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Title: Impact of the East African Rift System on the routing of the deep-water drainage network offshore Tanzania, western Indian Ocean.

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Abstract

The East African Rift Systems (EARS) exerted a major influence on river drainage basins and regional climate of east Africa during the Cenozoic. Recent studies have highlighted an offshore branch of the EARS in the western Indian Ocean, where the Kerimbas Graben and the Davie Ridge represent its sea floor expression. To date, a clear picture of the impact and timing of this EARS offshore branch on the continental margin of the western Indian Ocean, and associated sediment dispersal pathways, is still missing. This study presents new evidence for four giant canyons along the northern portion of the Davie Ridge offshore Tanzania. Seismic and multibeam bathymetric data highlight that the southernmost three canyons are now inactive, supra-elevated relative to the adjacent sea floor of the Kerimbas Graben and disconnected from the modern slope systems offshore the Rovuma and Rufiji River deltas. Regional correlation of dated seismic horizons, integrated with well data and sediment samples, proves that the tectonic activity driving the uplift of the Davie Ridge in this area has started during the middle-upper Miocene and is still ongoing, as suggested by the presence of fault escarpments at the sea floor and by the location and magnitude of recent earthquakes. Our findings contribute to placing the Kerimbas Graben and the Davie Ridge offshore Tanzania in the regional geodynamic context of the western Indian Ocean and show how the tectonics of the offshore branch of the EARS modified the physiography of the margin, re-routing the deep-water drainage network since the middle Miocene. Future studies are needed to understand the influence of changing sea floor topography on the western

Indian Ocean circulation and to evaluate the potential of the EARS offshore tectonics in generating tsunamigenic events.

1. Introduction

Tectonics exerts an overarching control on the evolution of terrestrial and marine landscapes, mainly through the modification of the topographic relief (Leeder and Jackson, 1993; Schumm et al., 2000). In the last decades, a huge effort has increased our understanding of geodynamic processes leading to the onset of the East African Rift Systems (EARS; Ebinger and Sleep, 1998; Moucha and Forte, 2011 and references therein). However, there is very little knowledge of the links between the Neogene tectonics of the EARS and the development of structural features in the western Indian Ocean.

The timing of the initiation of the EARS dates back to the Oligocene (Macgregor, 2015, and references therein). The origin of the EARS has been related to the onset of a mantle plume, which generated a topographic anomaly beneath the Ethiopian and East Africa plateaux (Ebinger and Sleep, 1998). Normal faulting and regional uplift associated with the EARS exerted a major control on the development of the drainage basins of large African rivers, such as the Congo, Nile, and Zambesi (Goudie, 2005; Stankiewicz and de Wit, 2006; Roberts et al., 2012), and on the formation of rift lakes (Cohen et al., 1993; Macgregor, 2015). After the seminal work of Mougenot et al. (1986), a recent study by Franke et al. (2015) highlighted the stratigraphy and architecture of the offshore branch of EARS in the western Indian Ocean offshore Mozambique. Here, the rift consists of a juvenile fault zone at about 17° S, and of the Lacerda half-graben and the southern part of the Kerimbas graben up to ca. 10° S (Franke et al., 2015). Farther north, offshore of Tanzania, the EARS stretches along the northern part of Kerimbas Graben, which is characterized by a well-developed N-S trending depression bordered by normal faults and confined on its eastern side by the Davie Ridge (Fig. 1). Although the effects of the rifting in modifying subaerial landscapes and the related consequences on the evolution of early hominids and atmospheric circulation have been established (Sepulchre et al., 2006; Maslin et al., 2014), the control of the EARS on location and shape of the deep-water drainage network has not been investigated, and a clear picture of the evolution of the western Indian Ocean is still missing.

This contribution presents the discovery of four giant deep-water canyons (up to 15 km wide and up to 850 m deep in water depths >2,500 m), herein named C-1 to C-4 from north to south, incising the Davie Ridge and of which three (C-2 to C-4) are currently disconnected from the active slope channels offshore the Rovuma and Rufiji River deltas. The three canyons appear to be relict features corroborating the existence of an older drainage network that was destroyed by the tectonic activity associated with the offshore branch of EARS. Our findings reveal how EARS affected the physiography of the western Indian Ocean, resulting in the formation of a new sediment routing system, and provide new insights in the chronology and architectural features of the margin.

2. Geological setting

The history of the western Indian Ocean can be traced back to the Early Jurassic, when the onset of rifting occurred between Madagascar and Africa (Revees and de Wit, 2000; Revees et al., 2016). Sea floor spreading started in the Middle Jurassic and continued until the Early Cretaceous (Coffin and Rabinowitz, 1992), leading to the southward drift of Madagascar along the dextral strike-slip structures of the Davie Fracture (or at least along part of it, see below and discussion in Klimke and Franke, 2016) and the Lebombo-Explora Fracture Zones (Revees and de Wit, 2000). From the Cretaceous to the Paleogene (mid-Oligocene), the East

African margin was characterized by a period of stability and thermal subsidence (Kent et al., 1971; Salman and Abdula, 1995), which was recorded by deposition of the Kilwa Group in Tanzania (Nicholas et al., 2006; 2007). The passive margin phase was interrupted by a period of neo-rifting and tectonic reactivation: the onset of new mantle circulation beneath the African continent (Ebinger and Sleep; 1998; Moucha and Forte, 2011), known as the African super-swell (Nyblade and Robinson, 1994), evolved into the EARS with synchronous initiation along its western and eastern branches (Chorowitz, 2005; Roberts et al., 2012). Normal faulting and rifting were widespread along the Tanzanian margin during the Miocene, promoting the formation of topographic highs, such as Zanzibar, Pemba and Mafia Islands, and lows, such as the coastal basins and the Kerimbas Graben (Kent et al., 1971; Mougenot et al., 1986). Recent studies, however, highlighted the presence of folding and inversion structures on a seismic profile across the channel north of Zanzibar Island (Sii and Underhill, 2015), suggesting that the islands are compressional features associated with fault reactivation and basin inversion.

2.1. Kerimbas Graben and Davie Ridge in the offshore of Tanzania

The EARS consists of a series of tectonic basins bordered by uplifted shoulders, which extend for thousands of kilometres along two main lineaments, called the western and eastern branches (Chorowitz, 2005). The continuation of the eastern branch offshore of Tanzania can be traced along the Pemba and Mafia basins, while farther to the south it runs along the Kerimbas and Lacerda grabens (Fig. 1), until ending in a juvenile fault zone at about 17° S, in the offshore Mozambique (Mougenot et al., 1988; Franke et al., 2015).

The Kerimbas Graben was firstly recognised by Mougenot et al. (1988) north of the Saint-Lazare Seamount (Fig. 1). A compilation of recently acquired multibeam data (Dorschel et al., 2018) highlights that the graben, north of 12° S, can be divided in four zones based on sea floor morphology and water depth (Fig. 2). In zone 1, which extends from the Saint-Lazare Seamount up to 11.5° S (Fig. 2), the graben is asymmetric, with the western side running along the base of the slope of the northern Mozambique margin and gently dipping at ca. 0.7° to the east, whereas the eastern flank corresponds to a 12° west-dipping fault escarpment (Fig. 2, blue arrow). The sea floor eastward of the escarpment shows a series of morphological steps related to N-S trending faults before gently dipping towards the Indian Ocean (Fig. 2). In zone 2, between 11.5° S and 10° S, the Kerimbas is a 30-40 km wide symmetric graben bounded by ca. 15° steep flanks (Fig. 2, green and red arrows). N-S trending lineaments, representing fault escarpments, are visible at the sea floor that lies at an average water depth of ca. 2,900 m and gently dips to the north (Fig. 2). The western side of the graben runs along the base of the slope in the offshore Rovuma River delta, whereas the eastern side corresponds to the Davie Ridge (Fig. 2). A series of channels and gullies cut the western flank and are visible on the sea floor (Figs. 1, 2). The third zone, located just offshore the Rovuma River between at 10° S (Fig. 2), corresponds to a bathymetric sill with a maximum water depth of ca. 2,750 m (Fig. 2). Here, the Kerimbas Graben shows asymmetric flanks, with a gentler western side up to 1.5° and a 12° dipping eastern side. In zone 4, reaching approximately 8.5° S, the graben shows a different morphology with a maximum water depth up to ca. 3,500 m and a maximum width up to 90 km (Figs. 1, 2). In this area, the western flank of the graben partially corresponds to a structural high (the Seagap Ridge) generated by the tectonics of the Seagap transform fault (Fig. 2; Revees et al., 2016), while the western side corresponds to the northern termination of the Davie Ridge (Fig. 2). A series of arcuate steps is visible on the sea floor of the graben, likely associated to normal faults developing at the base of the Davie Ridge (see supplementary Figure S1).

The Davie Ridge appears as a bathymetric high roughly extending N-S and dissecting the continental slope in the offshore East Africa for more than 1,000 km south of 9° S (Mahanjane, 2014; Courgeon et al., 2018). The maximum elevation curve of the Davie Ridge (calculated as the depth difference between the top of the ridge and the floor of the Kerimbas Graben along a section, see Figs. 1 and 2) shows an overall decrease in elevation to the north (Fig. 2). Heirtzler and Burroughs (1971) firstly described the Davie Ridge as a *ridge-like feature*, asymmetric, with a steep western flank (up to 30°) and a gently dipping eastern flank (ca. 0.65° in the offshore Rovuma delta; Fig. 1). Heirtzler and Burroughs (1971) interpreted the ridge as the bathymetric expression of the transform fault that accommodated the southward drift of Madagascar relative to the African continent. The continuation of the Davie Ridge north of 9° S, where the ridge does not have a prominent morphological expression on the sea floor (Fig. 1), has been derived by gravimetric and magnetic data showing a series of anomalies, up to 2.5° S (Rabinowitz, 1971; Scrutton, 1978; Coffin and Rabinowitz, 1987). The entire lineament, extending from ca. 20° S to 2.5° S, was named the *Davie Fracture Zone* by Scrutton (1978). A recent study from Klimke and Franke (2016), however, argued the existence of a transform fault extending from northern Mozambique to Kenya and interpreted the Davie Ridge visible on the bathymetry between 15° S and 9° S (on the eastern side of the Lacerda and Kerimbas grabens) as a rift-flank uplift, originated during the Neogene and probably correlated with the evolution of the EARS in the offshore domain. This interpretation is in agreement with GPS vector data and focal mechanisms of recorded earthquakes showing pure normal faulting with N-NW trending nodal planes and roughly E-W extensional failures (Grimison and Chen, 1988; Calais et al., 2006; Yang and Chen, 2010).

3. Data and Methods

3.1. 2D Seismic data

The present study uses two seismic datasets: (1) the GLOW survey (Paleogene GLObal Warming events, GLOW Cruise; Kroon and the Shipboard Scientific Party, 2010) performed onboard of the R/V Pelagia in 2009 and consisting of 2,450 km of seismic lines; and (2) the multi-client 2D seismic dataset Tanzania, acquired by WesternGeco-Schlumberger in 1999-2000 and consisting of 5,550 km of seismic lines.

The GLOW seismic survey was carried out using an array of four airgun sources (10, 20, and 2× 40 in^3, equivalent to 0.16, 0.33, 2× 0.65 litres, respectively) and a 24-channel streamer as a receiver. The seismic data were recorded using the GeoResources Geo-Trace 24 system. The far field signal of the source array shows a peak frequency centred within the range of 50-150 Hz, with a frequency content up to 400 Hz. The guns were towed in a frame at a depth of 1.7 m, 42 m behind the stern of the ship, and fired every 10 seconds at a pressure of 115 bars. The average sailing speed was 4.2 knots (7.8 kmh^{-1}) that resulted in an average distance between the shots of 21 m. The streamer consisted of four 63 m long active sections with 6 channels each (channel interval 10.5 m). Each channel consists of ten 1-m-spaced Teledyne T2 hydrophones. The streamer is ended by a 0.5 m tail-end, which contains the last terminating end connector. The receiver was connected to the ship by a 60-m-long tow leader and by 25-m-long stretch section. The streamer was towed at a depth of 1 m below the surface. Three (front, mid, end) I/O systems 5010 DigiBIRDS were used to keep the streamer at depth. During the recording of line 2 one bird failed. From line 3 onwards only 2 birds (front, end) were used. This had no noticeable effect on the streamer position. The record length was 7.5 s (including the water column) and the sampling rate was 2 kHz for the first lines. From line 5 onwards the sampling rate was 1 kHz. The data were recorded with a 10 Hz high pass filter. The vertical resolution of the seismic data in the investigated section ranges between 2.5 m and 5 m, calculated considering a peak frequency of 150-200 Hz and interval velocities of 1,800-2,900 ms^{-1}.

Processing of the data was performed at NIOZ by means of the software package RadexPro (DECO Geophysical, Moscow). The processing sequence included data loading, 30-700 Hz bandpass filtering, amplitude correction, an interactive velocity analysis, NMO correction, 6 fold CDP-stacking, Stolt F-K migration and water column muting.

The 2D survey offshore Tanzania was shot by WesternGeco using a 5,200-m-long streamer with hydrophones at a 12.5 m receiver interval. In 2012, the legacy 2D was reprocessed by WesternGeco using Anisotropic Kirchoff pre-stack time migration in order to improve signal resolution. One of the key processing challenges was represented by the presence of strong seabed multiples and inter-bed multiples. The reprocessed 2D seismic lines produced an overall better reflection detail, enhanced data resolution, and improved fault definitions and events continuity, thus providing much higher confidence during interpretation of geological features. The vertical resolution of the seismic data in the investigated section ranges between 7 m and 14 m, calculated considering a peak frequency of 50-60 Hz and interval velocities of 1,800-2,900 ms^{-1}.

A post-stack seismic attribute, i.e., the root-mean-square (RMS) amplitude, was used to support the interpretation. In detail, the RMS, which represents the square root of the arithmetic mean of the squares of the seismic amplitudes within a defined window interval, helped to unravel the presence of coarse-grained facies (Rijks and Jauffred, 1991; Chen and Sidney, 1997; Brown, 2004).

Additional data used in this study include the multichannel seismic profiles acquired during the R/V VEMA cruises 3618 and 3619 (Coffin and Rabinowitz, 1982), and available through the Marine Geoscience Data System (http://www.marine-geo.org/index.php), and published seismic profiles (Mougenot et al., 1986; Franke et al., 2015).

3.2. Multibeam echosounder data

During the GLOW survey, bathymetric data were collected with a Kongsberg EM302 multibeam echosounder, permanently installed on board the R/V Pelagia. The maximum swath opening angle was 150 degrees. The transmitter array had a beam opening angle of 1 degree while the receiver array had a beam opening angle of 2 degrees. These arrays were connected to a transceiver unit (TRU). The TRU received corrections for heave, roll, and pitch from a Kongsberg MRU5 motion sensor. A Seapath200 served as positioning and heading system. The sound velocity in the water column was determined from a salinity/temperature CTD deployment and calculated using the Chen-Millero formula (Chen and Millero, 1977). Data Processing was performed using the Neptune (Kongsberg) and Fledermaus (QPS) software packages. The data were presented as a 100 × 100 m surface grid and integrated with the Southwest Indian Ocean Bathymetric Compilation (swIOBC; Dorschel et al., 2018), available at a 250 m horizontal resolution.

3.3. Sediment samples

Short seabed samples were collected during the GLOW cruise using a NIOZ designed box corer with a diameter of 30 cm and a height of 55 cm. The box corer was supplied with a lid that closes the box from the top as soon as it penetrated the sediment. This configuration avoided the sloshing of water above the sediment surface during the recovery, resulting in an undisturbed sample of the seabed surface sediments. On deck the bottom water was siphoned off and the surface sediments were described and photographed. Four plastic liners were inserted and retrieved from the core. These subsamples were stored at a temperature of 4° C. A key objective of the GLOW survey was to take sediment cores where fossil stratigraphic layers crop out at the sea floor in order to provide age control on seismic reflectors. This occurred on flanks of submarine channels (see supplementary material). Samples were washed over a 63 micron sieve and dried at 40° C in an oven. Washed residues were studied for index fossils, and biostratigraphic age assignments were made following Wade et al. (2011).

3.4. Well data

Eight exploration wells (Fig. 1) with check-shots, velocity models, and biostratigraphic information were made available for this study by Royal Dutch Shell and Shell Tanzania. The wells were tied to specific seismic reflectors, allowing the age determination of the seismic horizons.

4. Results

4.1. Stratigraphy of the Davie Ridge

The stratigraphy of the Davie Ridge is highlighted in Figure 3, on a seismic profile oriented NNW-SSE along the crest of the ridge, and in Figure 4, on a section oriented W-E crossing the eastern side of the Kerimbas Graben.

Horizon H1 at the base of sequence S1 presents a laterally variable seismic reflection amplitude (Fig. 3). At places, H1 shows channel-like erosional features that cut older sediments, as highlighted by the presence of truncated reflectors (Fig. 4). Overall, sequence

S1 (confined between H1 and H2) shows low amplitude to transparent reflections, wavy, and discontinuous (Fig. 3). Overall, S1 has low RMS amplitude values (Fig. 4). Higher amplitude reflections, sub-horizonal or shingled, characterize the infill of the erosional features (Fig. 4). Below horizon H1, seismic reflections are mainly sub-parallel, with low RMS amplitude values.

Horizon 2 shows a lateral change in seismic reflection amplitude and a marked erosional character, as highlighted by truncated reflectors belonging to S1. Sequence S2 (confined between H2 and H3) is dived in two units by horizon J (Figs. 3, 4). Unit S2a (between H2 and J) shows complicated seismic facies, comprising parallel to wavy reflection packages laterally changing from low to high amplitude often accompanied by a change in thickness (Figs. 3, 4). Overall, S2a has high RMS amplitude values (Fig. 3). High amplitude reflections characterize the infill of v-shaped (channel-like) erosional depressions (Fig. 4). Tabular to lens-shaped deposits with chaotic to transparent reflections are widespread within S2a and are characterized by low RMS amplitude values (Fig. 4). Unit S2b (between J and H3) presents continuous, high-frequency and low amplitude reflections, mainly with low RMS amplitude values (Figs. 3, 4). The unit contains intervals with higher-amplitude and wavy reflections, and high RMS amplitude values. The upper part of S2b is concordant with the overlying sequence S3, and the main difference is an upward decrease in the reflection amplitude, as shown by the RMS profile (Fig. 3). Horizon J mainly develops at the top of a series of high-RMS-amplitude reflection packages (Fig. 3). In the high-resolution GLOW seismic profiles, sequence S3 (between H3 and the sea floor) presents a lower unit (S3a) mainly characterized by an alternation of parallel and continuous reflections, organized in high- and low-amplitude packages (Fig. 3), an upper unit (S3b) showing discontinuous to chaotic seismic reflections with a laterally variable amplitude. Overall, S3 has low RMS amplitude values, and a continuous positive reflection defines horizon 3 (Fig. 3).

4.2. Super-elevated abandoned canyons on the Davie Ridge

Four giant canyons intersect the crest of the Davie Ridge, approximately running WSW to ENE and named C-1 to C-4 from north to south (Figs. 3, 5). C-1 likely represents the landward continuation of the Tanzania Channel, discovered by Bourget et al. (2008) in the Indian Ocean abyssal plain (Fig. 1). The canyons are up to 15 km wide and up to 850 m deep (Fig. 5), and their thalweg, measured on the crest of the Davie Ridge, lies at progressively deeper water depths northward, changing from ca. 2,700 m for C-4 to ca. 3,500 m of water depth for C-1, which is located about 100 kilometres to the north (Fig. 5). While canyons C-4 to C-2 show a U-shaped basal surface, canyon C-1 has a flat bottom (Fig. 5). Seismic profiles highlight that most of the canyons lack a sedimentary infill, except for canyon C-1, showing ca. 0.13-sec-thick basal deposits with high-amplitude parallel reflections (Fig. 5). While canyon C-4 only cuts across horizon H3, C-1 cuts down to H1 (Figs. 3, 5). Multibeam data acquired along the crest of the Davie Ridge show the morphology of the canyons (Fig. 5). Channel C-1 presents steep flanks, up to 25°, with the southern one hosting the escarpments of two small landslides (Fig. 5, and see supplementary Figure S2). The lack of landslide deposits along the canyon axis suggests that the slumped material was removed by turbidity currents flowing along the canyon, indicating a recent activity. Direct sampling of the canyon supports this hypothesis, as coarse-grained turbidite deposits are present closely below the sea floor (see supplementary Figure S2). A gentler topography characterizes canyon C-2, showing < 10° dipping flanks (Fig. 5). The canyon is cut by a normal fault that creates a step on the sea floor on which sediments, probably transported by bottom currents, accumulate forming a field of sediment waves (Fig. 5 and see supplementary Figure S3). A small sediment drift is visible on its northern side and is probably originated by the action of bottom currents as well (Fig. 5). The North Atlantic Deep Water (NADW) current is responsible of the deep-water circulation in the western Indian Ocean along the Davie Ridge (van Aken et al., 2004). The orientation of the crest of the sediment waves suggests that bottom currents are directed towards NNE, in agreement with direct observations of the NADW in this area (van Aken et al., 2004). Canyon C-3 is the most noticeable feature on the sea floor as it shows a strong meandering behaviour while crossing the ridge (Fig. 5). The canyon presents up to 25° steep flanks, with normal faults on its western side (Fig. 5). The multibeam data reveal a small landslide escarpment on the eastern side, with slumped material accumulating on the canyon floor, suggesting that activity of turbidity currents along the canyon was ceased at the time the landslide occurred (Fig. 5 and see supplementary Figure S4). In addition, the smoothed surface topography of the landslide escarpment and of the deposits suggests that bottom currents probably reworked this area. C-4 is the shallower canyon discovered during the GLOW cruise (Fig. 5). The canyon shows a meander-like morphology, with a gentler southern side and steep, up to 20°, northern flank presenting a series of arcuate escarpments, probably generated by sediment failures (Fig. 5 and see supplementary Figure S5). The lack of a thick pelagic cover on the canyon flanks allowed direct sediment sampling of outcropping strata (samples GW04 and GW13), providing additional age constraints (Table 1). A 3D view of the area (Fig. 6) highlights the geometric relation between the canyons, the Davie Ridge, and the Kerimbas Graben. The canyons only incise the Davie Ridge, and are not visible on the sea floor of the Kerimbas Graben, which shows a rather flat topography only interrupted by N-S trending fault escarpments (Figs. 4, 6). Indeed, the thalwegs of the southernmost three canyons are uplifted relatively to the adjacent sea floor in the Kerimbas Graben, implying that the canyons are disconnected from the active slope canyons in the offshore Rovuma and Rufiji River deltas. The presence of N-S fault escarpments visible on the multibeam bathymetry and in cross section on seismic lines suggests a recent activity of the offshore branch of the EARS, as discussed also by Franke et al. (2015). This is further confirmed by the location and focal mechanism of recent earthquakes (Grimison and Chen, 1988; Yang and Chen, 2010, and supplementary Figure S1).

4.3. Chronology of the Davie Ridge

The chronology of the Davie Ridge, summarized in Figure 7, was estimated using biostratigraphic information from eight explorations wells, sediment samples, and correlations with published data (Scrutton, 1978; Mougenot et al., 1986; Coffin and Rabinowitz, 1992; McDonough et al., 2013; O’ Sullivan, 2013; Franke et al., 2015; Sii and Underhill, 2015; Klimke and Franke, 2016; Sansom, 2018). Taking into account the vertical resolution of the seismic data, sediments in proximity of Horizon H1 (Fig. 7) are dated by the Last Occurrence of *Sphenolithus delphix* (top Chattian, ~23.1 Ma; Raffi et al., 2006) and correlates with the base of Ng1 sequence of Sansom (2017), with the top Oligocene reflector (O) of Franke et al. (2015), and with horizon A_1 of Mougenot et al. (1986). Horizon H2 is dated by the disappearance of *Helicosphaera perch-nielseniae* and *Sphenolithus heteromorphus* (Serravallian, ~13.5 Ma; Raffi et al., 2006; Boesiger et al., 2017) and correlates with horizon A_2 of Mougenot et al. (1986). Horizon J, for which biostratigraphic information is not available in the wells, most likely corresponds to horizon A_3 of Mougenot et al. (1986), which has been also defined as the late Miocene reflector (LM) by Franke et al. (2015). Horizon H3 corresponds to the top of Ng1 sequence of Sansom (2017), base Pliocene (5.3 Ma), and correlates with horizon A_4 of Mougenot et al. (1986). In addition, the age of sequence S2, and consequently of horizon H3, is confirmed by the planktonic foraminifer assemblages sampled on Davie Ridge (Table 1). In detail, box corer sample GW04, recovered from the northern flank of C-1 (Fig. 5 and supplementary material), represents Zone M14 (age 5.57-6.13 Ma; Wade et al., 2011), while box corer sample GW13, recovered from the southern flank of C-4 (Fig. 5 and supplementary material), is constrained to Zone PL1 (age 5.54-5.82 Ma; Wade et al., 2011).

5. Discussion and Conclusions

Correlation of seismic data and related attributes allowed evaluation of the deep-water depositional history in the offshore Tanzania. In detail, moving upward from sequence S1 to sequence S2, the stratigraphy of the Davie Ridge records a progressive increase in the accumulation of coarse-grained gravity-driven deposits. This is suggested by the presence of large turbidite channels, visible in the seismic profiles as v-shaped erosional features hosting high-amplitude reflection packages with shingled reflections (Abreu et al., 2003), and by the overall increase in the RMS amplitude (Figs. 3, 7), considered a proxy for sandy sediments (Rijks and Jauffred, 1991; Chen and Sidney, 1997; Brown, 2004). In addition, in the lower part of sequence S2, turbidity current deposits alternate with mass transport deposits, as suggested by the seismic facies and internal architecture of specific intervals (Fig. 3). Mass transport deposits are the result of gravity-induced remobilization of pre-existing sediments on a submarine slope, and on seismic data are represented by a variety of facies, spanning from chaotic or highly disrupted seismic facies to coherent reflections (Hampton et al., 1996; Posamentier and Kolla, 2003; Frey-Martínez, 2010). The upper part of sequence S1 and the lower unit of sequence S2, which mainly accumulated between the lower and middle Miocene, formed after the establishment of the EARS in Tanzania (Roberts et al., 2012; Sansom, 2017; 2018): at that time, it is possible that topographic uplift in the hinterland increased the progradation of the paleo-Ruvuma and paleo-Rufiji deltas, enhancing deep-water sediment transport and triggering a widespread margin instability, as also discussed in Sansom (2017; 2018). The presence of turbidite channels and coarse-grained deposits in this stratigraphic interval of the Davie Ridge suggests that sediment sourced from the Tanzanian margin was directly delivered towards the basin, also by means of the giant canyons now present on top of the Davie Ridge. Indeed, considering that the canyons incise the Davie Ridge without reaching horizon H1, a maximum age for their formation is the age of sequence S2. Moving progressively upward, the upper part of S2 marks a decrease in the activity of turbidite channels, as testified by a reduction of channelized features, which are totally absent in sequence S3. The lack of deposits associated with turbidity currents and debris flows, as highlighted by the seismic data (Figs. 3, 5), suggests that the Davie Ridge was at that time a bathymetric high on the sea floor that acted as barrier for gravity-driven flows originated along the Tanzanian shelf and slope. During deposition of sequence S3, turbidite channels were still active in the slope area offshore the Rovuma River delta, and further to the north (Liu et al., 2016), and thick turbidite sequences accumulated in the Kerimbas Graben (Franke et al., 2015; Sansom, 2018). Box corer samples and sea floor features visible on the multibeam bathymetry (Fig. 5 and supplementary material) suggest that Canyon C-1, at the northern end of the Davie Ridge, is the only active system and that sedimentation from bottom currents and reduced pelagic and hemiplegic deposition dominates the stratigraphy of the basin outside it.

All these evidences suggest that the uplift of the Davie Ridge disconnected canyons C-4 to C-2 from their feeder systems, re-routing the sediments delivered into the western Indian Ocean towards the north. Canyon C-1, which is one of the largest deep-water system discovered so far (Fig. 8, supplementary S6), represents the termination of a large drainage basin that extends from the Rovuma River to the southern Rufiji River deltas, and that probably connects with the Tanzania Channel about 500 km away towards NE (Bourget et al., 2008). Hence, the Tanzania Channel currently is the main pathway of organic and inorganic particulate matter from the Tanzanian shelf and slope area towards the Indian Ocean abyssal plain. The chronological constraints available show that the topographic deformation of the sea floor associated with the offshore branch of the EARS can be traced back to the middle-upper Miocene, in agreement with previous studies (Franke et al., 2015). In addition, our results suggest that the tectonic processes driving the uplift of the Davie Ridge that progressively disconnected the deep-water canyons from their feeding systems are still active today, as demonstrated by the fault displacements visible on the modern sea floor (Figs. 5, 6) and by the recent recorded earthquakes (supplementary S1), showing a body magnitude M_b up to 6.4 (Grimison and Chen, 1988; Yang and Chen, 2010).

This study has two main implications regarding how the formation of the Davie Ridge relates with the regional geodynamic context and how the tectonics of the offshore branch of the EARS controls the depositional history of the western Indian Ocean. Based on gravimetric and magnetic data, previous studies proposed the existence of a continuation of the Davie Ridge north of 9° S, where it lacks a morphological expression on the sea floor (Coffin and Rabinowitz, 1987; Revees and de Wit, 2000; Revees et al., 2016). With this assumption, the Davie Fracture Zone was correlated up to 2.5° S (Scrutton, 1978; Rabinowitz, 1971; Coffin and Rabinowitz, 1987), and was interpreted as the result of the southward drift of Madagascar with respect to Africa, implying that Madagascar was previously part of the modern Kenya. The Miocene age for the Davie Ridge uplift may suggest that its origin is unrelated with the initial opening of the western Indian Ocean and with the strike-slip movement of Madagascar, as also proposed by Klimke and Franke (2016). This result would imply the need for new palaeogeographic models to explain the Mesozoic evolution of the Indian Ocean and the position of Madagascar when attached to Africa. Notwithstanding, it is also possible that the Davie Ridge formed in the response to the recent reactivation of pre-existing Mesozoic tectonic lineaments, but the lack of imaging of the deeper stratigraphic sequences down to the basement does not allow to discuss this point any further.

The discovery of giant and abandoned canyons on the deep-water Davie Ridge highlights that the tectonics of the offshore branch of the EARS has had a profound control on the physiography of the margin and on the transport of sediment and organic matter towards the Indian Ocean. Future studies supported by additional data acquisitions are needed to have a full picture of the modern drainage system and its distal continuation in water depths greater than 4,000 m. There are still outstanding questions regarding the role of sea floor deformation on bottom current circulation in the western Indian Ocean and the potential of the offshore tectonic activity of the EARS in generating tsunamigenic earthquakes or submarine landslides.

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Data Availability Statement

For more information about the data acquired during the GLOW cruise contact Dick Kroon and Henk de Haas. The bathymetric data are available at doi.org/10.1002/2017GC007274. The other data that support the findings of this study are not publicly available due to privacy restrictions.

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Figure captions

Figure 1. Bathymetry of the western Indian Ocean in the offshore Tanzania and northern Mozambique. Topographic and bathymetric data are from GEBCO and the Southwest Indian Ocean Bathymetric Compilation (swIOBC; Dorschel et al., 2018). The location of the Tanzania Channel, reported in yellow, is from Bourget et al. (2008).

Figure 2. Bathymetric cross sections across the Kerimbas Graben (KG) and the Davie Ridge (DR) north of the Saint-Lazare Seamount (SLS). The black dashed lines mark their location in the map. Note the structural high associated to the Seagap Ridge (SR) and the morphological subdivision of the area in four zones from south to north. Blue, green, and red arrows highlight the main fault escarpments, with the location reported in the 3D view of the sea floor with the same colour code.

Figure 3. Seismic line 1, oriented along the Davie Ridge (see location in Fig. 1). Top: Seismic amplitude; Centre: Root Mean Square (RMS) seismic attribute; Bottom: Seismic amplitude with highlighted the main stratigraphic horizons (H1 to H3) and depositional sequences (S1 in red, S2 in blue, S3 in green). Note that the thalweg of the canyons C-1 to C-4 lies in progressively deeper water towards NNW.

Figure 4. Seismic line 2, oriented W-E across the Kerimbas Graben and the Davie Ridge (see location in Fig. 1).

Figure 5. Seismic profiles across the canyons and high-resolution multibeam bathymetry (location in Fig. 1) of the crest of the Davie Ridge (see supplementary material for close-up views of each canyon). Note the location of the box-corer samples (red dots).

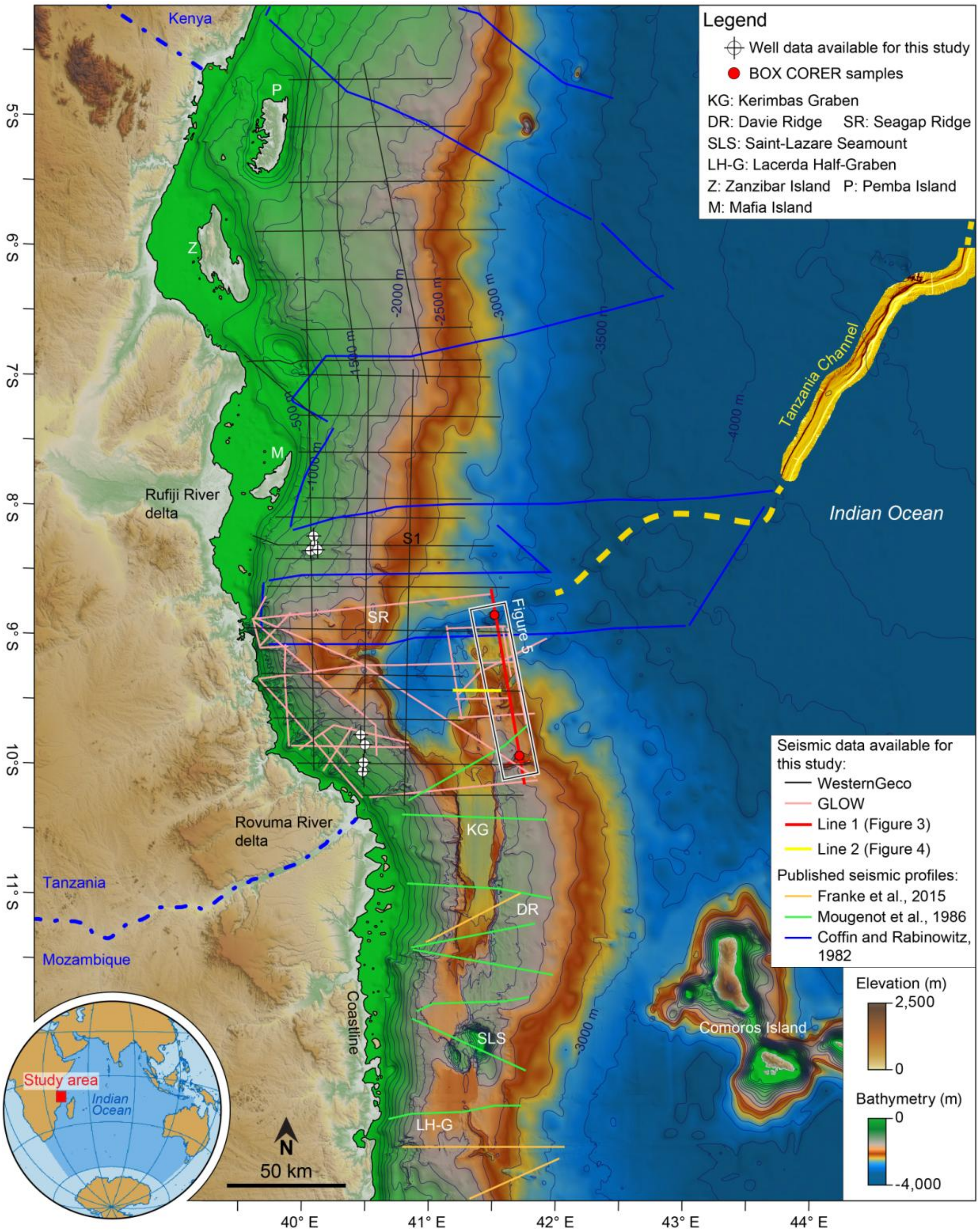
Figure 6. 3D view of the Kerimbas Graben and Davie Ridge in the offshore Tanzania.

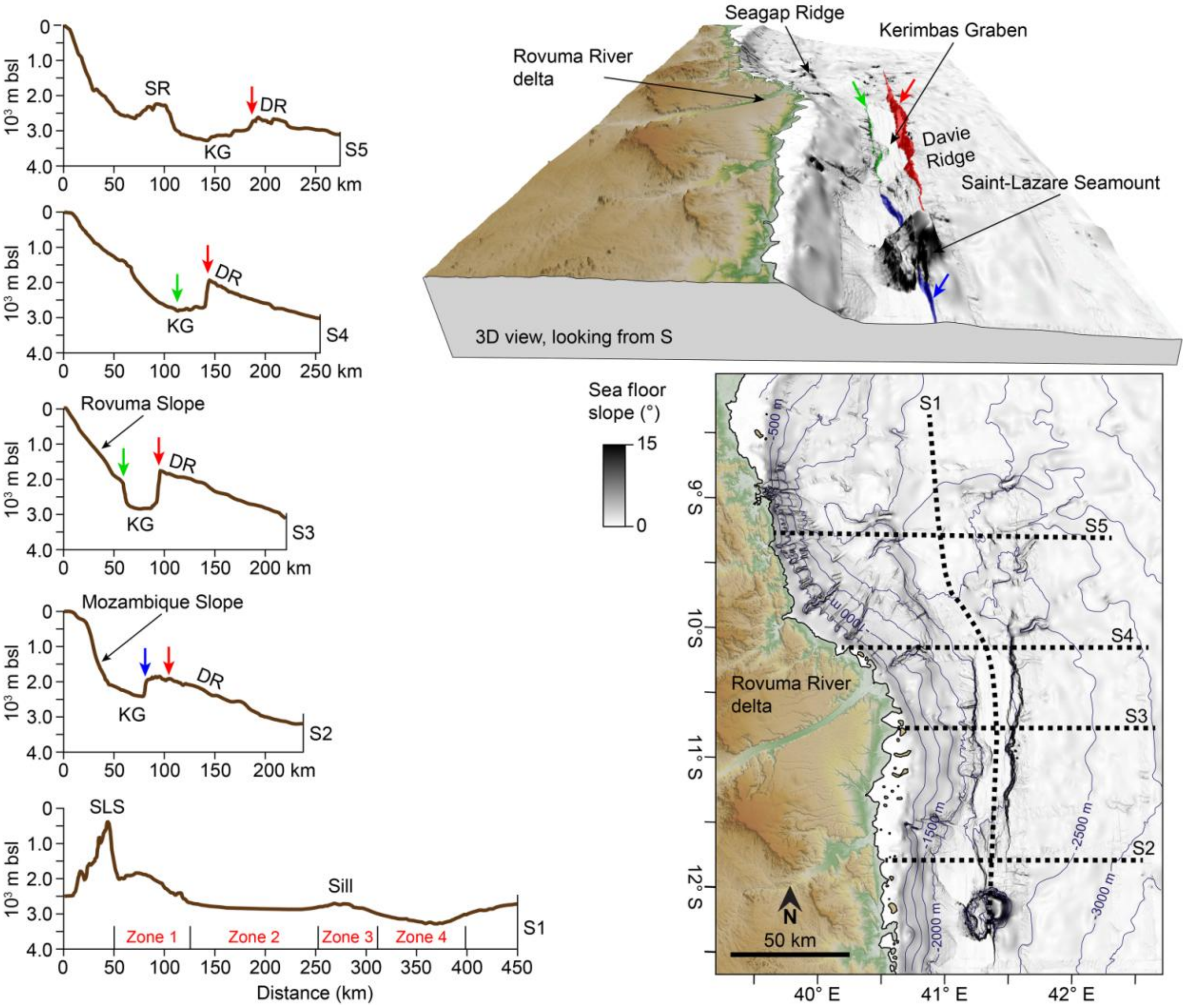
Figure 7. Chronology of the Davie Ridge. 1: Stratigraphic sequences from Sansom (2017); 2: Dated horizons from Mougenot et al. (1986); 3: Dated horizons from Franke et al. (2015); 4: Age of box corer samples GW04 and GW13 (red bars); 5: Seismic horizons of the present study; 6: Extraction of a seismic line across one of the exploration wells used in this study (depth in seconds below the sea floor) with dated stratigraphic sections marked by red rectangles; 7: Interval velocity model of the well; 8: Stratigraphic sequences and units of this study.

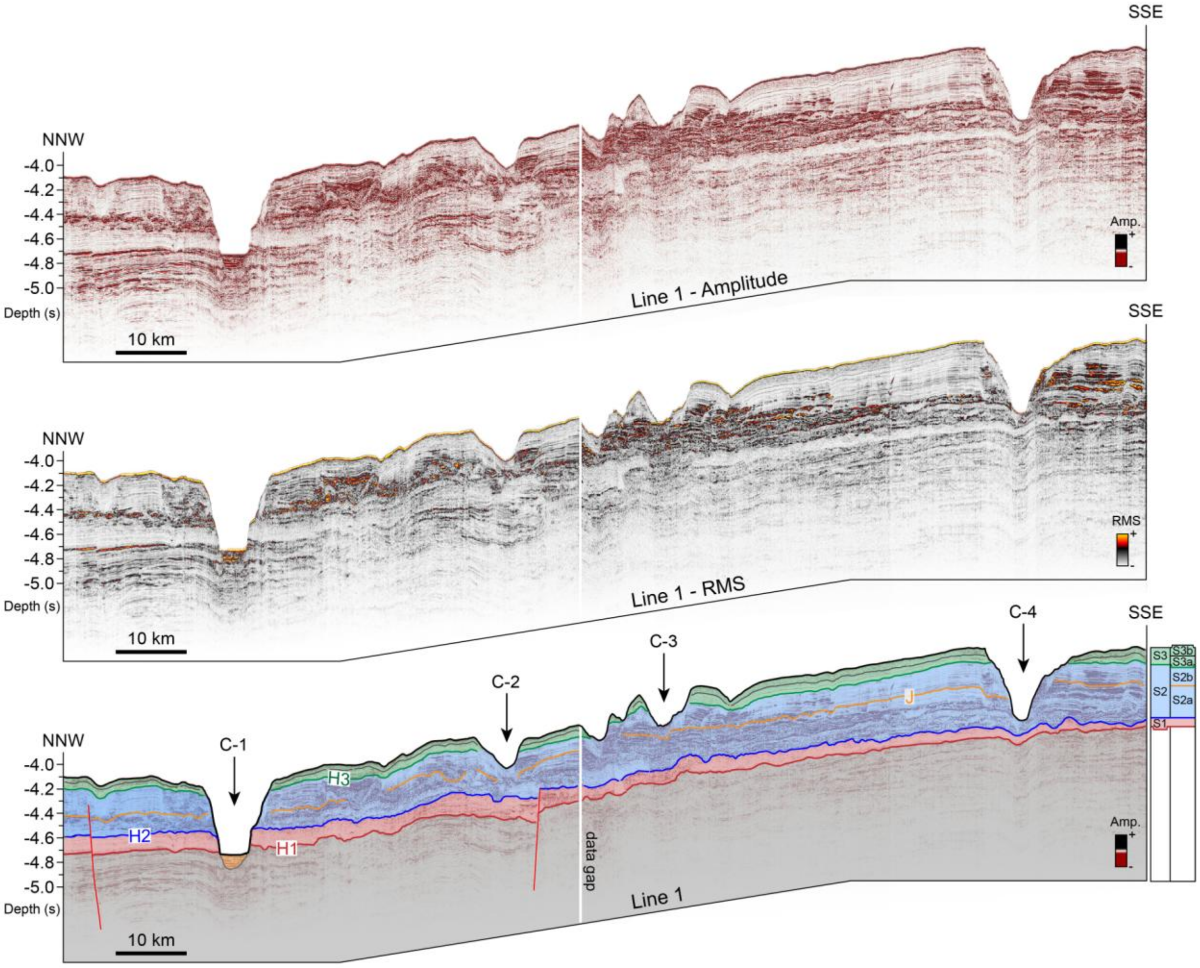
Figure 8. Conceptual scheme for the evolution of the study area since the upper Oligocene. Age constraints on key horizons suggest that the uplift of the Davie Ridge (DR) and the formation of the Kerimbas Graben (KG) started during the middle-upper Miocene. The Seagap Fault (SF) is highlighted in yellow. Note how the deep-water drainage system changed through time in response to the tectonics of the offshore branch of the EARS, from a series of coalescing canyons to a single system, where the Tanzania Channel is the only active conduit.

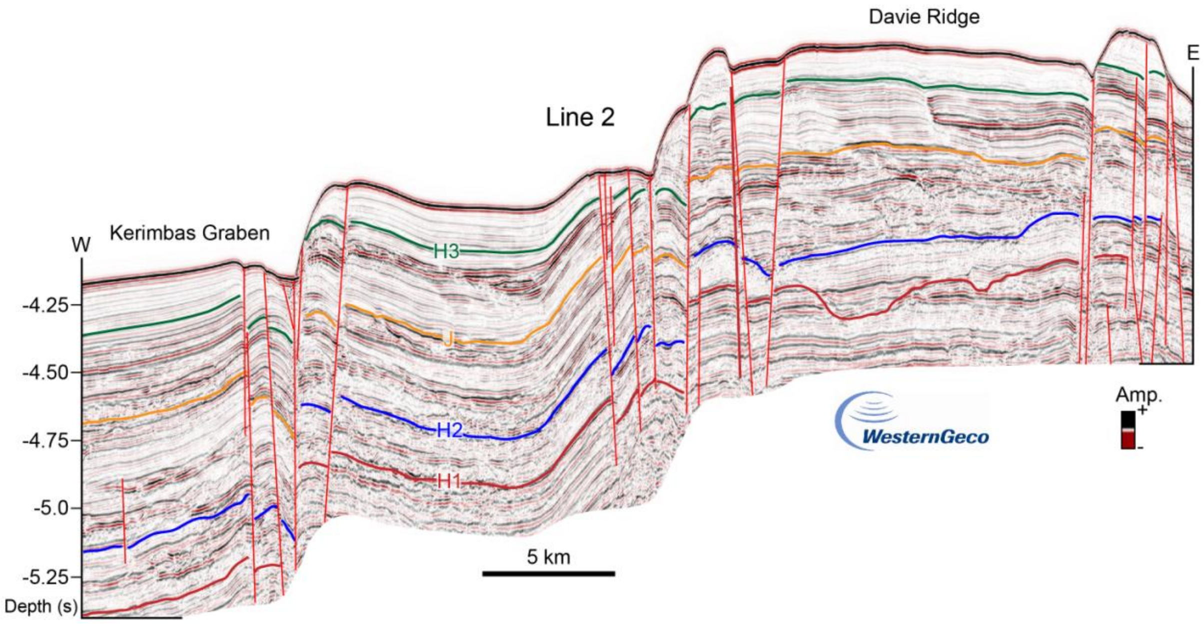
Sample name	Water depth (m)	Sample depth in the core (cm)	Specimens	Age (Ma)	Biozone
GW04	3,170	29	*Globorotalia plesiotumida*, *Globigerinoides conglobatus* (in the absence of *Globoquadrina dehiscens*, *Globorotalia tumida* and *G. lenguaensis*). Additional marker species include: *Sphaeroidinellopsis seminulina* (in the absence of *Sphaeroidinella* spp.), *Globoturborotalita nepenthes*, *Dentoglobigerina altispira*, *Pulleniatina primalis*, *Globigerinoides extremus*, *Globigerinoides conglobatus*	5.57-6.13	M14
GW13	2,451	33	*Globorotalia tumida*, *Sphaeroidinellopsis seminulina* (in the absence of *Sphaeroidinella*. Additional marker species include: *Menardella limbata*, *Globigerinella siphonifera*, *Globoturborotalia nepenthes*, *Dentoglobigerina altispira*, *Pulleniatina primalis*	4.36-5.57	PL1

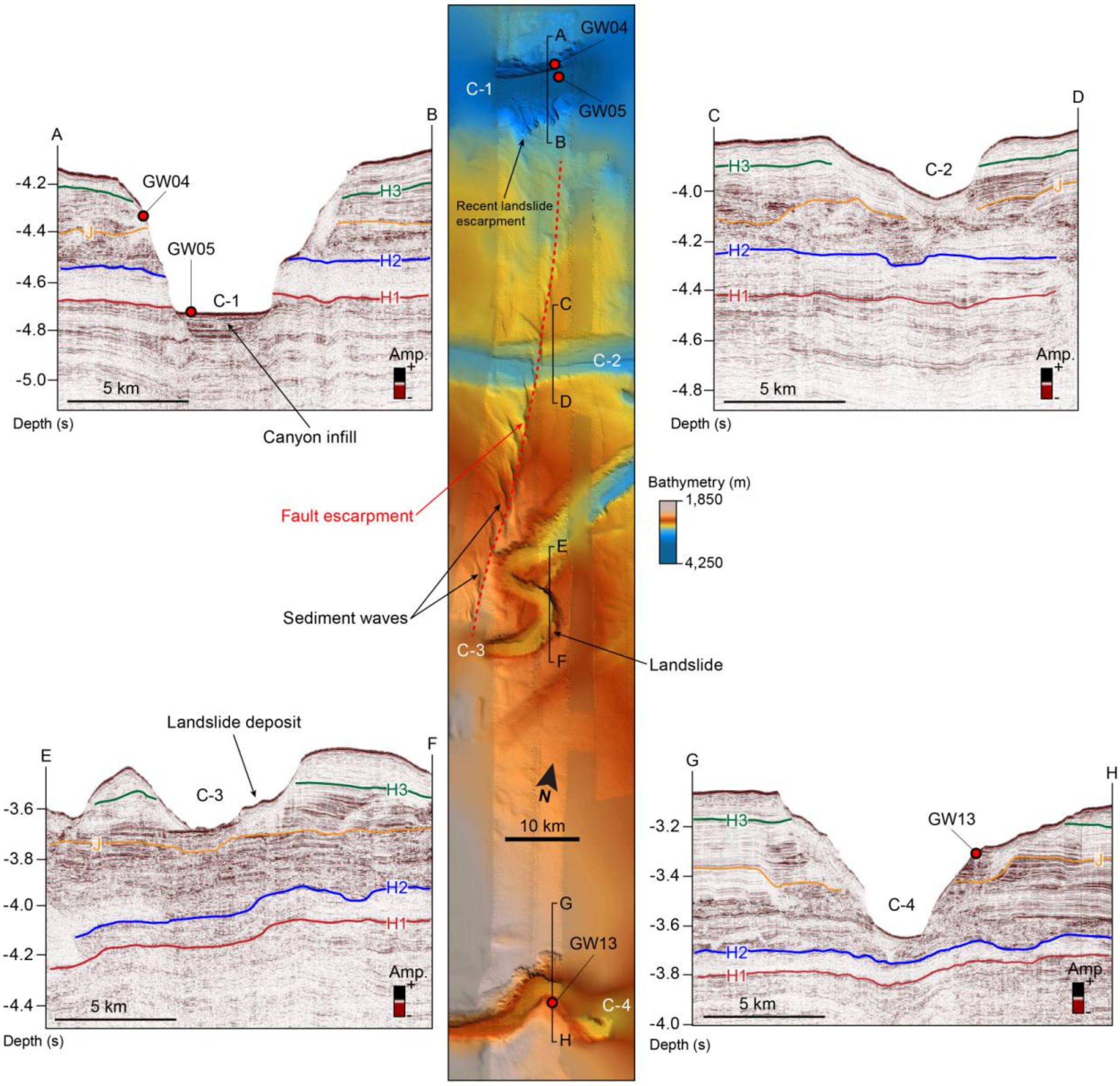
Table 1. Microfauna assemblages from box-corer samples GW04 and GW13, and associated chronologies and biozones (see also Wade et al., 2011).

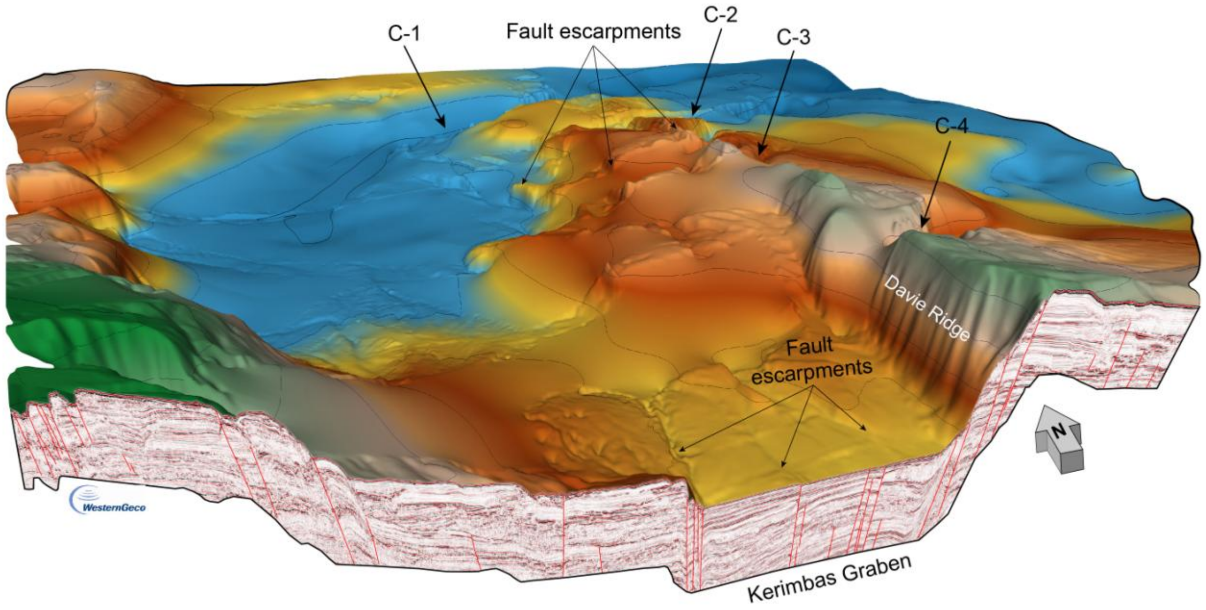

Legend
Well data available for this study
BOX CORER samples
KG: Kerimbas Graben
DR: Davie Ridge
SR: Seagap Ridge
SLS: Saint-Lazare Seamount
LH-G: Lacerda Half-Graben
Z: Zanzibar Island
P: Pemba Island
M: Mafia Island
Seismic data available for this study:
WesternGeco
GLOW
Line 1 (Figure 3)
Line 2 (Figure 4)
Published seismic profiles:
Franke et al., 2015
Mougenot et al., 1986
Coffin and Rabinowitz, 1982
Elevation (m)
2,500
0
Bathymetry (m)
0
-4,000
Kenya
Tanzania
Mozambique
P
Z
M
Rufiji River delta
Rovuma River delta
Coastline
S1
SR
KG
DR
SLS
LH-G
Figure 5
Tanzania Channel
Indian Ocean
Comoros Island
-500 m
-1000 m
-1500 m
-2000 m
-2500 m
-3000 m
-3500 m
-4000 m
-3000 m
N
50 km
Study area
Indian Ocean
5° S
6° S
7° S
8° S
9° S
10° S
11° S
40° E
41° E
42° E
43° E
44° E

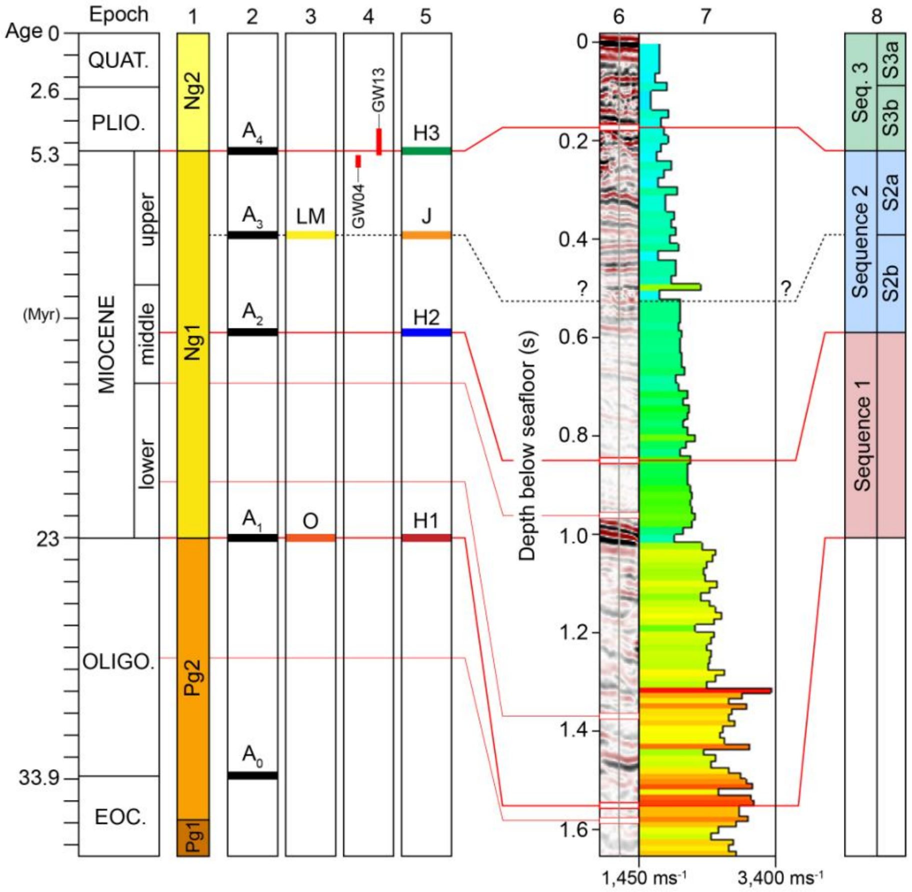

Seagap Ridge
Kerimbas Graben
Rovuma River delta
Davie Ridge
Saint-Lazare Seamount
3D view, looking from S
Sea floor slope (°)
15
0
10³ m bsl
SR
DR
KG
S5
S4
Rovuma Slope
S3
Mozambique Slope
S2
SLS
Sill
Zone 1
Zone 2
Zone 3
Zone 4
S1
0
1.0
2.0
3.0
4.0
0
50
100
150
200
250
300
350
400
450
250 km
200 km
Distance (km)
S1
S5
S4
S3
S2
9° S
10°S
11° S
12° S
-500 m
-1000 m
-1500 m
-2000 m
-2500 m
-3000 m
Rovuma River delta
N
50 km
40° E
41° E
42° E

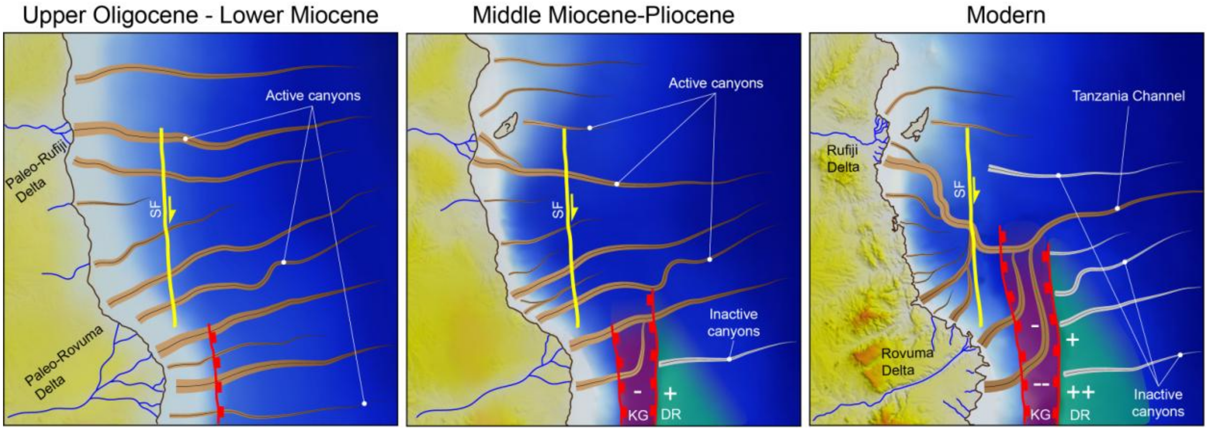

SSE
NNW
-4.0
-4.2
-4.4
-4.6
-4.8
-5.0
Depth (s)
10 km
Line 1 - Amplitude
Amp.
+
-
SSE
NNW
-4.0
-4.2
-4.4
-4.6
-4.8
-5.0
Depth (s)
10 km
Line 1 - RMS
RMS
+
-
C-4
SSE
C-3
C-2
C-1
NNW
-4.0
-4.2
-4.4
-4.6
-4.8
-5.0
Depth (s)
10 km
H3
H2
H1
J
data gap
Line 1
Amp.
+
-
S3
S3b
S3a
S2
S2b
S2a
S1


Davie Ridge
Line 2
W
Kerimbas Graben
E
H3
J
H2
H1
-4.25
-4.50
-4.75
-5.0
-5.25
Depth (s)
5 km
WesternGeco
Amp.
+
-


A
B
GW04
GW05
H3
J
H2
H1
C-1
-4.2
-4.4
-4.6
-4.8
-5.0
5 km
Amp.
+
-
Depth (s)
Canyon infill
C-1
Recent landslide escarpment
C
D
C-2
Fault escarpment
Sediment waves
E
F
C-3
Landslide
10 km
N
G
H
GW13
C-4
Bathymetry (m)
1,850
4,250
C
D
C-2
H3
J
H2
H1
-4.0
-4.2
-4.4
-4.6
-4.8
5 km
Amp.
+
-
Depth (s)
E
F
Landslide deposit
C-3
H3
J
H2
H1
-3.6
-3.8
-4.0
-4.2
-4.4
5 km
Amp.
+
-
Depth (s)
G
H
GW13
C-4
H3
J
H2
H1
-3.2
-3.4
-3.6
-3.8
-4.0
5 km
Amp.
+
-
Depth (s)


C-1
Fault escarpments
C-2
C-3
C-4
Davie Ridge
Fault escarpments
N
WesternGeco
Kerimbas Graben


Age
Epoch
1
2
3
4
5
6
7
8
0
QUAT.
2.6
PLIO.
5.3
MIOCENE
upper
middle
lower
(Myr)
23
OLIGO.
33.9
EOC.
Ng2
Ng1
Pg2
Pg1
A$_4$
A$_3$
A$_2$
A$_1$
A$_0$
LM
O
GW13
GW04
H3
J
H2
H1
0
0.2
0.4
?
0.6
0.8
1.0
1.2
1.4
1.6
?
Depth below seafloor (s)
1,450 ms^{-1}
3,400 ms^{-1}
Seq. 3
S3a
S3b
Sequence 2
S2a
S2b
Sequence 1


Upper Oligocene - Lower Miocene
Middle Miocene-Pliocene
Modern
Active canyons
Paleo-Rufiji Delta
SF
Paleo-Rovuma Delta
Active canyons
SF
Inactive canyons
-
+
KG
DR
Tanzania Channel
Rufiji Delta
SF
Rovuma Delta
-
+
--
++
KG
DR
Inactive canyons