# Active fault system across the oceanic lithosphere of the Mozambique Channel: Implications for the Nubia–Somalia southern plate boundary

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## ABSTRACT

Seismic reflection and multibeam echosounder data were acquired in the Mozambique Channel in 2014 and 2015 during the PTOLEMEE, PAMELA-MOZ02 and -MOZ04 marine surveys aboard the *RV Atalante* and *Pourquoi Pas?* These data revealed that an active fault system is deforming the oceanic lithosphere of the Mozambique Basin which has developed during Jurassic-Cretaceous times. The correlation between the fault system and the arrangement of earthquake epicenters suggests that this tectonically active zone directly connects northward with the southern part of the eastern branch of the East African Rift System which corresponds to the seismically active graben system bounding the northern part of the Davie ridge. The fault zone extends southwestward of the Mozambique Ridge along the same trend as the Agulhas-Falkland transform fault zone. The general organization of the fault zone shows the characteristics of an extensional system north of the Mozambique Channel (north of the Europa Island) and a right-lateral transtensional system with coeval normal faults and strike-slip faults south-west of Europa. This tectonic activity is associated with volcanic activity since at least Late Miocene times. Our findings emphasize that the eastern branch of East African Rift System is extending largely toward the south, not only in continental domains but also through the oceanic lithosphere of the Mozambique basin. This fault zone is participating to the complex plate boundary between the main African continent (Nubia Plate) and Madagascar (Somalia Plate).

*Keywords:* Active faults, Mozambique Channel, plate boundary, Nubia plate, Somalia plate

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# 1. Introduction

The East African Rift System (EARS), originally described by Suess (1891), corresponds to the northern part of the divergent plate boundary system between the Nubian (West African) and Somali (East African) plates. This rift system is connected northward to the Afar hot spot which is related to the opening of the Red Sea and the Gulf of Aden, which began being active about 30 Ma ago. However, it is considered that the EARS began to be active only later, starting 24 Ma ago in the Afar area (Chorowicz, 2005). Although the EARS is commonly considered as the modern archetype of rifted plate boundaries, the current Nubia-Somalia kinematics is among the least well-known of all the major plate boundaries (Calais et al., 2006; Stamps et al., 2008). The plate boundary between Nubia and Somalia developed over thousands of kilometers across the eastern part of Africa during Late Oligocene and Neogene times (Chorowicz, 2005; Ebinger, 2012; McGregor, 2015). The location of the plate boundaries is well-defined along the continental branches of the EARS which include a western branch and an eastern branch (Fig. 1). The eastern branch (Gregory Rift) is characterized by high volcanic activity (including Mount Kilimanjaro, the highest point of Africa) and the western branch (Albertine Rift) is characterized by a moderate volcanic activity relative to the eastern branch and by deeper basins, containing lakes and sediments. The Great Lakes (Albert, Tanganyika, Rukwa, Malawi) are located in highly rifted basins bounded by normal and strike-slip faults of the western branch of the EARS. The two branches of the EARS delineate major relatively poorly deformed blocks: Victoria and Rovuma (Hartnady, 2002; Calais et al., 2006; Stamps et al., 2008, 2014; Fernandes et al., 2013; Saria et al., 2014; Fig. 1). The eastern branch of the EARS extends off Tanzania and in the northern part of the Mozambique offshore, bounding notably the Davie Ridge (Mougenot et al., 2005; Mahanjane et al., 2014 a & b; Franke et al., 2015; Mulibo and Nyblade, 2015). But south of the Davie Ridge in the eastern branch and south of the Machaze epicentral area in the western branch (Fig. 1 & 2), the exact location of the EARS still remains a topic of discussion. Scattered extensional structures associated with seismic activity are found onshore in Mozambique, Swaziland and South Africa (Foster and Jackson, 1998; Yang and Chen, 2010; Fonseca et al., 2014; Domingues et al., 2016) and also along the Comores and Mayotte islands and within Madagascar (Grinison and Chen, 1988; Bertil and Regnoult, 1998; Kusky et al., 2007, 2010; Michon, 2016; Fig. 1). Active tectonics across Madagascar has been interpreted as a possible extension connected to the East African Rift System (Kusky et al., 2007; 2010). It forms a segment running through Comores, across Madagascar and finally extends to the Southwest Indian spreading ridge. This extension is associated to Neogene-Quaternary alkaline volcanic activity associated with active hot springs. It also causes high and young topography and seismic activity and it is probably associated to mantle rise under Madagascar (Kusky et al., 2010). Earthquakes have also been recorded within the Mozambique Channel (Hartnady, 2002; Stamp et al., 2008) but prior to this study no data were available to characterize structural evidence for recent to active deformation within the Mozambique Channel (Fig. 1). Marine geophysical surveys carried out in 2014 and 2015 provided evidence for a recent/active fault system running crossing the Mozambique Basin (Fig. 4). This paper aims providing an analysis of the spatial distribution of active faults as well as faults sealed by recent sediments within this area. We notably present some examples of bathymetric data and seismic lines showing these structures and we discuss the significance of this fault system in the plate tectonics framework of the East African offshore.

## 2. Geodynamic and geological framework

North of the Mozambique Channel, the southern extension of the eastern branch of the EARS off Tanzania and Mozambique (eastern boundary of the Rovuma block) has been well-established by seismic reflection data (Mougenot et al., 1986; Mahanjane, 2014a; Franke et al., 2015), earthquake slip vector data and GPS data (Calais et al., 2006; Stamps et al., 2008; Saria et al., 2014), and spatial distribution of earthquake focal mechanisms (Grimison and Chen, 1988; Yang and Chen, 2010; Delvaux and Barth, 2010; Franke et al., 2015). The offshore segment of the eastern branch of the EARS is characterized from north to south by Neogene extension tectonics overimposed on former strike–slip structures of the Tanzanian-northern Mozambique transform margin which have developed during Mid Jurassic-Cretaceous times in relation with the drift of Madagascar with respect to Africa (Rabinowitz et al., 1983; Coffin and Rabinowitz, 1987; Storey et al., 1995; Reeves, 2014; Franke et al., 2015). Regarding the current kinematics of the plate boundary between Nubia and Somalia, Chu and Gordon (1999) analysis placed the pole of rotation of Nubia versus Somalia in the offshore of southeastern cost of South African, in the Mozambique Ridge or south of the Mozambique basin (Fig. 1), which imply that south of the rotation pole, the southern part of the Nubian-Somali plate boundary is a diffuse zone of convergence (up to ~2mm yr$^{-1}$). This interpretation is consistent with subsequent work integrating seismicity studies (Horner-Johnson et al., 2007) and coupled seismicity-GPS studies (Calais et al., 2006; Stamps et al., 2008; Argus et al., 2010; DeMets et al., 2010; Saria et al., 2014; Stamps et al., 2014; Fig. 1). Clusters of earthquake epicenters are located in continental Africa (Fonseca et al., 2014). In addition, evidence for volcanism and tectonic activity characterized by earthquakes has been reported along faults in the Comoros and Mayotte (Emerick and Duncan, 1982; Michon, 2016) and Madagascar (Kusky et al., 2007; 2010). This seismic activity shows that the deformation between the Nubian and Somali plates is distributed over a wide area, in several segments. In this complex tectonic setting, the exact location and the processes of deformation related to plate tectonics movements in the area of the Mozambique Channel remain poorly understood. West of the Mozambique Channel, surface structural evidence for rifting appears to stop around 22°S, south of the Lake Malawi and the Inhaminga fault, in the Machaze epicentral area (Fig. 1), whereas seismic activity at depth extend farther to the south in Swaziland and South Africa (Fonseca et al., 2014). On the other hand, east of the Mozambique Channel, the presence of active volcanism, recent faults, and seismic activity suggest that active deformation running through wide parts of Madagascar might correspond to the western boundary of the Somali plate (Kusky et al., 2007, 2010; Stamps et al., 2008; Saria et al., 2013). Several authors have proposed the presence of a dominantly oceanic Lwandle block (name derived from the Xhosa word for ocean) extending south of the Rovuma block in the Mozambique Channel between southern Mozambique and Madagascar (Hartnady, 2002 ; Horner-Johnson et al., 2007 ; Stamps et al., 2008, 2018; Saria et al., 2014). The dimension and precise boundaries of this block are very poorly constrained at this stage. Kinematic models proposed by Stamps et al. (2008) and Saria et al. (2014) invoke a possible extensive/transform zone in the Mozambique channel distributed along a NE-SW trend crossing the channel (Figs. 1 and 2). Between Africa and Madagascar, the deep water area of the Mozambique basin is characterized by the development of an oceanic lithosphere which began to develop during the Mid Jurassic-Cretaceous drift of Antarctica with respect to Africa (Rabinowitz et al., 1983; Coffin and Rabinowitz, 1988). The oceanic domain of the Mozambique basin is largely invaded by sediments forming the turbidite system connected to the sediment supply coming from the Zambezi River (Walford et al., 2005). The main channel of this turbidite system shows locally strong evidence of erosion (Kolla et al., 1991). The Mozambique Channel is also characterized by the presence of the Davie ridge which runs NNW-SSE west of Madagascar and which delimits the eastern part the oceanic domain of the Mozambique Channel. It corresponds to the extinct transform fault system along which

Madagascar separated from the future Somali plate between 160–115 Ma ago. Dredge samples collected along the Davie Ridge show that isolated blocks of Precambrian basement and volcanics are preserved along this paleo-transform ridge. These volcanics include Late Cretaceous and Cenozoic lava flows (De Wit, 2003; Courgeon et al., 2016, 2017). The oceanic domain of the Mozambique Channel is also the site of volcanic edifices forming seamounts covered by Neogene carbonate deposits forming locally modern reefs and emerged lands at Bassas da India and Europa (Jorry et al., 2016; Courgeon et al., 2016, 2017). The average elevation of the Mozambique basin is anomalously high with respect to its age even taking into account the sedimentary and volcanic input (Castelino et al., 2016) and this anomalously shallow area extends largely southwesterly to the southwest offshore of South Africa (Nyblade and Robinson, 1994). This topographic anomaly, as well as the significance of the volcanism discovered in this area remained both largely unexplained before this study.

## 3. Methodology

In this paper, we present seismic reflection data coupled with multibeam echosounder acquisitions. Geophysical data were acquired in the Mozambique Channel in 2014 and 2015 during the PTOLEMEE (Jorry, 2014), PAMELA-MOZ02 (Robin and Droz, 2014) and PAMELA-MOZ04 (Jouet and Deville, 2015) marine surveys aboard the RV *L'Atalante* and *Pourquoi Pas?* The seismic source used for the seismic acquisitions was 2 GI air guns (105/105 ci, 45/45 ci). The streamer had 48 seismic traces with inter-traces of 6.25 m and 4 hydrophones SFH with a spacing of 0.78 m per trace. The total length of the streamer was 531.6 m. Acquisition time was 9 seconds and the sampling frequency was 1 kHz. The seismic acquisition system was a SEAL 428, V1.1 Patch 23. Seismic data were processed using Ifremer QC-Sispeed software and integrated in Kingdom Suite software for the interpretation of seismic profiles. A map of the fault zone was produced (Fig. 2), encompassing the spatial distribution of active faults (i.e. faults expressed up to the seafloor) and sealed faults (*i.e.* faults covered by sediments). Bathymetric data were acquired using the multibeam echosounders Kongsberg EM122 (Frequency of 12 kHz) and EM710 (Frequency bandwidth of 71-100 kHz). The data were processed using Ifremer Caraïbes software and integrated in ArcGis software for morphobathymetric analysis of seafloor features. The map of the fault zone based on seismic data was compared with morphobathymetric analysis.

In order to provide a reliable mapping of the fault zone, we compared the morphologic features visible on bathymetric data and the visible structures on the seismic lines (Fig. 3), in order to distinguish notably linear sedimentary features (e.g. dunes crests) and structural lineaments (active faults; Fig. 3). The map of fault zone was completed for active faults whose linear extent and orientation are visible on the bathymetric profiles (Fig. 3).

## 4. Results and interpretation

### *4.1 Spatial distribution of the faults*

Several seismic profiles, especially around the Bassas da India and Europa islands, show the presence of a wide system of faults (Fig. 2, 3). Some of the most characteristic lines illustrating this fault system are presented in figure 4, 5, 6, and 7. The penetration in the sediments is slightly than 1.5 s TWT (Two Way Travel time) and deepest observations reach 5.5 s TWT.

The results of the bathymetry-seismic reflection correlation are synthetized in Fig. 3 and examples of the most characteristic bathymetric data showing morphologic expressions at the seabedrelated to fault activity are shown along seismic lines of the Fig. 5 and 6. The comparison between the morphological features visible on bathymetric data and the structures visible on the seismic lines shows a good fit concerning the location of the fault system (Fig. 2, 5, 6). It also allows estimating the main strikes of the faults which is not possible with the seismic data alone because  the density of the available seismic data does not allow correlating faults from one line to another. This combined approach using bathymetry and seismic data allows defining the main  fracturing zones within the Mozambique Channel. This work shows that between latitudes 18°S and 20°S, the fault zone merges with the active fault system adjacent to the northern part of the Davie Ridge which has been described in recent papers (Mahanjane, 2014; Franke et al., 2015; Fig. 3), including notably, N-S trending faults found along the Sakalaves Mounts (Courgeon et al., 2018; Fig. 3). From the Davie ridge, the fault zone develops to the southwest across the Mozambique Channel. This fault zone, more than 200 km-wide, crosses the seamounts of Europa, Bassas da India, and Hall bank (Fig. 2, 4) and joins the northern part of the Mozambique Ridge to the southwest. Two main trends of fault strikes have been observed, one trending N160-180°, the other N45-80° (Fig. 2). This confirms the results of a recent study of the Mounts Sakalaves and the Bassas de India-Jaguar-Hall banks, which showed the existence of faults trending NE-SW that can be tracked on bathymetric data affecting the carbonates of the seamounts, some of these faults being associated with volcanic activity (Courgeon et al., 2016, 2017; Fig. 4). In the vicinity of the seamounts which include volcanic edifices, acoustic masks prevent these faults from being imaged under volcanic rocks (probably related to the contrast of the high seismic velocity of the volcanics compared to the seismic velocity of the sediments around; Fig. 7) but apart from seamounts, faults are clearly visible on the seismic reflection lines. The fault system is trending toward the southwest of the Mozambique Basin as a continuation of the Agulhas major fracture zone (Fig. 1), which extends largely westward along the Falkland fault zone in Southern Atlantic.

On some of the seismic lines considered approximately perpendicular to the strike of the faults, depth-conversion with an average velocity of 2000 m/s (mean velocity deduced from refraction studies and ODP drilling in the area, ODP leg 25, wells 242, 248, 250; see Supplementary Material, Figs. S2 and S3) shows that most of these faults, north of the Europa island, correspond to normal faults. Indeed, these faults have apparent conjugated dips showing absolute values between 50° and 70° (Fig. 4, 5, 6, *i.e.* compatible with conjugated normal faults). In the south of Europa Island, to the southwest, the faults tend to be steeper and many of them are almost vertical (Fig. 7). As such, the fault system of this SW area is different from the characteristic conjugated systems of normal faults present in the northern part of the Mozambique Channel and the presence of nearly vertical faults suggests a strike-slip activity. In addition, well-expressed and localized depressions forming traps for the sediments of the Mozambique turbidite system may correspond to pull-apart basins associated with strike-slip activity. This interpretation is consistent with the fact that some border faults systems of these depressions show clear evidence for the development of en-échelons systems of faults probably related to right lateral strike-slip component (Fig. 9). The general characteristics of the fault geometries in the southwestern part of the Mozambique Channel can be regarded as related to transtensional structures.

The most recent faults affect all sedimentary series down to the penetration window and are well-expressed in the seabed topography with fault scarps up to 50 ms TWT visible on both the seismic lines and multibeam data. It is therefore likely that these faults were active during Quaternary times and some of them are probably active and contemporaneous with the most recent volcanism events. The fault zone described here is indeed still partly active as shown by the seismicity data in the Europa and Bassas da India area (Fig. 1; see discussion below). The profile L4 in figure 6 shows a major syn-sedimentary fault with very high amplitude reflectors in the shallow layers. The syn-tectonic character of this fault is demonstrated by the presence of syn-tectonic pinch-out clearly visible on the seismic line (Fig. 6). This fault, well-expressed in the topography of the sea bottom, is probably an active fault. Throughout the study area, the major faults affect the sedimentary series down to the penetration limit of the seismic data.

In addition to the faults that affect the uppermost sedimentary series many faults do not reach the seabed. The interpretation of the timing of activity of these buried faults is questionable. They can either correspond to sealed faults which were active in the past and then became inactive after or, depending on the rheological properties of the sedimentary series, some faults may be expressed at depth (brittle deformation), while deformation is accommodated by continuous creeping in shallower layers. The observed offsets of the sealed faults seem to be lower than the one of the active faults (maximum ~ 30 ms TWT, ~ 20 m) but these faults are much more numerous than the recent faults (Fig. 5, 6, 7). This suggests that early deformation was more diffuse and widely distributed and that, overtime, deformation tended to be more localized. Some of these faults are hardly detectable (if at all) in a poorly reflective interval (Fig. 5, 6, 7). This could be related to the rheological properties of these levels which can correspond to relatively plastic clays-rich horizons. On the other hand, many faults are sealed by the uppermost sedimentary series and partly by volcanic flows (Fig. 5, 6, 7).

### *4.2 Chronostratigraphic framework of fault activity*

The picking of these faults shows that they are not always sealed at the same level but, depending of the cases, the throw of the fault stops at different stratigraphic layers (Fig. 4). In addition, in some cases, the values of the fault throw are higher at depth with some values above 100 ms TWT. This suggests a relatively long duration of fault activity (since the

Miocene). It is worth noting that sealed faults are also observed on the inactive part of the Davie Ridge (southernmost area of this ridge) as evidenced by the draping of faults by the sediments (Fig. 5).

In order to propose a timing of the beginning of the fault activities, we picked some characteristic horizons which are interpreted as time lines (Fig. 4, 5, 6, 7). The ages proposed for these horizons are consistent with the interpretations of Franke et al. (2015) in the northern part of the Mozambique Channel and Mahanjane et al. (2014b) and Ponte (2018) from well calibration located on Zambezi platform (yellow marker: near top Miocene, orange marker: near top Oligocene, red marker: near top Eocene). According to this interpretation, it appears that all the faults affect Miocene and older sediments but some being sealed at the top of the Miocene whereas, as mentioned previously, others affect the whole stratigraphic series up to the sea-bottom. Accordingly, we deduced that the global period of faulting lasted from late Miocene to present-day.

## 5. Discussion

### *5.1. Structural trends within the fault zone*

Between the Davie Ridge and the Mozambique Ridge, the fault system developed within the oceanic lithosphere of the Mozambique Basin (see Fig. 10, with location of the oceanic crust from Konig and Jokat, 2010; Leinweber and Jokat, 2012; Davis et al., 2016; Mueller and Jokat, 2017). In this area, the tectonic style is different from the dominant one north of 20°S which corresponds to rift-related structures including the tilt of wide continental crustal blocks (Franke et al., 2015). South of 20°S, the fault zone forms a wide area (> 200 km wide) characterized by a diffuse deformation made of a relatively dense system of faults with moderate throws. These faults are mostly straight (planar), whereas the main faults are mainly listric north of 20°S (Franke et al., 2015). This may be due to the fact that the oceanic lithosphere does not includes decoupling layers like the lower thick continental crust, the faults being here rooted deeply within the oceanic lithosphere.

Within this fault zone affecting the oceanic lithosphere of the Mozambique Basin, two main strikes of fault were observed, N160-180° and NE-SW. The N160-180° trends are predominant in the northern area (north of Bassas da India), while fault trends from the southern area are mostly oriented NE-SW. These different trends are possibly controlled by inherited fracture zones within the oceanic lithosphere, the N160-180° trends being probably controlled mainly by transform fracture zones parallel to the Davie Ridge transform system (Fig. 10), and the NE-SW trends being possibly influenced by fractures which are parallel to the magnetic anomalies of the oceanic crust (normal faults from the oceanic accretion period; Fig. 10).

### *5.2. Active earthquakes along the fault zone*

A correlation exists between the area of recent faulting evidenced within the Pliocene-Quaternary sediments and the location of the earthquakes (Fig. 10). Indeed, the most significant earthquakes (Mw > 4) recorded within the Mozambique Channel are trending mostly along the zones where the faults described in this paper are reaching the sea floor (Fig. 2). Only a few isolated and relatively shallow earthquakes (focal depths < 25 km) occurred south of this fault zone in the deep water part of the Mozambique Basin south of 26°S (Fig. 10, see also supplementary material Fig. S1, Table S1). These isolated earthquakes show focal mechanisms consistent with a NW-SE extension (Fig. 10), while earthquake focal mechanisms north of Mozambique Channel along the Davie Ridge are consistent with roughly a E-W extension with focal depths mostly shallower than 25 km, some being between 25 km and 50 km (Foster and Jackson, 1998; Yang and Chen, 2010; Saria et al., 2014; Fig. 2, 3). The 4 larger earthquakes (Mw 5.0 to 5.7) over the last 50 years were recorded between 1980 and 1983, in the Europa/Bassas da India region. In 1951 and 1950, earthquake magnitudes reached Mw 6.1 and 6.2 in the area of the Davie Ridge (Fig. 2). South of 20°S, the Davie Ridge is mostly tectonically inactive (no recorded earthquake > Mw 3 and no evidence of recent tectonics on the seismic lines as shown by the fault sealing of the Ridge; Fig. 2). As mentioned above, to the southwest, the studied active fault zone seems to be aligned with Agulhas-Falkland fault zone where important earthquakes have been mentioned, notably one Mw 6.8 located offshore of Durban in the Natal valley (point A in Fig. 1), which occurred December 31$^{st}$, 1932 (focal depth 15 km). This area of the Natal valley is possibly associated with volcanic seamounts which might be related to the EARS extension tectonics (Wiles et al., 2014). The active fault system described in this paper which is associated to seismic activity is clearly distinct from the deformation trend onshore Mozambique which is associated to seismic activity characterizing an E-W extension or local strike-slip movements (Fig. 10). It is also clearly distinct from the deformation processes recorded within Madagascar which are associated to scattered earthquakes some of them being compressional (Fig. 10).

### *5.3. Fault zone and volcanism*

As described in previous works, the carbonate seamounts of the Mozambique Channel have developed either on crystalline basement rocks or on volcanic systems (Bassias, 1992; Courgeon et al., 2016, 2017). Faults are expressed at the seabed even in the most recent carbonate deposits covering the volcanic edifices (Figs. 4 and 7). The main volcanic edifices trending along the fault zone described in this work were most likely developed during Mid-Miocene but volcanism went on to be active until very recent times forming dykes and lava flows visible at the sea bottom (Courgeon et al., 2016, 2017). The acoustic masks below the volcanics around Bassas da India, Europa Islands and Hall Bank being located along the fault zone, we can assume that the volcanic mounts are rooted on deep faults that cannot be imaged from the seismic data because of the acoustic mask under the volcanics. In the peripheral areas of the Mozambique Channel, the end of the Miocene corresponds to a period of significant volcanism, probably the major episode in the region (Roberts et al., 2012). Therefore, some of the faults were probably already active as soon as Miocene times which is consistent with the tectonic framework of the EARS (Chorowicz, 2005; McGregor, 2015).

### *5.4. Significance of the fault zone in the framework of plate tectonics*

In terms of global plate tectonics and location of deformation zones between the Nubian and Somali plates, this study shows that one of the branches of this complex plate boundary (the eastern branch of the EARS) can be followed at least as south as 25°S trending toward the area where most of the kinematic studies locate the pole of rotation between Nubia and Somalia plates (see discussion above § 2; Fig. 1). As such, this study shows that the eastern branch of the East African Rift System is extending much further south than previously demonstrated with facts, not only in continental domains but also across the oceanic lithosphere of the Mozambique basin. As it is the case along the eastern branch of the EARS north of the studied area (Mulibo and Nyblade, 2013), the zone of lithospheric divergence presented in this paper, with a transform component toward the south, is probably responsible for the thinning and the rise of the mantle below which may be the cause of partial melting in the mantle sourcing the volcanic systems associated with the fault zone. This oceanic mantle rise is also probably responsible for the regional uplift linked with the anomalously high topography of the northern part of the Mozambique basin mentioned previously.

## 6. Conclusion

This study has shown that the eastern branch of the EARS extends offshore across the Mozambique Channel from the Davie Ridge to the Mozambique Ridge, where it is characterized by a zone of densely distributed faults, trending NNE-SSW and deforming the oceanic lithosphere of the Mozambique channel that developed much earlier, during Jurassic-Cretaceous times. The fault zone is well characterized within the sediments of the Mozambique basin and shows that faults have been active since at least the Miocene times and some of them are still seismically active (Fig. 10). Earthquakes with magnitude reaching Mw 6.1 around the Davie Ridge and Mw 5.7 around the Europa-Bassas da India Islands occurred along the fault zone during the last decades. The focal depths of the earthquakes are deeper than the sedimentary accumulations, probably within the mantle of the oceanic lithosphere of the Mozambique Basin. The fault zone structure is compatible with a purely extensional deformation around the Davie Ridge and a dextral transtensional system between the Davie Ridge and the Mozambique Ridge. This interpretation is also compatible with earthquake focal mechanisms (Fig. 10) and recently published kinematic models (Stamps et al., 2008; 2014, 2018; Saria et al., 2014). The fault zone activity is associated with volcanic activity controlling the development of the seamounts present within the Mozambique Channel. This active extensional process taking part of the EARS is probably associated with mantle rise that might be responsible for the anomalously high topography of the northern part of the Mozambique basin due to the presence of relatively hot rising mantle at depth. With active deformation onshore Africa, notably along the Inhaminga fault zone, and also along the Comoros-Mayotte and Madagascar system, the active fault zone of the Mozambique Channel is participating to the complex plate boundary between the African main continent (Nubia Plate) and Madagascar (Somalia Plate).


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## Appendix A. Supplementary data

Supplementary data to this article can be found at http://www.seanoe.org/data/00445/55634/ (Licence: Creative Commons Attribution, no commercial usage, sharing under the same conditions).

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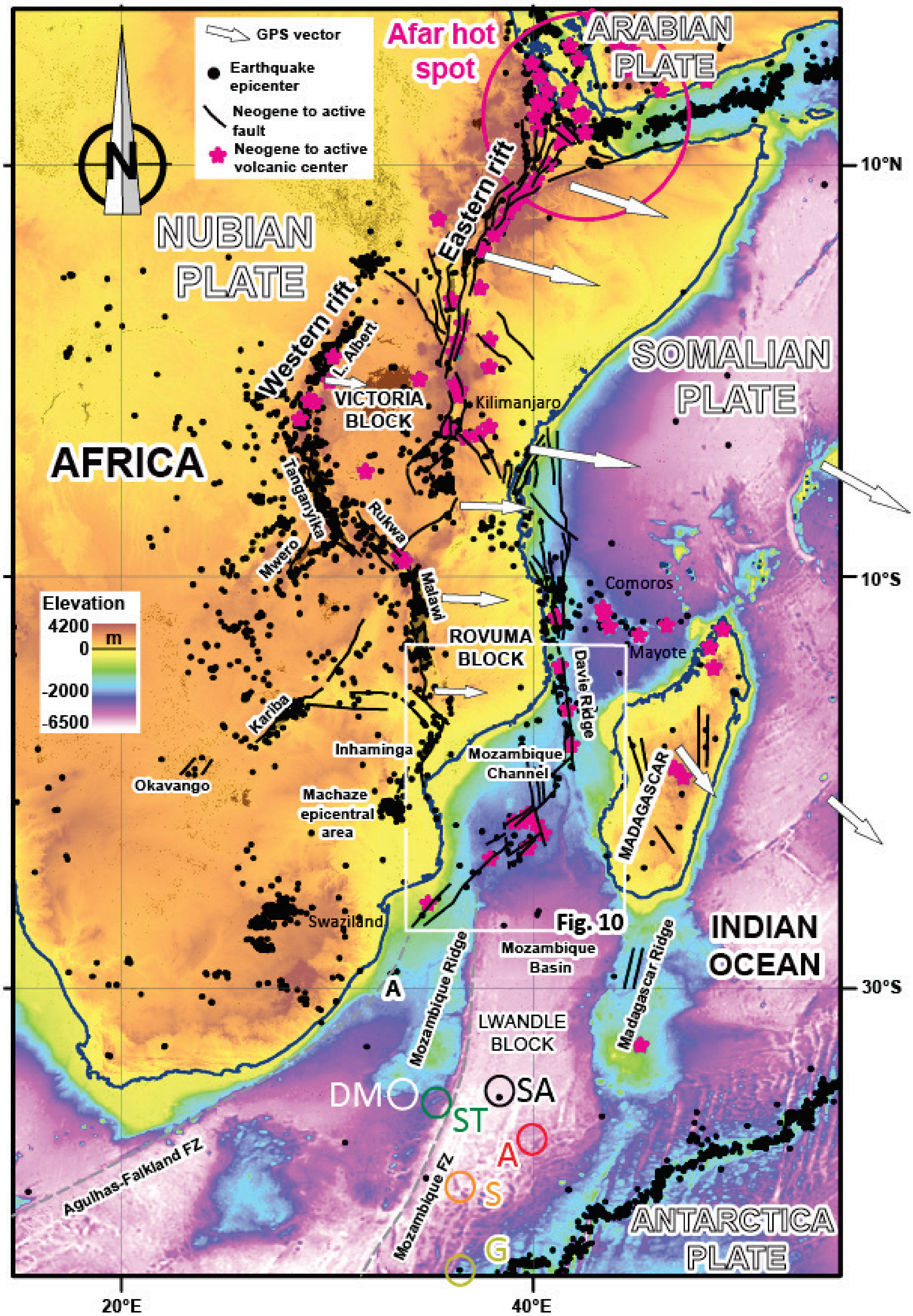
571 **Figures**

572




573

**Fig. 1.** Location of the study area in the context of plate boundary between the Nubian and Somali plates. Elevation/bathymetry grid from GEBCO. Black dots represent earthquake epicenters from the NEIC catalog (USGS). Black lines represent major faults along the EARS (compilation from Chorowicz, 2005; McGregor et al., 2015 on land; Franke et al., 2015 and this study offshore). Vectors show GPS velocities in a Nubia-fixed reference frame from Saria et al. (2013). The location of the rotation poles of Nubia *versus* Somalia are from Stamps et al., 2008 (ST), DeMets et al., 2010 (DM), Argus et al., 2010 (G), Altamimi et al., 2012 (A), Saria et al., 2013 (S), Saria et al., 2014 (SA). The Victoria, Rovuma and Lwandle plate are considered by these authors as relatively rigid poorly deformed blocks between the Nubia and Somalia plates. The limits of the Lwandle plate are poorly constrained by structural data. Point A corresponds to the location of the 31/12/1932 M 6.8 earthquake offshore South Africa.

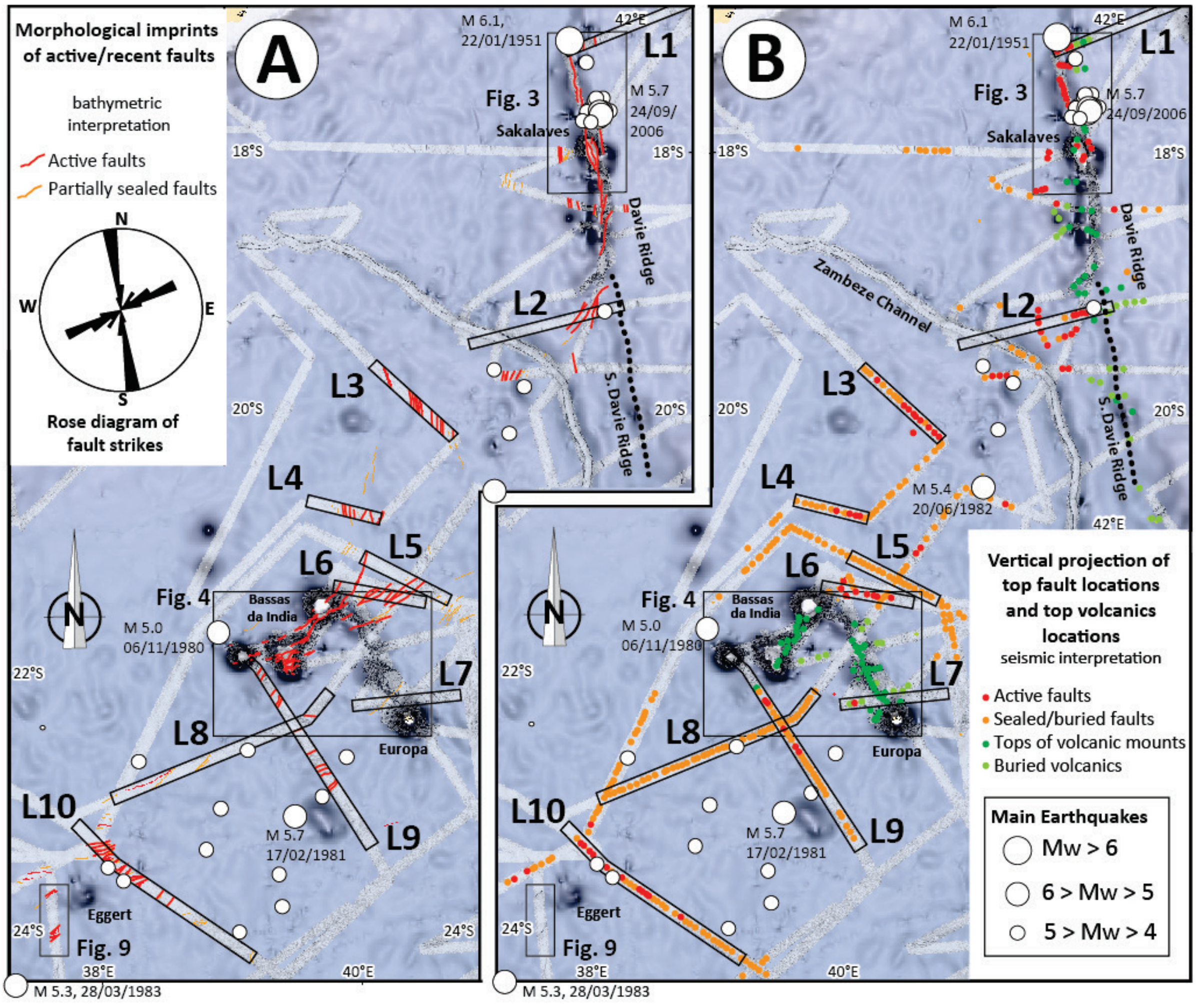



**Fig. 2.** Spatial distribution of faults in the Mozambique Channel. (**A**) Map showing the main faults visible at the sea bottom on multibeam data and rose diagram showing the preferential orientation of these faults. (**B**) Map showing the vertical projection at the sea floor of the top of the main faults and volcanic mounts interpreted on the vertical seismic data. Rectangles correspond to the location of figures 3, 4 and 9. L1 to L10 correspond to the location of the seismic profiles shown in figures 5 to 8. The comparison between map A and map B shows a very good fit for the location of the active fault zones in the area. The location of the faults is consistent with the location of the main earthquakes epicenters. The location of the piercing

volcanic spots is located along the active fault zones. Note also that the southern part of the Davie Ridge shows no evidence of active faulting or volcanism.

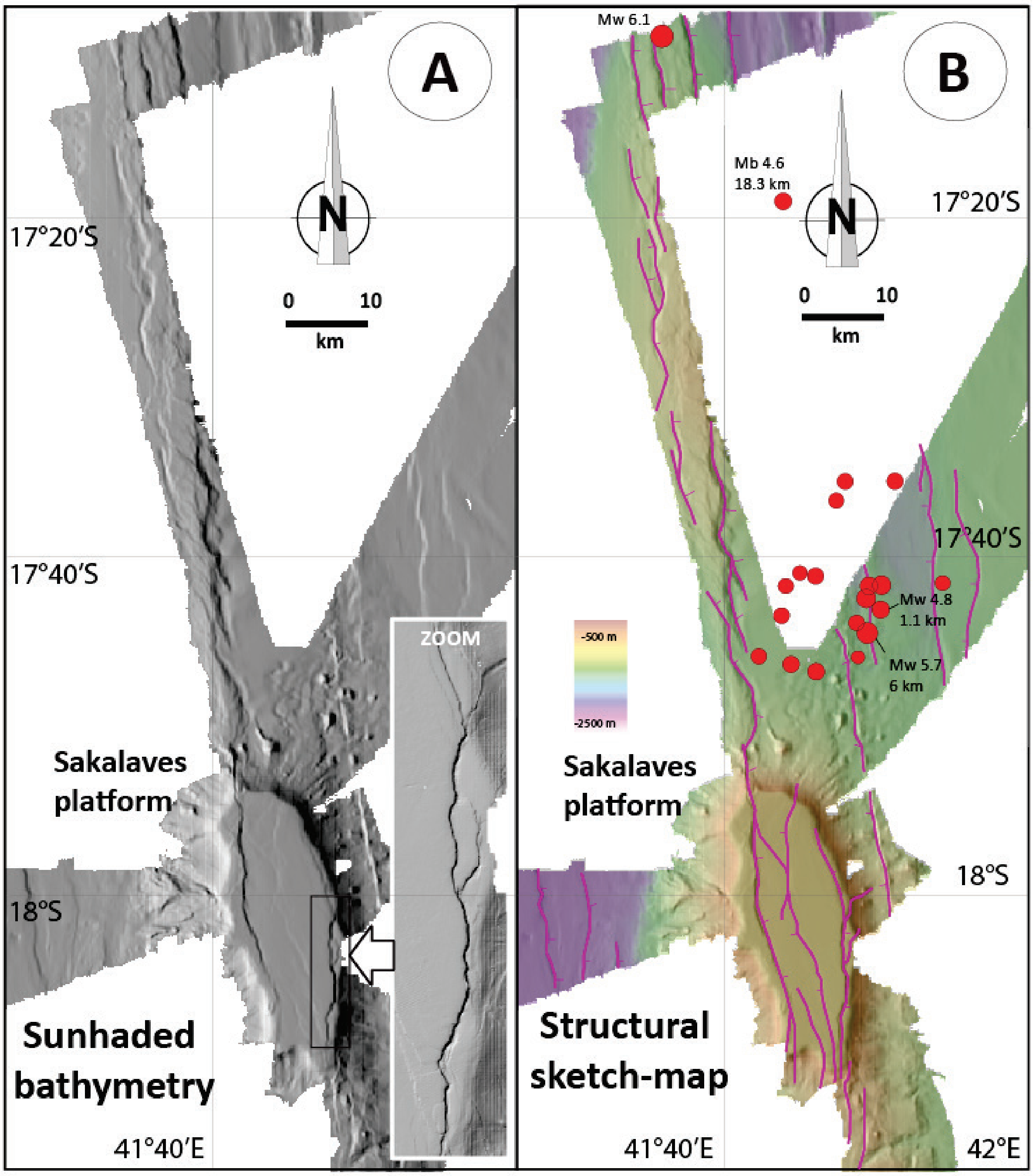
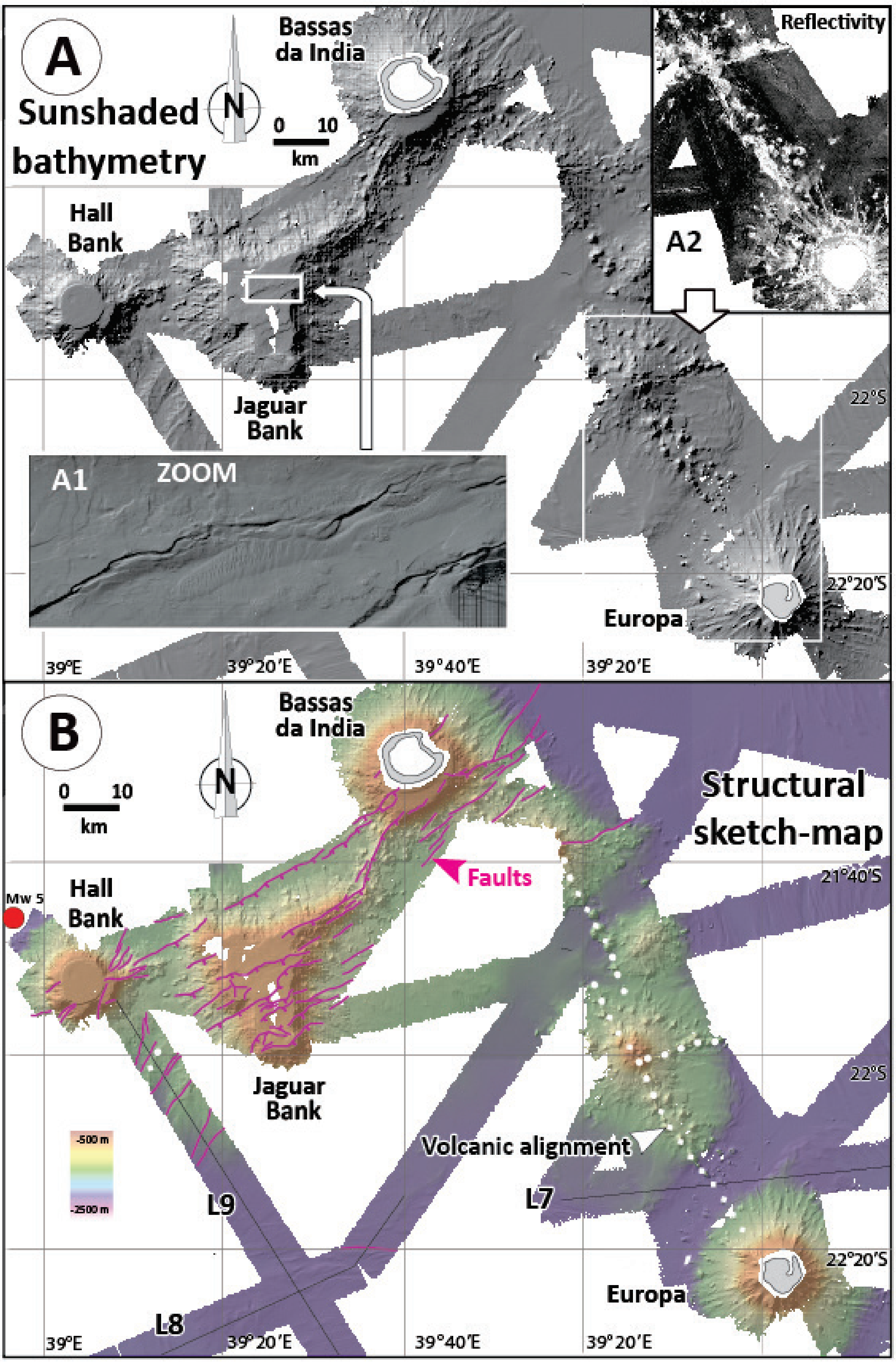



**Fig. 3.** Sunshaded bathymetry (**A**) and interpretative structural sketch-map (**B**) showing the fault pattern in the Sakalaves area. Dashes along faults indicate the down-thrown compartments.


A
Sunshaded bathymetry
Bassas da India
N
0 10
km
Reflectivity
A2
Hall Bank
Jaguar Bank
A1
ZOOM
22°S
22°20'S
Europa
39°E
39°20'E
39°40'E
39°20'E
B
Structural sketch-map
Faults
21°40'S
Mw 5
-500 m
-2500 m
Volcanic alignment
L9
L7
L8

609

610

**Fig. 4.** (**A**) Sunshaded bathymetry of the Bassas da India and Europa area. A1 is a zoom focusing on morphologic evidence of faults at the sea bottom. A2 corresponds to the reflectivity map outlining the volcanic alignments north-west of Europa. (**B**) Interpretative structural sketch-map showing the fault pattern in the Bassas da India and Europa area (modified from Courgeon et al., 2016, 2017). Dashes along faults indicate the down-thrown compartments.

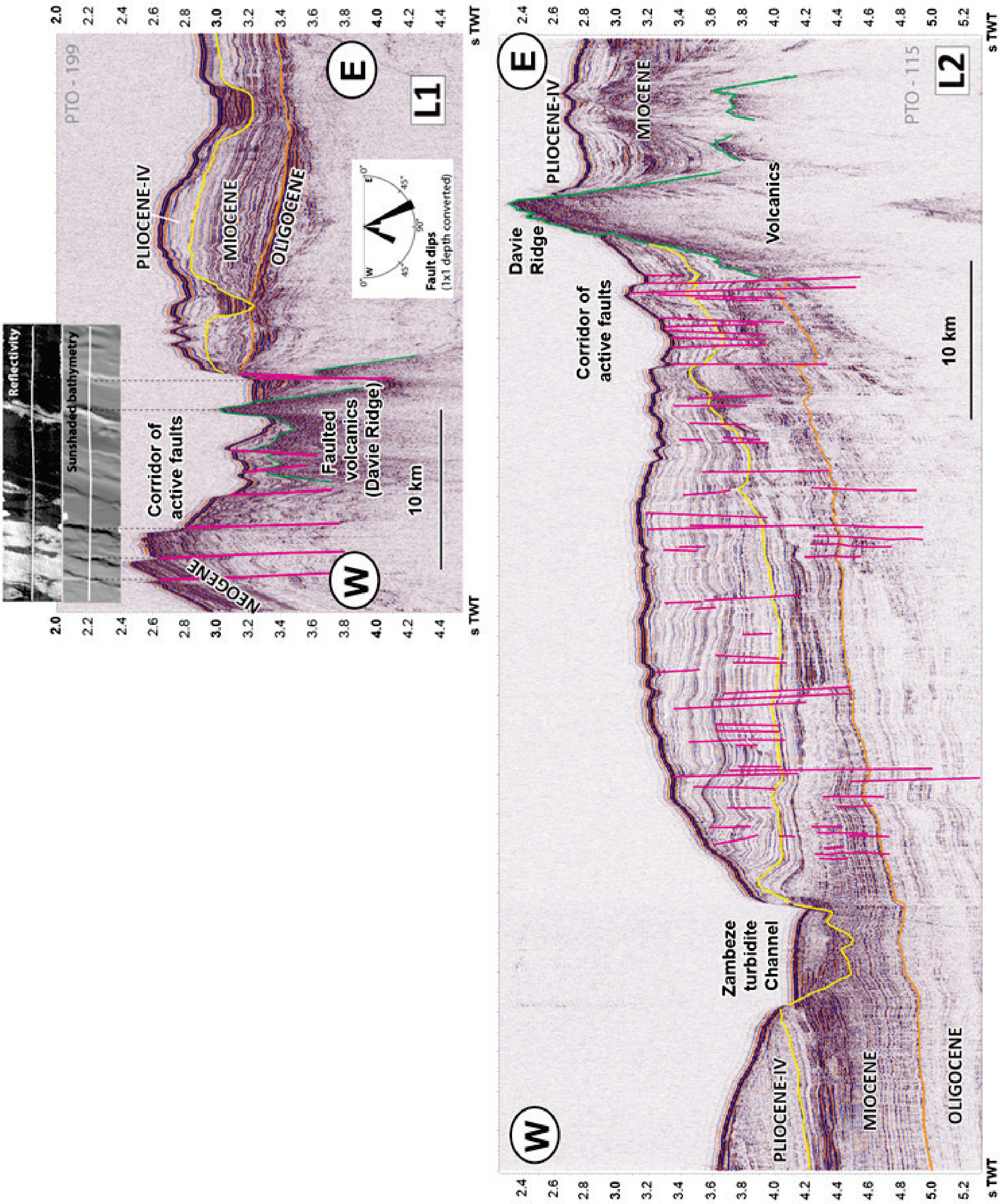



**Fig. 5.** Seismic profiles L1 and L2 illustrating the fault zone system of the Mozambique Channel in the area of the Davie Ridge. Location of L1 and L2 in figure 2.

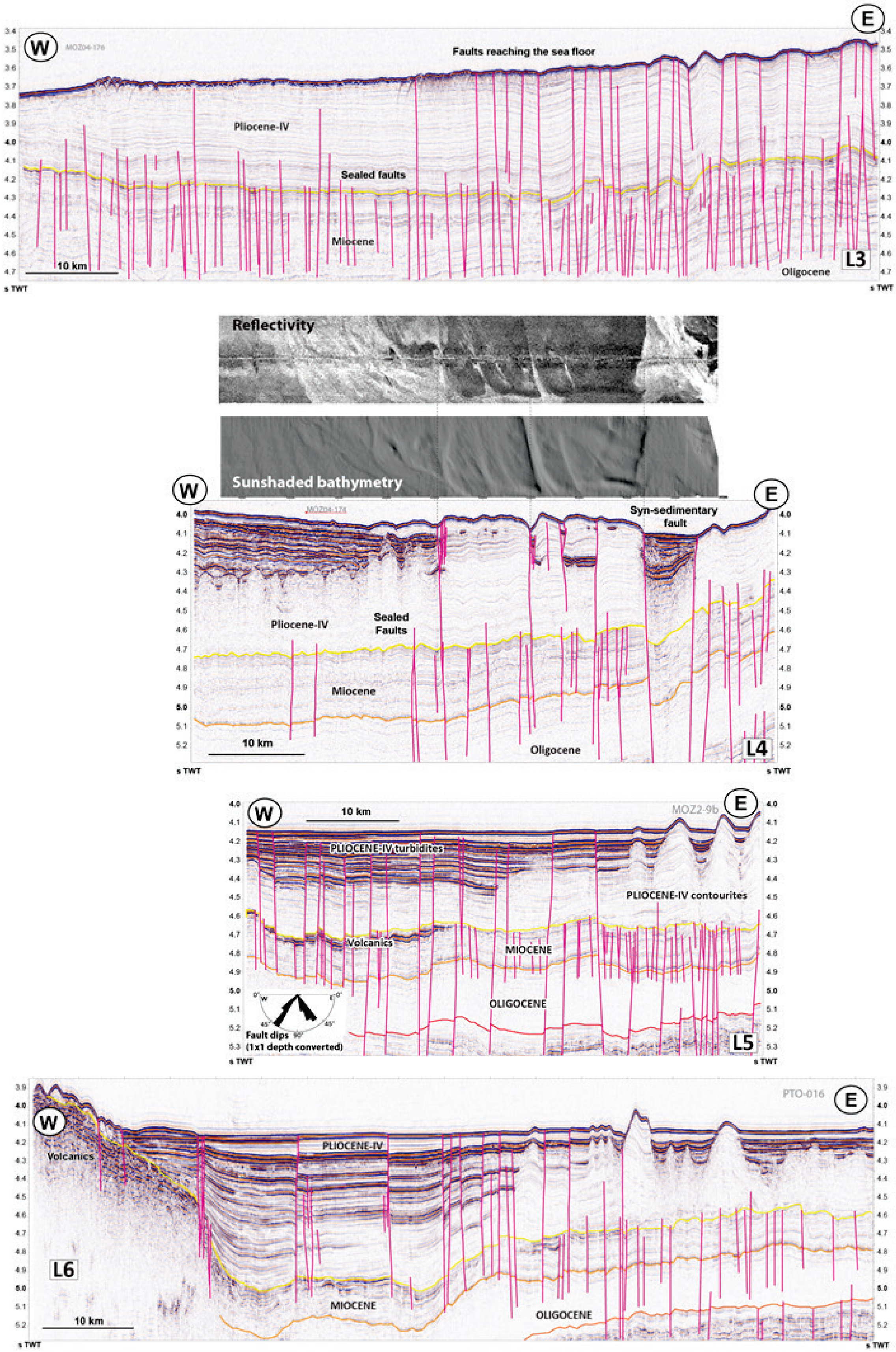

W
E
MOZ04-176
Faults reaching the sea floor
Pliocene-IV
Sealed faults
Miocene
Oligocene
10 km
L3
s TWT
Reflectivity
Sunshaded bathymetry
MOZ04-174
Syn-sedimentary fault
Pliocene-IV
Sealed Faults
Miocene
Oligocene
10 km
L4
MOZ2-9b
PLIOCENE-IV turbidites
PLIOCENE-IV contourites
Volcanics
MIOCENE
OLIGOCENE
Fault dips (1x1 depth converted)
L5
PTO-016
PLIOCENE-IV
Volcanics
MIOCENE
OLIGOCENE
L6

**Fig. 6.** Seismic profiles illustrating the fault zone system of the Mozambique Channel north of Bassas da India (profiles location in figure 2).

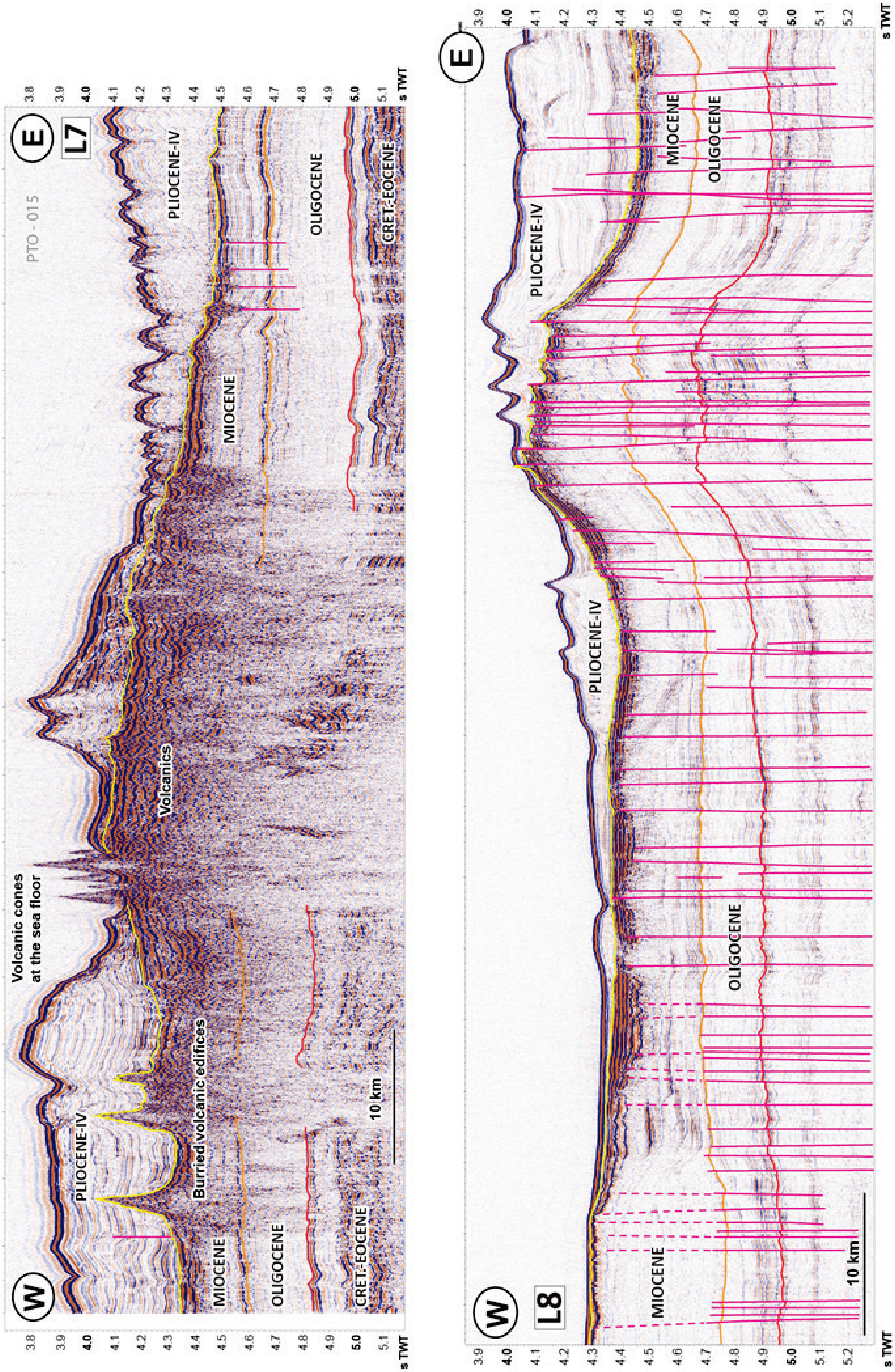

W
E
L7
PTO - 015
PLIOCENE-IV
MIOCENE
OLIGOCENE
CRET.-EOCENE
Volcanic cones at the sea floor
Burried volcanic edifices
Volcanics
10 km
s TWT
L8

**Fig. 7.** Seismic profiles South of Bassas da India (profiles L8 and L7 located in figure 2). L7 illustrates the presence of volcanic systems and deeply buried seamounts. L8 shows local folding and uplift at least of the pre-Pliocene sediments.

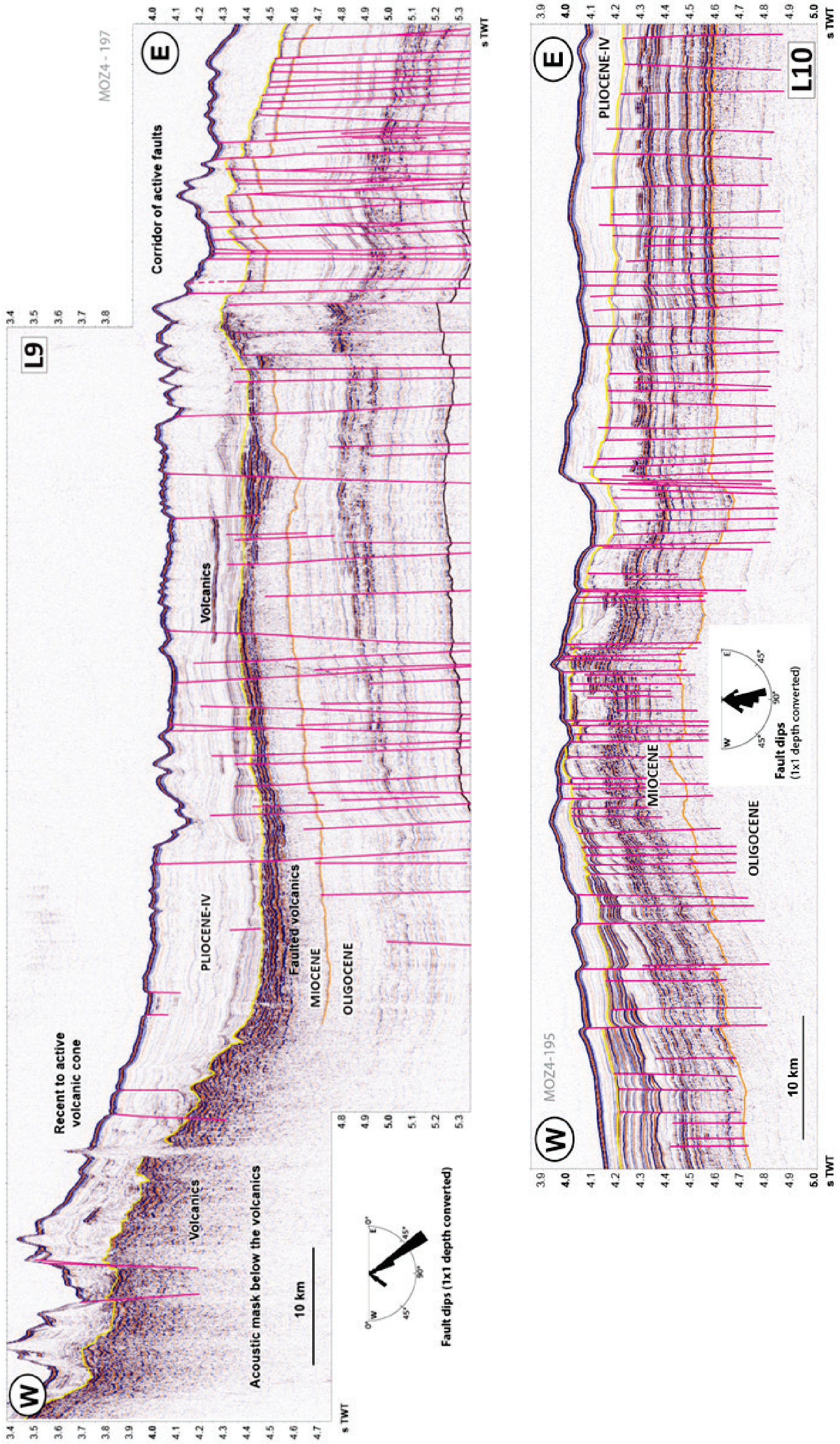

L9
MOZ4 - 197
W
E
Corridor of active faults
Recent to active volcanic cone
Volcanics
PLIOCENE-IV
Faulted volcanics
MIOCENE
OLIGOCENE
Acoustic mask below the volcanics
10 km
Fault dips (1x1 depth converted)
s TWT
L10
MOZ4-195
Fault dips (1x1 depth converted)

**Fig. 8.** Seismic profiles illustrating the fault zone system of the Mozambique Channel south of Bassas da India (profiles L9 and L10 located in figure 2).Profile L9 illustrates the relationship between the fracture network and volcanic activity. The faults expressed at the bottom of the sea are recent to active whereas the faults sealed by the superficial sediments indicate a stoppage of their functioning. Note the presence of a volcanic peak and a volcanic unit marked by very high amplitudes which covers the older sedimentary series.

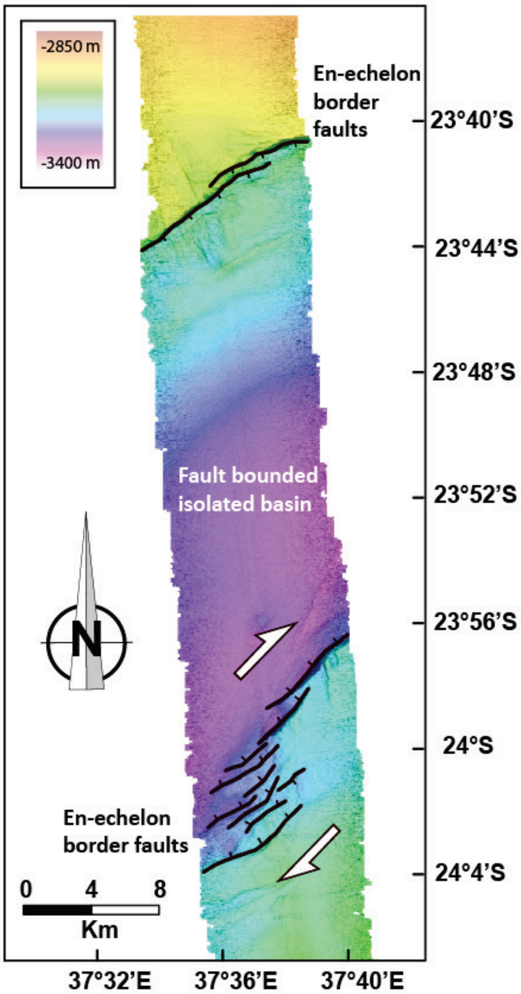
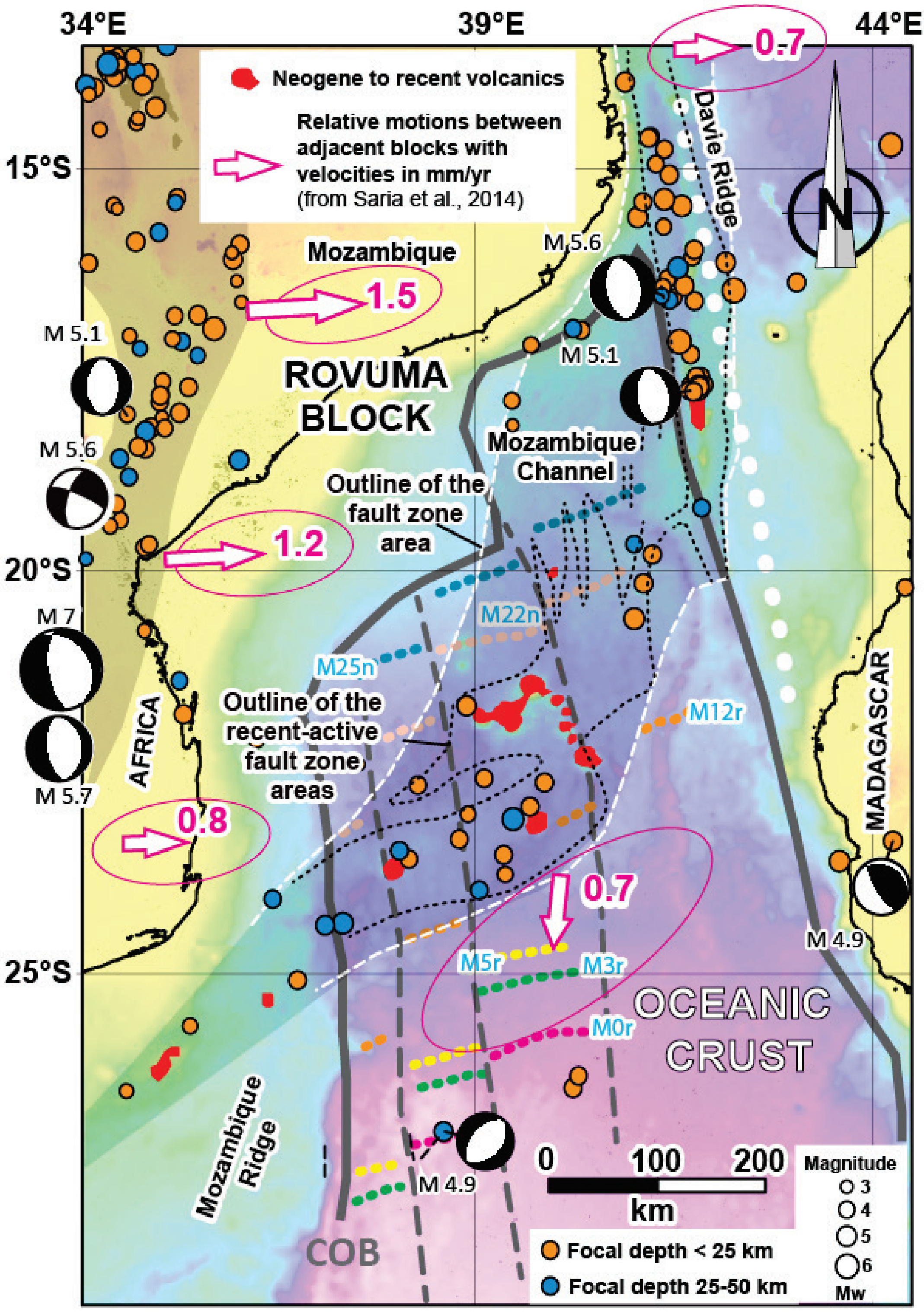



**Fig. 9.** Multibeam map crossing a depression along the fault zone showing en-échelons border fault system characterizing a normal-dextral movement.


34°E
39°E
44°E
15°S
20°S
25°S
Neogene to recent volcanics
Relative motions between adjacent blocks with velocities in mm/yr
(from Saria et al., 2014)
0.7
Davie Ridge
Mozambique
1.5
M 5.6
M 5.1
M 5.1
ROVUMA BLOCK
M 5.6
Mozambique Channel
Outline of the fault zone area
1.2
M22n
M 7
M25n
M12r
Outline of the recent-active fault zone areas
AFRICA
MADAGASCAR
M 5.7
0.8
0.7
M 4.9
M5r
M3r
M0r
OCEANIC CRUST
Mozambique Ridge
M 4.9
0
100
200
km
Magnitude
3
4
5
6
Mw
COB
Focal depth < 25 km
Focal depth 25-50 km

651

652

**Fig. 10.** Structural sketch-map of the Mozambique channel area (see location in Fig. 1) showing the extent of the fault zone crossing the Mozambique Channel from NE to SW with the location of the main corridors of recent to active faults (area bounded by white dotted lines: fault zone studied in this paper; area bounded by black dotted lines: active fault zones). grey areas correspond to the western and eastern branch of the EARS and the fault system area described in this paper. Thick dotted line: Davie Ridge. Earthquake depths from the NEIC catalog (USGS). Earthquake focal mechanisms from the Global Centroid Moment Tensor database (Ekström et al., 2012). Pink arrows: relative motions between plate tectonic blocks from Saria et al. (2014). Elevation/bathymetry grid from GEBCO. In red: main volcanic systems. Location of the oceanic crust and oceanic fracture zones compiled from Konig and Jokat (2010), Leinweber and Jokat (2012), Davis et al. (2016) and Mueller and Jokat, (2017). Magnetic anomalies are from Davis et al. (2016). COB: Continent-Ocean Boundary.

## Supplementary files

| DATE | TIME | LON | LAT | DEPTH | AUTHOR | MW | STRIKE | DIP | RAKE |
|---|---|---|---|---|---|---|---|---|---|
| 24/07/1991 | 54:52.4 | 34.62 | -18.3 | 24.7 | HRVD | 5.1 | 0 | 45 | -90 |
| 22/02/2006 | 19:07.8 | 33.33 | -21.2 | 12 | HRVD | 7 | 172 | 65 | -78 |
| 23/02/2006 | 23:42.2 | 33.18 | -21.33 | 12 | HRVD | 5.7 | 172 | 58 | -91 |
| 17/09/2006 | 24:54.5 | 41.71 | -17.54 | 19.6 | GCMT | 5.1 | 174 | 52 | -86 |
| 24/09/2006 | 56:21.7 | 41.78 | -17.59 | 12 | GCMT | 5.6 | 171 | 50 | -89 |
| 09/10/2011 | 47:16.8 | 38.88 | -26.89 | 30.8 | GCMT | 4.9 | 44 | 40 | -86 |
| 25/01/2013 | 37:02.1 | 43.58 | -23.73 | 24 | GCMT | 4.9 | 149 | 70 | 102 |
| 24/06/2017 | 02:37:20 | 34.48 | -19.42 | 27 | GCMT | 5.6 | 292 | 67 | 163 |

**Table S1 –** Earthquake focal mechanisms used in this paper.

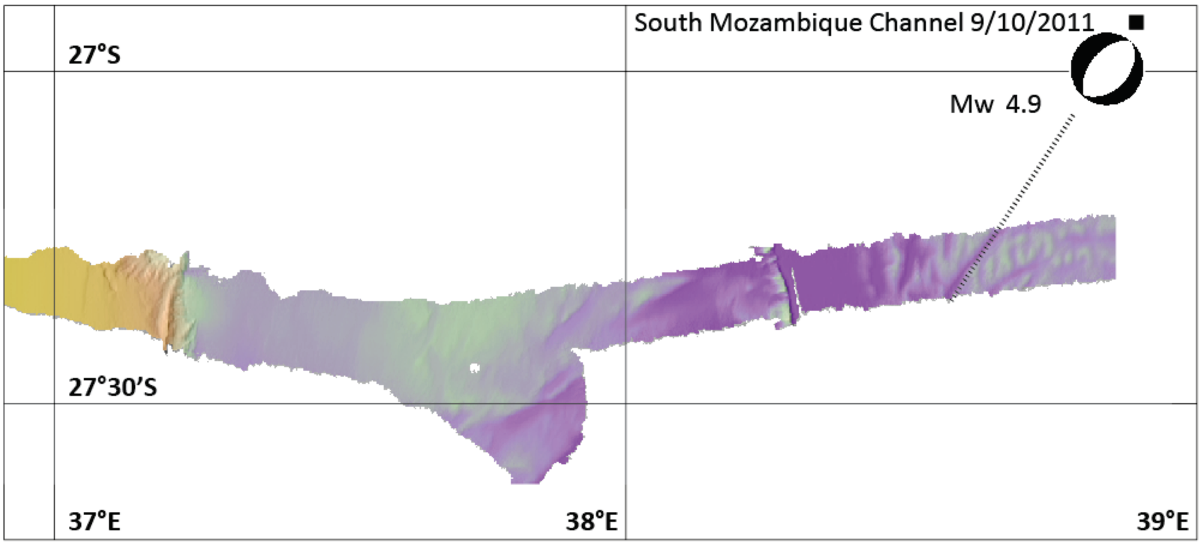



**Fig. S1 –** Available bathymetric data close to the Mw 4.9 earthquake (9/10/2011) south of the Mozambique Channel.

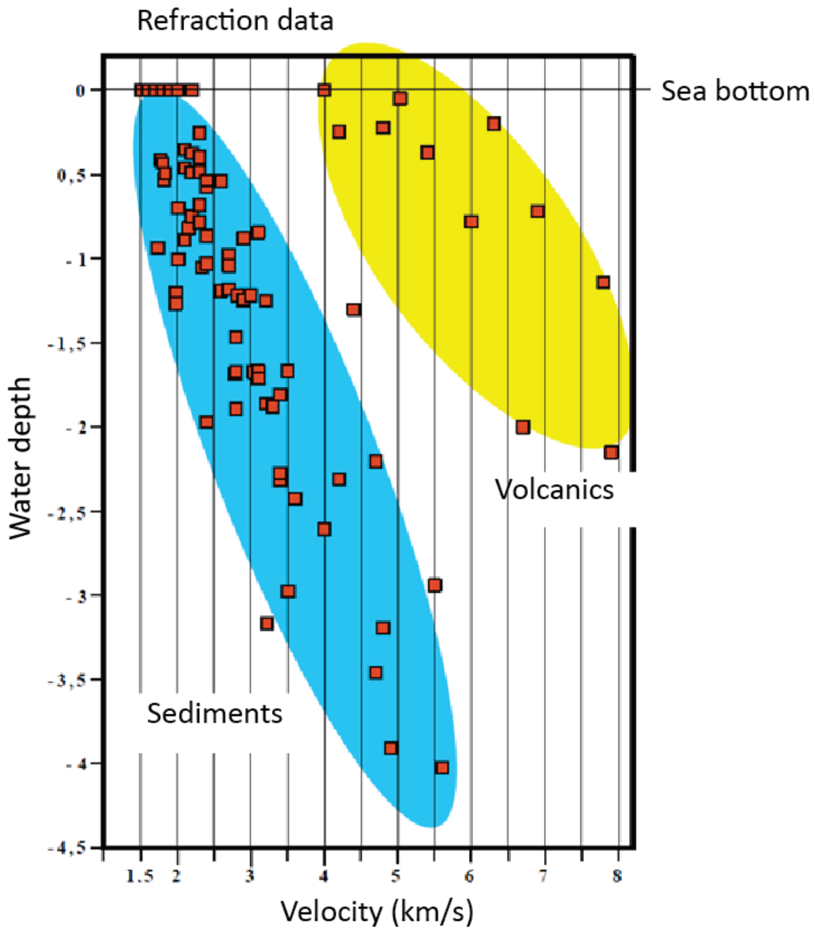



**Fig. S2** – Seismic velocities deduced from refraction studies (from unpublished IFP rapport).

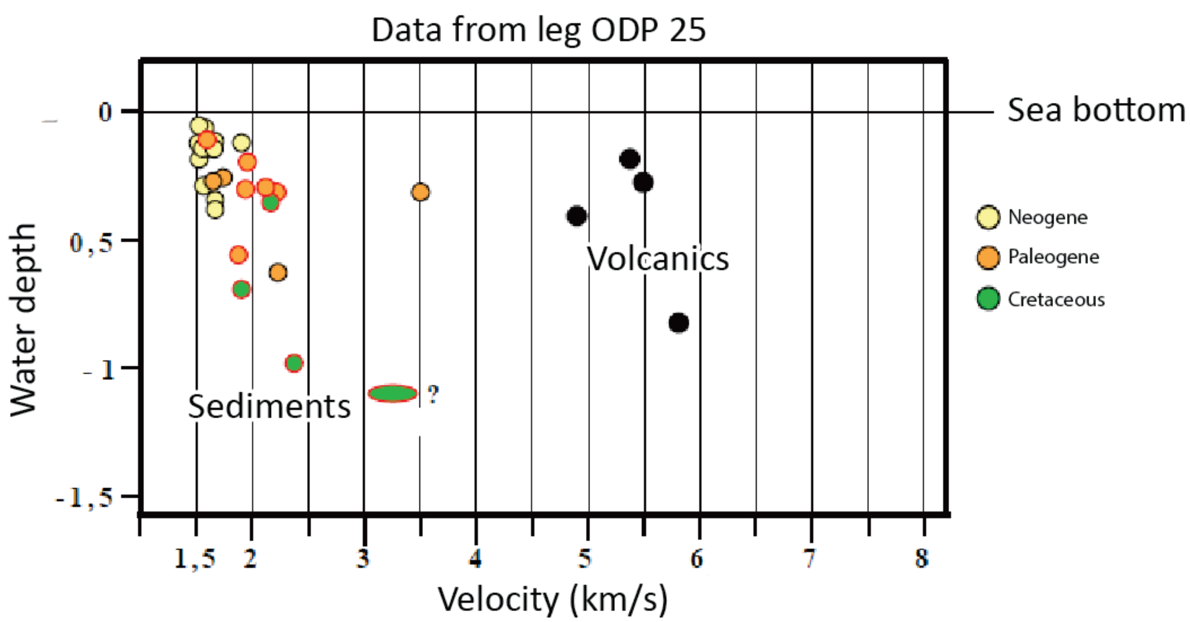


**Fig. S3** – Seismic velocities deduced from available well data (ODP leg 25, wells 242, 248, 250).