crust of the Mozambique Belt. This profile shows a 220-km-wide HVLC body beneath the COT (Müller and Jokat 2017)

with a mean thickness of about 5 km. Oceanic crust appears only 100 km off the coast, where it is constrained by linear magnetic reversal anomalies interpreted as isochrons in the sequence starting at M38n.2n (Müller and Jokat 2017, 2019).

The two southern deep seismic sounding lines (D + E) image a typical volcanic rifted margin with a HVLC body and seaward dipping reflectors (SDRs) within the COT (Leinweber et al. 2013; Müller and Jokat 2017; Vormann et al. 2020). Onshore up to 15.5°S, the landward limit of Jurassic rifted crust is marked by intrusions of middle Jurassic age in the coastal areas (Müller and Jokat 2017). The northern terminations of the intrusions and the HVLC body coincide.

Consequences for geological interpretations off Mozambique

The velocity-depth models described in the previous chapter support proposals to split the DR into two structurally different parts (Mascle et al. 1987; Klimke and Franke 2016; Klimke et al. 2018; Vormann et al. 2020; Vormann and Jokat in review). In the northern part of the DR, between 9°S and 13°S, we observe no basement elevation in the seismic data (Fig. 2, profiles A and B). The DR on profile A is merely the eastern rift shoulder of the Kerimbas Basin, whereas on profile B, no elevation is observed at all. The middle part of the DR is described by profiles C and D: on both profiles, the DR is situated in stretched continental crust. On profile C, the DR is located within the COT, as characterised by 10 km thick crust. Further south (profile D), the crust beneath the DR is up to 15 km thick and has nearly no sedimentary cover (Fig. 2). Its velocity structure fits well to that of stretched continental crust (Christensen and Mooney 1995), with slightly lower velocities in the upper mantle (Vormann et al. 2020). The analysis of seismic reflection data (Mougenot et al. 1986; Klimke and Franke 2016; Klimke et al. 2016, 2018) also supports the interpretation of the southern part of the DR as a continental fragment. Our data confirm older interpretations made on the basis of continental rock samples dredged between 14° and 16°S along the flanks of the DR (Virlogeux 1987; Bassias 1992). Geochemical analyses of the dredge samples indicate strong similarities with Tanzanian and Madagascan sediments (LeClaire et al. 1989). The southernmost part (17–20°S) of the DR was not investigated by seismic refraction data, but previous gravimetric and seismic reflection studies (Mougenot et al. 1986; Klimke et al. 2018) as well as dredged rocks (Virlogeux 1987; LeClaire et al. 1989; Bassias and Leclaire 1990; Bassias 1992) also strongly support a continental origin. The outline of the presumed continental part of the DR is illustrated in Figs. 1 and 3 (126 Ma).

The COT and the onset of oceanic crust were defined on the basis of structural changes in the seismic refraction profiles, such as a reduced crustal thickness, changes in the mantle density and seismic velocity changes in the crust. The western boundary of the COT to normal continental crust was not sampled by the experiment, since the profiles could not be extended onshore for political reasons (Fig. 2). The prominent gravity low along the northern Mozambican margin was interpreted by several studies to mark the continent-ocean boundary. Our study shows that this gravity low is mainly caused by variations in composition within the COT. However, there are exceptions where the gravity low does not coincide with the COT. In the north along profiles A and C, the COT correlates with the prominent gravity low having values of 90 mGal and 110 mGal. On profile B, in contrast, the overall gravity variation is very small (less than 40 mGal), and the gravity low in the middle of the profile is related to the underplated material added to the oceanic crust. Thus, the COT cannot be determined by gravity. Along the southern profiles D and E their COT lies directly next to the Mozambican coast and coincides with a positive gravity anomaly, which is typical of a rifted margin. In summary, the pronounced negative gravity anomaly cannot explicity be interpreted marking either the COT nor the continent-ocean boundary.

Refined(?) kinematic model

The detached continental sliver of the southern DR is not included in any existing kinematic reconstruction. In this section, we do this for the first time. For the kinematic reconstruction, we used the software GPlates (Müller et al. 2018) to fit the small continental fragment of DR between southern Madagascar and the Kenya/Tanzania coastline on the basis of their previously identified similar geologic properties (LeClaire et al. 1989; Bassias 1992). The rotation parameters for the surrounding plates are taken from Müller and Jokat (2019), who based their model on the interpretation of the most extensive marine magnetic data set in the region. The DR is fitted to the straight, steep, south-western shelf of present-day Madagascar in the southern Morondawa Basin (Fig. 1), whose ~800 km length fits that of the continental fragment. So located, Fig. 3 (182 Ma) shows the DR in a pre-breakup (182 Ma) position prolonged to the northern Rovuma Basin and adjacent to the southern Morondawa Basin. According to our adapted model, the DR is placed northwards of the Gunnerus Ridge, a feature off East Antarctica, which is located at 182 Ma between northern Mozambique and Sri Lanka (Fig. 3 (182 Ma)) (Leitchenkov et al. 2008). Northern Madagascar fits close to the Somali and Kenyan shores (Leinweber and Jokat 2012; Davis et al. 2016; Phethean et al. 2016; Reeves 2018; Tuck-Martin et al. 2018; Müller and Jokat 2019; Sinha et al. 2019).
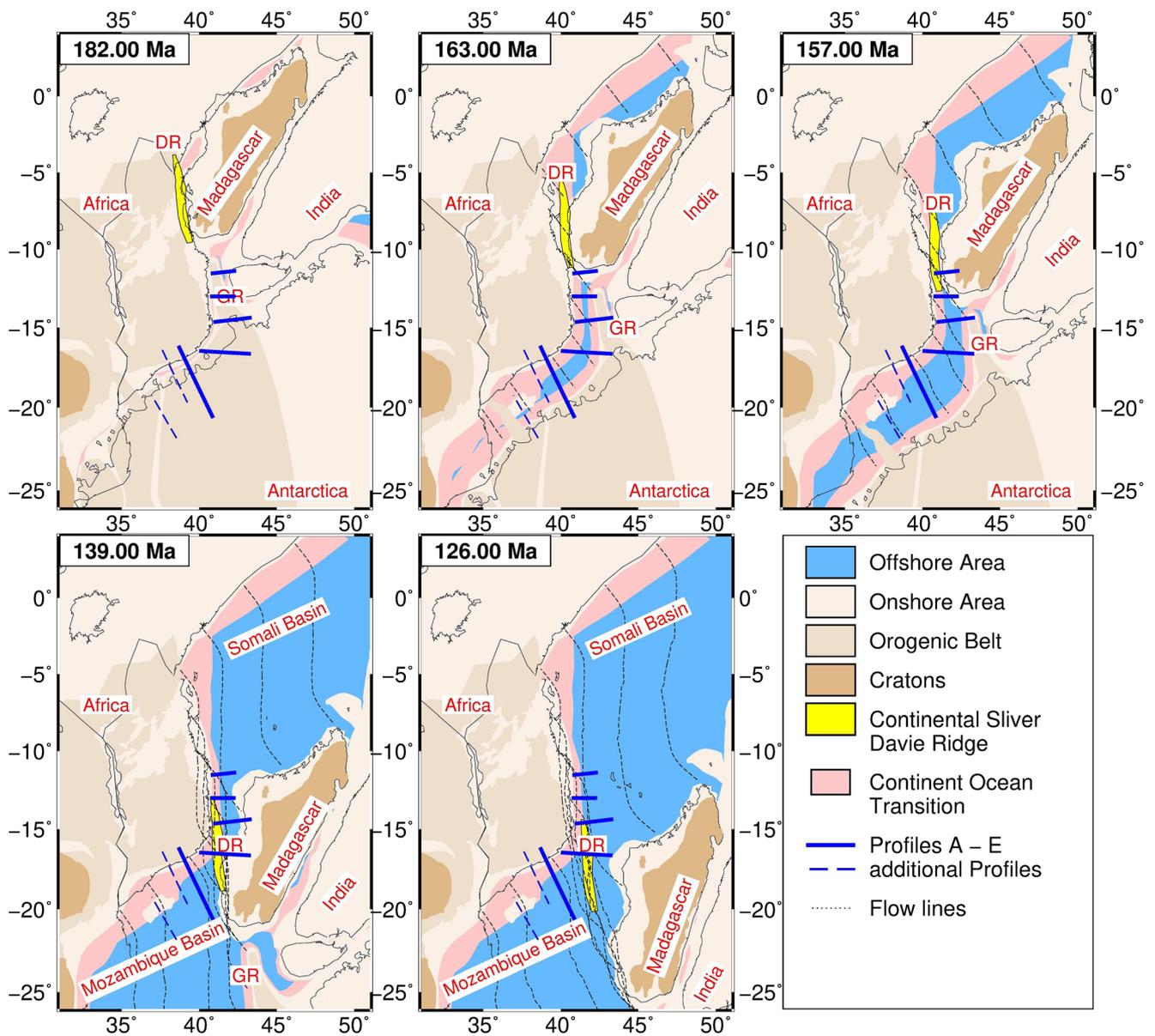
Fig. 3 Kinematic reconstruction of the southern, continental Davie Ridge (DR, yellow) with respect to Africa. The blue lines show the location of the five seismic refraction lines. Rotation poles are taken from Müller and Jokat (2019)

In our reconstruction, the DR is primarily connected to East Gondwana. According to the Müller and Jokat (2019) model, the initial plate divergence direction was perpendicular to the present-day coastlines of central Mozambique and Somalia. At these margins, a volcanic rifted margin evolved as described by Müller and Jokat (2019). During this oblique phase of East Africa, we propose with the refined model that continental stretching and then accretion of oceanic crust mainly took place between Africa and the DR, and only minor stretching between DR and Madagascar as part of East Gondwana (Fig. 3; 163 Ma, 157 Ma). After Basile (2015), oblique rifting can produce variable geometries in a COT,

especially when imaged along profiles that are not aligned parallel to the direction of plate divergence. Between 157 and 144 Ma, the orientation of plate motion changed to N-S (Müller and Jokat 2019). In our refined reconstruction, the continental DR fragment remained part of East Gondwana during this change (Fig. 3; 157 Ma, 139 Ma), with a transform margin located at what is now its western edge. Most of the DFZ, however, then developed in transitional and oceanic crust that had formed during the first phase of continental breakup. Consequently, the pre-existing pull-apart sedimentary basins and earliest oceanic crust of the East African margin were deformed/ overprinted. In this model, the DR reached its final

position with respect to East Africa between 140 and 137 Ma (Fig. 3, 139 Ma). At this time, Reeves (2018) reports initial movements between India/Madagascar and Antarctica. Davis et al. (2016) state that until 135 Ma, East Gondwana rotated as a single cohesive unit, whereas Müller and Jokat (2019) present independent rotation poles for Madagascar and Antarctica from 139 Ma. These events possibly led to a change of the transform margin from the western to the eastern side of the DR. Anyhow, the described complex spreading pattern of East Gondwana detached a continental sliver, the southern continental DR, from Madagascar to become part of the African plate. Around 126 Ma (Fig. 3), when spreading ceased in the Somali Basin, Madagascar reached its final position with respect to Africa and became part of the African plate.

This scenario explains the findings along the northern Mozambican margin and the DR, such as the narrow rifted margin on profiles B and C, the wide DFZ partly in oceanic crust and the complex crustal structure of profile A, and the volcanic rifted margins imaged along profiles D and E.

Conclusion

The existence of a simple transform margin at the northern Mozambican coast is not supported by the deep seismic data reviewed in this contribution. The geological evolution is more complex. Large parts of profiles C and B represent oceanic crust and the DFZ is located in oceanic crust (Vormann et al. 2020; Vormann and Jokat in review). Both profiles show a wider COT (> 50 km (B) resp. 100 km (C)) than would be expected for a sheared margin (Bird 2001). Further north, profile A has an even broader COT of at least 100 km beneath the Kerimbas Basin (Figs. 1 and 2) and does not show a sharp decrease of the Moho depth. This hints to a complex opening history for the northern Mozambican margin and probably the Somali Basin. In contrast, the southern profiles (D and E) show clear indications of the presence of a normal rifted margin.

The margin, including the detached continental sliver forming the southern DR, evolved after an initial oblique rifting period and was then overprinted by the southward movement of East Gondwana. North of 12°S, the Mozambican Margin cannot be classified as a simple transform margin. Here, we assume that the Kerimbas and Rovuma basins are strongly influenced by the initial (oblique) rifting and movement of the DR during the dispersal of Gondwana.

Consequently, we fitted the continental sliver of the DR into a kinematic reconstruction between southwestern Madagascar and Tanzania/Kenya. During initial rifting and subsequent southward movement until 139 Ma, the continental DR remained mainly connected to East Gondwana to reach

its final position relative to Africa. In our reconstruction, around 139 Ma, the fracture zone shifted to the eastern side of the DR where it remained until the cessation of spreading in the Somali Basin around 126 Ma.

Availability of data and material The authors have no permission to share the data.

Code availability Gplates: https://www.gplates.org/.

Declarations

Conflict of interests The authors declare no competing interests.

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