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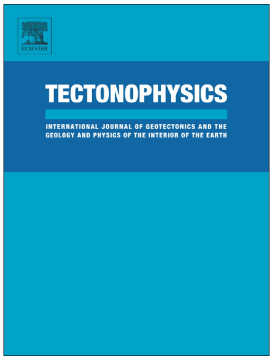

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# The Davie Fracture Zone: a recorder of continents drifts and kinematic changes

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Highlights

- The Davie Fracture Zone shows a large variability of vertical displacements due to its composite origin and its long-lived evolution
- The Davie transform system started at ca. 166Ma along discrete NW-SE trending segments and then became an N-S mature segment at ca. 155Ma
- Transform boundaries are lithospheric-scale structures sensitive to kinematic changes

Keywords:

West Somali Basin, Mozambique Basin, Davie Fracture Zone, Transtension, Transpression, Plate kinematics

## Abstract

Transform continental margins play a major role in plate tectonics. In the last 10 years' petroleum exploration has moved to the hunt of stratigraphic traps in the passive margin sequence of continent-ocean transforms. The result has been a drastic increase in modern deep seismic data and more well calibrations. Considered as one of the longest continental transform plate boundaries, the Davie transform system (East of Africa) is one of the best places to investigate the evolution of a major transform linking two oceanic basins. Based on a new basement and structural maps and schematic cross-sections, our findings show that the Davie Fracture Zone (DFZ) is made of several transform segments with two main trending directions related to the plate scale kinematic reorganization occurring at ca. 155 Ma. The early proto-segments trend NW-SE in the oldest oceanic domain and are broadly in the same trend that onshore major faults and lineaments implying African structural inheritance. The second set of transform segments trends N-S and the most important corresponds to a plate boundary between the Mozambique Basin and the Madagascar margin. Results further show that the DFZ offers great variability of transpressional and transtensional structures and vertical displacements along its different segments from the onset of the transform activity until today. These main phases of inversion are also interpreted as a consequence of plate scale kinematic reorganizations. The DFZ is thus an excellent marker to follow the long-term evolution of plates tectonics, but also the short-term as attesting the presence of Neogene to present magmatic centers and active faults along the Mozambique coastline.

# 1. Introduction

Until the last decade, continental transform margins known across the Earth have only been sparsely studied (*e.g.*, Basile, 2015; Lepinay et al., 2016; Nemčok et al., 2016a), and most of the structural regional studies focused on Aghulas (Scrutton, 1973 and 1976; Ben-Avraham et al., 1997), Ivory Coast-Ghana (Blarez and Mascle, 1988; De Caprona, 1992; Basile et al., 1993), Exmouth Plateau (Lorenzo et al., 1991), Gulf of California (Bischoff and Henyey, 1974; Moore,1982) and Newfoundland (Keen et al., 1990). These previous researches were relying on potential field data, poor seismic images, dredging, and kinematic assumptions. Following the discovery of the Jubilee field in Ghana (Dailly et al., 2013), a stratigraphic trap along the continental segment of the Romanche Fracture Zone (FZ), petroleum exploration has been oriented toward the search of similar structures along transform margins with associated petroleum systems. Romanche, Aghulas, Guyanas, and Davie are now covered with deep industrial seismic data (2D and 3D) and more wells allow better calibration of the sedimentary records.

So far, several works based on these data have been published (*e.g.*, Attoh et al., 2004; Dailly et al., 2013; Mahanjane, 2014; Mahanjane et al., 2014; Nemčok et al., 2016b; Klimke and Franke, 2016; Klimke et al., 2018; Sauter et al., 2018; Baby et al., 2018; Sinha et al., 2019). They showed different structures and evolutions suggesting a considerable degree of variability. Recent synthesis (*e.g.*, Lepinay et al., 2016; Loncke et al. 2020) highlighted also common characteristics of transform margins such as steep continental slopes, marginal ridges along the edge of the continental slope, and marginal plateaus systematically located between the platform and the lower continental slope. But these criteria are not systematic, suggesting that key parameters, such as lithospheric inherited heterogeneities and thermal state, may strongly influence the dynamics of their formation (*e.g.*, Sinha et al., 2019).

Further, these lithospheric-scale structures seem then correspond to weakness areas focusing on magmatism and earthquakes after their main activity which occurs during the oceanic spreading (Sykes, 1978).

The continental rifted margins off Gondwana, and more particularly the Davie FZ (Fig. 1) provide an excellent example to study the dynamics of a major transform system (one of the longest segments) from its birth in a heterogeneous inherited basement, through rifting, spreading of the Somali and Mozambique basins until its latter reactivations. In most studies (Heirtzler and Burroughs, 1971; Coffin et al., 1986; Raillard, 1990; Leinweber and Jokat, 2012; Mueller and Jokat, 2017; Sinha et al., 2019), it is interpreted as a major transform fault system accommodating the southward movement of Madagascar and Antarctica to Africa following the break-up of the Gondwana super-continent (Fig. 2). Even though several studies have been carried out to describe the origin and evolution of such transform system, the sequence of processes that controls the development of such large-scale feature and the nature of the crust on both sides of this ridge, are still poorly known and debated (*e.g.*, Coffin et al., 1986; Raillard, 1990; Klimke and Franke, 2016; Phethean et al., 2016; Sinha et al., 2019; Vormann et al., 2020). As a consequence, the opening geometries of the East Africa margins along this structure, are not clear. The precise initial position of Madagascar and India relative to Africa is thus still controversial (*e.g.*, Reeves and de Wit, 2000; König and Jokat, 2006; Eagles and König, 2008; Leinweber and Jokat, 2012; Seton et al., 2012; Gaina et al., 2013, 2015; Reeves et al., 2016; Davis et al., 2016; Klimke and Franke, 2016; Phethean et al., 2016; Thompson et al., 2019).

Based on the interpretation of an extensive regional seismic dataset, wells, and potential field data, we bring new constraints on the structure and evolution of the Davie Fracture Zone (DFZ). We proposed a map of the crustal domains along the rifted margins of the Somali and Mozambique basins and the DFZ. We then characterize the main phases that have shaped

DFZ from its formation until the latest reactivation in Quaternary and propose a relation to the regional plate kinematic reorganizations.

## 2. Geological background

### 2.1. Geodynamic evolution of the East Gondwana

The geology of East Africa consists of cratonic bodies embedded into surrounding Proterozoic orogenic belts (*e.g.*, Begg et al., 2009) forming the supercontinent Gondwanaland. The main structures limiting the cratons are generally NE-SW (*e.g.*, the South Trans African Shear System) and NW-SE (*e.g.*, the Aswa shear zone) oriented depending on the area (*e.g.*, Reeves and De Wit, 2000; Reeves et al., 2016). It is commonly acknowledged that the Phanerozoic evolution of East Africa is dominated by Permo-Triassic and Early Jurassic extensional events which overprint the mobile belts accreted during and after the Panafrican orogeny (Rosendhal, 1987; Reeves and De Wit, 2000; Reeves et al., 2016). Inherited structures played a fundamental role in the mechanisms of rift propagation and subsequent continental breakup at the southern Africa scale.

The first rifting event in Permian-Triassic is compatible with a regional E-W extension (*e.g.*, Daly et al., 1989; Macgregor, 2018; Roche et al., 2021). It is mainly characterized by localized and fault-bounded rifts in central and East Africa and appears related to intra-continental rifting. The East Africa margins then recorded about 180 Ma of geodynamic history starting with the emplacement of the main phase of the Karoo Large Igneous Province (Fig. 2a), that crops out in southeast Africa (Duncan et al., 1997; Jourdan et al., 2008). NW-SE rifting and early oceanic opening phase, clearly visible in the Mozambique Basin (see *e.g.*, the trend of magnetic anomalies (Mueller and Jokat, 2019) and structures (Senkans et al., 2019)) are recorded in the Middle Jurassic (Fig. 2b). Oceanic seafloor spreading led to the formation of Somali and Mozambique basins (*e.g.*, Segoufin, 1978; Norton and Sclater, 1979; Segoufin and Patriat, 1981; Rabinowitz et al., 1983) formed concurrently between Madagascar/India/Seychelles – Africa and Antarctica – Africa, respectively. N-S spreading was then recorded over the entire area at ca. 156 Ma inducing the drift of Madagascar and Antarctica along the Davie and the Mozambique FZ (Figs. 2c and 2d) (Cox, 1992; Sahabi, 1993; Thompson et al., 2019).

### 2.1.1. The West Somali Basin

The Western Somali Basin is located between the south of Somalia and the north of Madagascar (Fig. 1a). It is bounded by the DFZ to the west (between 40 and 41°E) and by the Ars FZ and Carlsberg FZ to the east (between 50 and 51°E) (Fig. 1a). The East Africa margin segmentation can then be summarized as follows, from north to south, we recognize three extensional segments, the northern Somalia segment (from the horn of Africa down to the Mudugh High latitude), and the Mudugh High segment and the South Somalia segment and two transtensional segments showing pull-apart structures (Sinha et al., 2019), the Kenya segment and the Tanzania segment (Fig. 1b). The north Mozambique segment which bounds the Western Somali Basin is purely transform. Conjugate segments of East Africa are Majunga and Morondava segments are conjugate (Fig. 1b). Recently, Davis et al. (2016) reported new magnetic anomalies, showing an onset of the oceanic spreading at chron 24Bn (ca. 152 Ma) until chron M0r (ca. 121 Ma), which corresponds to the extinct ridge (Fig. 1b). This is quite consistent with previous studies that recognized a similar timing of spreading ranging from chron M25 (ca. 153 Ma, Rabinowitz et al., 1983) to M21n (ca. 145 Ma, Ségoufin and Patriat, 1980) along an E-W ridge that becomes an extinct oceanic ridge at chron M9n (ca. 128 Ma, Rabinowitz et al., 1983) or M0r (ca. 126 Ma, Ségoufin and Partiat, 1980). But, Gaina et al. (2013) proposed an early break-up and seafloor spreading at ca. 167.5 Ma (chron M41). This latter interpretation is more suitable because the oceanic crust extends beyond the magnetic anomaly M24Bn (see Fig. 1b). This is also more consistent with the study of Geiger et al. (2004) showing the presence of Early Bajocian breakup unconformity identified in the Morondava Basin. Using a spreading rate of 2.5 cm/yr which may correspond to slow conditions (*i.e.*, lower than 5 cm/yr which corresponds to the conditions of the spreading rate between M22r and M0r), we estimate an age of ca. 166 Ma for the first occurrence of oceanic crust. Geophysical interpretations in the Western Somali Basin that utilize recent free-air-gravity data and vertical gravity gradient data (Sandwell et al., 2014; Davis et al. 2016; Phethean et al., 2016) shows the position of the extinct spreading ridge that is composed of approximately E-W trending segments.

### 2.1.2. Mozambique Basin

The Mozambique Basin is situated between central Mozambique and west- to-southwest of Madagascar (Fig. 1a). It is bounded by the Mozambique FZ (recently interpreted as the Limpopo volcanic transform faults zone, Roche et al., 2021) to the west (between 36 and 37°E) and by the Davie Ridge (DR) to the east (between 41 and 43°E). We recognize from east to west, the Angoche and Beira High volcanic extensional segments in Mozambique (Fig. 1b) (Müller and Jokat, 2017, 2019; Senkans et al., 2019). Both conjugate segments are in Antarctica. The onset of seafloor spreading is still discussed in this area. Based on magnetic measurements, Leinweber and Jokat (2012) proposed age of ca. 166 Ma (chron M41n) whereas Mueller and Jokat (2019) suggested an age of ca. 164 Ma (chron

M38n. 2n). Recent wide-angle and ship-borne magnetic data (Leinweber et al., 2013; Müeller et al., 2016; Müeller and Jokat, 2017; Vormann et al., 2020) reveal a high velocity lower crustal body (HVLCB) near the continental margin of central Mozambique, including the previous magnetic anomaly. Vormann et al. (2020) propose that this area corresponds to oceanic crust. Conversely, Senkans et al. (2019) interpret this area as a proto-oceanic crust (basalts with a "lithospheric continental component") and thus suggest that spreading started at ca. 159 Ma (chron M33).

## 2.2. The DFZ: structures and main controversies

The DFZ is a major structure, around 2300 km long from the Kenya margin to the southwest Madagascar margin, which becomes an oceanic FZ southwards until the Southwest Indian Ridge at 45°S of latitude. In the Western Somali Basin and Mozambique Basin, this structure is characterized by a gravimetric gradient from 2° to 27°S where it forms a marked bathymetric ridge (*i.e.*, the DR) between west Madagascar and the Mozambique Basin. Here, using the P wave propagation residues, Recq (1982) showed a transition from a thick continental crust (30 km) to oceanic crust (6 km) in the Western Somali Basin along the northern Mozambique coast. More recently, based on wide-angle data as well as additional seismic amplitude modeling and 2.5D density modeling, Vormann et al. (2020) showed the presence of fragments of continental crust with a thickness of 10 to 12 km along the northeastern part of the Mozambique Basin. In detail, they observed on the Madagascan side of the DR (at 16.5°) a highly intruded and stretched continental crust which is possibly underlain by a high-velocity body of 2.9 km thickness. They also showed that oceanic crust extends northward between the DR and the Central Mozambique margins at 16.5°S in the Mozambique Basin and northeast of the DR at 41.8°W/14.5°S in the Western Somali Basin.

Along north Mozambique and southern Tanzania, the DFZ is a steep and sharp transform margin between the African continent and the South Western Somali Basin from 15° to 10°S (Sinha et al., 2019). This area is the locus of the giant gas field system discovered in 2010 by Anadarko in the front of the Rovuma delta (Martindale, 2016). Further north, it seems to split into two segments corresponding to the Seagap Fault and the Davie-Walu Fault (Fig. 1a, Sinha et al., 2019), which may be seen on gravity data until the Kenya margin (9°S) but are buried under unfaulted sediments in the north. They reach the Kenya passive margin at about 4°S.

Thus, the DFZ is a complex feature that may be subdivided into different sections showing various crustal and structural styles. Deformation along the DFZ, therefore, encompasses a large range of strike-slip structures (with many reactivations, *e.g.*, Raillard, 1990; Macgregor, 2018) with extensional to compressional components depending on the area and the period (*e.g.*, Mahanjane, 2014; Klimke and Franke, 2016; Sauter et al., 2018; Sinha et al., 2019). For instance, extensional structures such as Neogene rift-grabens along north Mozambique are observed in seismic profiles (*e.g.*, Nacala and Kerimbas basins, Mahanjane, 2014; Klimke and Franke, 2016). Sauter et al. (2018) noted the presence of buckle folds associated with thrust faults within the oceanic Jurassic crust. Such deformation is localized along a deformation corridor (about 15 – 30 km wide) starting before Hauterivian (~132 Ma) and ending in Aptian time. Mahanjane (2014) also suggested compression within the eastern boundary of the Mozambique Basin, along the west DR (Fig. 1), forming a typical thrust wedge associated with sediment growth strata and proposed an age at ca. 150 Ma. Conversely, Intawong et al. (2019) suggested that the thrust wedge was created during an incipient stage of subduction of the Angoche’s oceanic crust along the DR below the west Madagascar margin zone possibly during Early Cretaceous to Turonian.

The reason why the interpretation of the DFZ is still debated (Scrutton, 1978; Coffin et al., 1986; Raillard, 1990; Klimke and Franke, 2016; Phethean et al., 2016; Sinha et al., 2019; Vormann et al., 2020) can therefore certainly be found in its complexity and north-south variability and the lack of well calibrations.

## 3. Data and interpreted horizons

Gravity (*e.g.*, free-air gravity from Sandwell et al. (2014) and Phethean et al. (2016)) and magnetic (EMAG 2 gridded version, Maus et al., 2009) data have been used together with a screening of the available seismic survey to define the major crustal domains. Except for offshore south Somalia and north Kenya where seismic data quality is low, the continental margin is mapped with a good degree of confidence. Conversely, the sparse dataset in the west and northwest Madagascar only allows a very schematic interpretation. The oceanic crust has been mapped using some of the long ION lines that run far into the oceanic domain (*e.g.*, Lines TZ3-1200 and TZ4-1275) and published magnetic anomaly maps (Maus et al., 2009). In detail, here we present examples of some of the most useful datasets of industrial seismic reflection profiles: ION-GXT in Kenya and Tanzania and WesternGeco and Institute of National Petroleum (INP) for Mozambique. The data quality allows us to image sedimentary sequences and basement, and locally the deep crustal structures, the Moho and for some, intra-mantle reflections may also be seen.

Most calibration wells are located on the proximal margins in shallow water domains or even onshore. A deep-water well (Kiboko-1 in Kenya, Fig. 1a) has been used to constrain markers and seismic facies down to Hauterivian in the western Western Somali Basin. For the central part of the DFZ (close to the Kerimbas basin, Fig. 1b) an offshore well calibrating down to Barremian-Aptian (Cachalote-1, Fig. 1a) is also used. Note that these new calibrations have been realized recently by TotalEnergies (not shown for confidentiality issues) and differ from previous studies (*e.g.*, Mahanjane, 2014; Mahanjane et al., 2014; Franke et al., 2015; Pilskog et al., 2017) indicating some discrepancy in the literature as to the dating of the Cretaceous-Jurassic sequence. In addition, it is important to note that these two wells are located in the area west of the DFZ, implying that it is difficult seismically to make the passage between this part and the DR eastward (Fig. 1a).

The overall seismic facies and structural features have first been used to constrain continental crust, exhumed mantle, and oceanic crust along key sections (Fig. 3) and extend their mapping with variable degrees of uncertainty depending on data coverage and quality. The presented interpreted lines and maps are based on the interpretation of the full dataset available in TotalEnergies and continuously updated from new wells, seismic and acquired knowledge since 2014. Part of this work is available in Sauter et al. (2018) even though our ocean-continent transition is slightly different.

## 4. Crustal domains: seismic facies observations and mapping

The key horizons used to interpret the dataset and constrain the timing of deformation are visible on the seismic lines (Figs. 4 to 8). The deepest calibration which corresponds to the Kiboko-1 well on the Walu Ridge (WR) (Figs. 1 and 4) lies in the vicinity of the 3D line shown in Fig. 5. This constrains well the early Cretaceous horizons that are concomitant with (i) spreading in the Somali Basin - Neocomian (light green) - and (ii) the end of spreading - Aptian (120Ma-dark green). The oldest oceanic crust is estimated at ca. 166 Ma, hence, the syn-rift series below Neocomian horizons are considered Early Cretaceous to Middle Jurassic. The youngest post-rift on the margins and the oldest sediments on the oceanic crust are both estimated Middle to Late Jurassic. Three convenient markers are also used in the Cretaceous-

Cenozoic, Campanian (lighter green), Base Tertiary (orange), and Paleocene (orange). Local consistent datasets and interpretations have been used to help constrain the different segments of the DFZ.

### 4.1. The continental domain

The continental domain is generally characterized by a shallowing Moho and rifted blocks. Seismic profile ION - KE1000 (Fig. 4) is possibly the most convincing with two distal tilted blocks and associated Liassic syn-rift reworked by inversion structures in the layered late Jurassic and lower Cretaceous facies (see also Fig. 3). Facies 1 from the proximal to distal domains shows a chaotic pattern (Fig. 4a) and may be an equivalent of the Cabo Degado Complex of the Mozambique belt that crops out in south Kenya and east Tanzania (*e.g.*, Bingen et al., 2009). Over the whole area, the continental crust has transparent facies and its top and base are rarely visible. Its structure and the image of Moho are blurred due to the presence of high-velocity Late Jurassic carbonates. Syn-rift sediments are generally characterized by bright and coherent reflectors with medium to high frequency (Facies 2, Fig. 4a), showing wedge-shaped geometries in the proximal part of the Kenyan margin (see Central Kenya – Western Somali Basin cross-section in Fig. 3) with up-dip onlaps onto a basement high. Such geometry is less clear in the distal part of the margin (Fig. 4). They look like more or less homogenous sediments, tentatively attributed to Liassic in the proximal domains to the Middle Jurassic period in the distal ones although the Triassic period cannot be excluded for the deepest deposits (*i.e.*, the Karoo Supergroup, Catuneanu et al., 2005). Such a hypothesis is consistent with the presence of Jurassic and Triassic sediments cropping out near the coast, right to the west of profile ION – KE1000 (Fig. 4). These observations, from North Kenya to Somalia are diagnostic of a rather typical magma-poor margin setting

(Stanca et al., 2016; Sapin et al., 2020, Hassan et al., 2020) that is consistent with the Madagascar margin interpretation (Davison and Steel, 2017).

Conversely, NW-SE seismic lines along the Mozambique Basin show evidence for a volcanic margin setting (Senkans et al., 2019). The Angoche segment is magmatic with seaward dipping reflectors (SDRs) (see Mozambique – Madagascar cross-section in Fig. 3) and the Beira High segment is separated from the continent by an aborted magmatic propagator with facing SDRs (Fig. 1) (Senkans et al., 2019; Roche et al., 2021). Facies from the continental basement along the central Mozambique margins is mostly chaotic (Senkans et al., 2019) and may be correlated with rocks from the Mozambique belt (Roche et al., 2021). SDRs are defined by continuous, medium amplitude reflectors that dip down onto the footwall of normal faults. Interpretations of deep structures and the image of Moho are complicated due to the presence of the lava flows which obstruct the penetration of seismic energy at greater depth.

## 4.2. The oceanic domain

In the Western Somali Basin, steady-state magmatic oceanic crust is mostly found east of the DFZ, in the Early Cretaceous crust, where magnetic anomalies M20 to M0 are well-*expressed* (Fig. 1b). The Middle to Late Jurassic crust close to the margins and west of the DFZ is characterized by a reflective top basement, either fairly smooth and horizontal (Facies 3, Fig. 6a) or rougher and faulted (*e.g.*, Fig. 5) at a kilometric scale. Below the rugged oceanic crust, a fair Moho is generally absent while it is present at 14 km below the smooth oceanic crust. Here, the oceanic crust reaches a thickness of ~ 6 km which corresponds to a “normal” thickness according to the recent synthesis of Christeson *et al*. (2019). Such difference in architecture may be related to the dynamic of spreading ridge (*e.g.*, Reeves et al., 2016; Sinha et al., 2019) and their description and analysis of oceanic facies have been dealt with in Sauter et al. (2016; 2018). Although the transition from continental to oceanic is difficult to deduce southwest of the Western Somali Basin, our mapping shows that oceanic crust is observed east of the DR until at least 15°S. This interpretation, which differs from Klimke et al. (2016) that suggested the presence of a stretched continental basement, is based on seismic observations. The oceanic crust here is highly faulted with a Moho depth of around 14 km. The seismic facies is almost transparent as in the northern part of the basin (Facies 3, Fig. 6a). In terms of structural pattern, this oceanic crust has been first affected by (i) listric faults during the oceanic spreading and then by (ii) wrench faulting in localized areas related to the southward drift of Madagascar (Klimke et al., 2016). Similarly, the oceanic crust in the Mozambique Basin is defined by a reflective top basement which is smooth and horizontal (Facies 3, Fig. 6a). Although recent studies showed an HVLCB near the continental margin of central Mozambique (*e.g.*, Müeller and Jokat, 2017; Vormann et al., 2020), no clear difference in the seismic pattern was observed along the oceanic domain.

Furthermore, the last Facies (Facies 4, Fig. 6a) which differs from the previous ones, is observed at the toes of the DFZ and continental blocks south of the WR (Fig. 1). There, the basement in the oceanic domain is highly deformed (Figs. 5 and 6). Such facies shows wedge-shaped geometries indicating a syn-tectonic origin. It is characterized by a series of alternating strong and weak reflectors. This sequence is similar to the volcano-sedimentary sequence described by Sauter et al. (2018) that results from ultra-slow spreading. Hence, doubts can be raised about the straightforward interpretation of this sequence: either the oceanic crust or exhumed mantle (mostly oceanic, possibly sub-continental close to the continent). Regarding the complexity of the area and the absence of a clear Moho, such facies may correspond to serpentinized and faulted exhumed oceanic mantle. This is also consistent with the recent study of Hassan et al. (2020) that reports upper exhumed mantle based on seismic reflection data along the Somalia coast. A similar sequence may be also reported along the Rovuma Basin (Fig. 1b) close to the reported fossilized oceanic - Aptian in age - spreading center (Sauter et al., 2016; 2018; Sinha et al., 2019). The absence of clear Moho and the presence of extinct ridge axes here may also suggest exhumed mantle during the transform activity.

### 4.3. The crustal domains Map

The interpretation of the full seismic dataset supplemented by potential field data allows us to propose a new map of the crustal domains (Fig. 1). It shows the Western Somali Basin and the northern Mozambique Basin. The Lower Cretaceous crust from M20 to M0 (Aptian) shows extensive E-W magnetic anomalies diagnostic of steady-state magmatic crust. The oldest crust is rugged, often devoid of Moho, and associated with NW-SE transform faults in the Western Somali Basin (Sauter et al., 2018). Locally, exhumed mantle (subcontinental of oceanic?) may be mapped. In addition, although Milsom et al. (2016) suggest the presence of continental crust below the Comoros archipelago based on seismic data, we favor the presence of oceanic crust which is consistent with the recent study of Sinha et al. (2019). Such hypotheses of different types of unknown / debated crust are at the heart of the recent SISMAORE and COYOTES projects (Thinon et al., 2020a; Thinon et al., 2020b) and beyond the scope of this paper.

Other structural information is superimposed: the tectonic inversions of Cretaceous to Cenozoic ages that will be illustrated and described below through a series of cross-sections (Fig. 3) and seismic lines (Figs. 4 to 8), the volcanoes and their ages, the Neogene troughs and the Cenozoic gravity cells.

## 5. The DFZ through seismic interpretation and cross-sections

The DFZ is mapped from north Kenya to west Madagascar. The mapping of crustal domains and the geometrical consistency of the different episodes that have formed or re-used such large structures allow us to recognize various segments and structures detailed below.

### 5.1. Central Kenya – Western Somali Basin cross-section and 3D seismic profile

Central Kenya – Western Somali Basin cross-section runs WNW-ESE across the north of the DFZ where it joins the Kenya margin (Figs. 3 and 4 located on Fig. 1a). It is perpendicular to the DFZ that is at this latitude represented by one transform segment (the Davie-Walu) that sharply separates the proximal and the distal continental domains (Figs. 3 and 4). It is almost perpendicular to the Kenya margin, between 45-80° to the expected rifted blocks. Despite a poor seismic image at that depth, interpretation of the deep continental domain of the margin is proposed. Here, the Moho is not visible, and therefore likely deeper than 30 km. Often clearer on nearby lines, a strong reflective package around 15-22 km is attributed to the lower crust (deep reflectors, Fig. 4). As previously mentioned (see 4.1), the proximal part of the Kenyan margin, is characterized by tilted blocks and Liassic growth structures whereas the rifted series of the distal continental domain are interpreted Middle Jurassic in age (medium blue in the cross-section, Fig. 3) if the breakup is assumed around 166 Ma. Thus, the light blue horizon, late Jurassic to early Cretaceous, is the early post-rift of the Western Somali Basin. Reverse faulting is locally recognized east of the offshore Anza half-graben (Fig. 4), suggesting a diffuse pre-Aptian event. At the same time, in the prolongation of the onshore Anza rift (Fig. 4), Neocomian rifting rejuvenates the Davie-Walu Fault and forms a half-graben sealed by the Aptian-Campanian series (the upper dark green) in the offshore extension of the Anza Graben. The half-graben inversion (*i.e.*, local uplift) is recorded by the thinning of the Campanian-Cenozoic and associated extrados normal faults and the westwards downlaps of Cenozoic sediments at the boundary between the proximal and distal domains. Note that in the central lower part of the graben, thrust-folds record the inversion of distal rifted blocks during the early subsidence of the half-graben (see also Fig. 4). The Tertiary subsidence continues west of the Davie-Walu Fault whereas early Tertiary rifting phases occurred in the proximal continental domain (Fig. 3). The youngest structural event is a Plio-Quaternary diffuse normal and strike-slip faulting, en-échelon and sinistral, in the Neogene depo-centers on the proximal margin, between the islands and the coast (Fig. 1b).

Early Cretaceous tectonics in the Middle Jurassic 'proto'- oceanic domain is also nicely illustrated by the high-quality 3D seismic line over the WR (Figs. 1a and 5). It shows with a high resolution the oldest sediment locally calibrated by the deepest Kiboko-1 well (down to Hauterivian). The top basement is clear, the basement facies is transparent with high amplitude rugged and discontinuous markers attributed to magmatic intrusions. Not on this line, but in the same domain, wedges of probable lava flow and deep offshore sediments are associated with listric faults shallowly rooted into the basement (see Sauter et al., 2018). The basement is interpreted here as an exhumed mantle, locally serpentinized and affected by sparse volcanism. In this position, it is not possible to draw the limit between sub-continental lithospheric or oceanic asthenospheric mantle in a context of ultra-slow spreading (Sauter et al., 2018). The layered high amplitude series below the Neocomian horizon records the activity of small normal faults, possibly post exhumation extension in the subcontinental mantle. Reverse faulting and folding occurred between 132 and 120 Ma (Hauterivian-Aptian) as clearly evidenced by growth strata, implying pre-Aptian inversions. Reverse faults are steep, some of them are related to the inversion of normal faults, some others are originally steep and short-cut tilted blocks. The main fold is associated with one of these steep faults, it may be interpreted as a short-cut of a basement normal fault block. Like the previously described inversion along the Davie-Walu Fault, the anticline has been deeply eroded in Aptian, likely by waves (wave-cut surfaces are highlighted in red on sections). The folds and thrusts system is mapped as a sigmoidal transpressive ridge trending NW-SE in its center, located at the southeast termination relay of the NNW-SSE Davie-Walu Fault (Fig. 1b).

### 5.2. Southern Kenya – Western Somali Basin cross-section

Southern Kenya – Western Somali Basin cross-section (Fig. 3) is E-W, further south in north Tanzania (Fig. 1a). It is again perpendicular to the margin's structure and shows the northern tip of the Seagap Fault and intersecting the Davie-Walu Fault inside the Jurassic oceanic crust. The Seagap Fault is steep and separates the oceanic domain from the Pemba margin, with a top basement significantly higher on the oceanic side. This segment records an uplift and inversion of the oceanic domain in the late Cretaceous and Paleogene, synchronously with the inversion of the Anza trough (extending offshore southward of the Anza basin, Fig. 1b). In the ocean domain, the Davie-Walu segment of the DFZ exhibits significant thrust components. On the cross-section, the Davie-Walu steeply dips to the west. It separates a domain of typical oceanic crust with Moho to the east from a poorly magmatic crust devoid of Moho to the west (mantle domain in our interpretation), suggesting that it was active as an oceanic transform during the Jurassic spreading stage. It records also a vertical displacement in the range of 3 km in the Lower Cretaceous (Fig. 6). In detail, the seismic profile shows reverse faulting and folding occurring mainly between Hauterivian and Aptian as clearly evidenced by growth strata (Fig. 6). The associated ridge is deeply cut by waves suggesting that the ridge was an island in the Aptian when spreading was dying out in the

Western Somali Basin. This is also consistent with the presence of carbonate rocks observed on a nearby line.

### 5.3. Central Tanzania – Western Somali Basin cross-section

Central Tanzania – Western Somali Basin cross-section (Fig. 3) is NE-SW and cuts across the Western Somali Basin in offshore central Tanzania (Fig. 1a). Similar to the previous one, the Seagap Fault and the Davie-Walu Fault are observed. However, in this part of the oceanic domain, the Davie-Walu Fault is discrete and hard to trace. The first one is almost vertical and limits the old oceanic domain from the young one (*i.e.*, Cretaceous in age) with a top basement again significantly higher on the eastern side. Here more than an inversion, the anomalous relief at the basement is more likely related to oblique-slip along the vertical plane during the Cretaceous. It shows locally Upper Cretaceous and Cenozoic reactivation with a probable strike-slip component. The Davie-Walu Fault steeply dips to the east and offsets the oceanic crust. Little further east, the oceanic crust is very thin and it is still difficult to identify eastwards, particularly in-between the two oceanic transform segments (Fig. 3).

### 5.4. Profile ION - MZ1-7500

Located along the north Mozambique segment (Fig. 1a), the seismic profile (Fig. 7) is roughly perpendicular to the coastline and the DFZ. A parallel line of the same ION survey in the north close to the Tanzania border (ION MZ1- 8700) is shown in Sinha et al. (2019). They showed that the continental domain and its limit with the ocean are affected by several splays of the DFZ that exhibit normal transtensional components. The main fault zone is marked by a negative flower structure that limits the south of the Neogene Kerimbas graben (Fig. 1b).

The profile (Fig. 7) shows a quite similar crustal structure and tectonic style as the ION MZ1- 8700 profile. The western quarter is interpreted as continental, based on gravity data and seismic interpretation. It is bounded by the Davie Main Fault which corresponds here to the continent-ocean boundary. This major structure controls also the development of the Lacerda Neogene graben which is still active (its northern end here, Fig. 1b) and cuts a previous fault that structures the Ibo Ridge (IR). Westward of this fault, the IR is marked by a conspicuous wave-cut surface with an unknown age from 13°00’S under the south of the Rovuma Delta to 15°75’S. The IR continues along the south of the Davie Main Fault, hence witnessing a Lower Cretaceous activity along the segment. The next splay of the DFZ to the east corresponds to the Davie-Walu Fault (Fig. 7). Such structure shows local Early Cretaceous inversions in the oceanic domain. At the latitude of profile MZ1-7500, the Davie-Walu Fault seems to be inactive in the Cenozoic (even though a pure strike-slip component cannot be excluded) while its northern extension records a transtensional opening with the Kerimbas trough (Fig. 1b and Sinha et al., 2019) which is still active (Franke et al., 2015).

The oceanic domain is very irregular at the top basement and Moho levels. The lower crust is rather transparent with high amplitude markers, intrusions, underlining the Moho and faults. The upper crust shows variable thicknesses of high amplitude series that are likely volcano-sedimentary. It is highly sheared/faulted by intra-oceanic splays of the DFZ until 41°30’E where the mature oceanic basin can be mapped.

### 5.5. Mozambique – Madagascar cross-section and WesternGeco seismic profile

Mozambique – Madagascar cross-section (Fig. 3) illustrates the DR in the Mozambique Basin from Angoche Margin in Mozambique to Morondava Basin in Madagascar (Fig. 1a). At first glance, it shows a complex structure defined by Jurassic – Lower Cretaceous depocentres cut by thrust and normal faults. It has been previously described by several studies (*e.g.*, Mahanjane, 2014; Mahanjane et al., 2014; Franke et al., 2015) as a growth wedge structure related to the Davie compression zone. Its whole content has been attributed to Jurassic based on (i) the approximative extension of the seismic horizon described in the Rovuma Basin by Salman and Abdula (1995) and (ii) an optimistic exploration perspective. In any case, the area lacks well calibration and their interpretation can be questioned. Indeed, the closest one to extrapolate the late Jurassic-early Cretaceous is Kiboko-1 (Fig. 1a). Seismic profile (Fig. 8) shows our assumption for the lower Mesozoic with a top Jurassic horizon not too far above the top of the oceanic crust, an Aptian horizon above the transpressional and transtensional structures in the ridge, and one intra-Neocomian marker to show internal deformation. The Aptian unconformity is the onlap surface that delineates the DR forming a bathymetric high based on the Cachalote-1 well calibration. Thus, our interpretation differs from others (Mahanjane et al., 2014; Franke et al., 2015) that suggested a top Jurassic unconformity.

In detail, the Mozambique – Madagascar cross-section shows from west to east:

- The Angoche volcanic margin with its SDRs (Senkans et al., 2019). A salt layer (see thin red lines in the cross-section in Fig. 3), deposited on the lava flows has allowed the Neocomian gliding of the Jurassic cover bordered by a diapir squeezed on the edge of the oceanic crust (outer-high). The north of the Mozambique oceanic basin of the estimated Middle Jurassic age (anomalies M38, Mueller and Jokat, 2019) is covered by a thin layer of upper Jurassic. Sub-horizontal in the Mozambique Channel, it dips east under the DR until 9sTWT where the Jurassic thickens in the foredeep basin.

- The DR is a continent-ocean transform boundary between the Mozambique Basin and the Madagascar Margin. The contact is not imaged, but the flexure of the top oceanic crust and the presence of the compressional wedge suggest a component of underthrusting of the oceanic crust below Madagascar. This wedge is dominantly made of Neocomian sediments and shows a polyphase evolution below the top Aptian unconformity highlighting that uplift is still active until this time (Fig. 8). The thrust wedge is recorded in the lower Neocomian and its frontal fold is locally cut by an unconformity with unknown age. This compression is considered contemporaneous with what has been described above in Fig. 5 and along the Davie-Walu segment even though this latter seems to finish before the previous ones. Indeed, the upper part of this wedge is affected by strike-slip faults showing normal components (Fig. 8). This transtensional deformation is then sealed by the Aptian unconformity that delineates the DR. The top of the ridge is asymmetrical with a steep west limb and a shallow-dipping to horizontal east limb. The west limb is onlapped by the upper Cretaceous-Cenozoic and is still a relief at the seabed (starved conditions). This geometry may be attributed to late Cretaceous-Cenozoic differential passive subsidence (isostasy) between the oldest part of the Mozambique Basin and the continental margin. On the east limb, a Tertiary reactivation is marked by the unconformable base Tertiary and by localized graben. Some of the normal faults are also still active. The ridge and the basin to the east are frequently accompanied by Turonian sills and dikes (Bassias, 1992; Klimke et al., 2016), and some larges volcanoes of that age are still visible at seabed along trend.
- The Morondova margin of Madagascar shows a thicker Jurassic syn-rift section in the Juan de Nova Ridge (JDR in Figs. 1a and 8, see Mozambique – Madagascar cross-section), inverted during the early Cretaceous and possibly even in late Jurassic (lack of valuable calibrations). Besides this local event, it records passive margin subsidence.

## 6. Discussion

Our series of cross-sections based on seismic interpretation and a few wells illustrate the main crustal domains and the limits of the continental margins. The continental ocean boundary (COB) is often sharp along the splays of the DFZ whereas distal hyperextended margins with sometimes visible mantle exhumation of extensional and oblique segments are present (though mostly poorly imaged) along the Somalia, Kenya, and Tanzania segments. They are the remnants of the pull-apart opening during the Lower/Middle Jurassic (Sinha et al., 2019). The structure of these margins (*i.e.*, Kenyan-Tanzanian margin, Mozambique margins, and the Madagascar margin) and their proximal oceanic basins, derive therefore from the formation and evolution of the Davie transform system even though the main transform segment (*i.e.*, the Davie Main Fault) was formed in the Latest Jurassic.

### 6.1. Structural style along the DFZ

The DFZ corresponds to a corridor of strike-slip faults and continent-ocean transform faults composed of several splays with branching and relays recording variable extensional or compressional components through time (see our simplified geodynamic chart, Fig. 9 and Sinha et al., 2019). At first glance, the deformation zone is wider and more diffuse in the north in the oldest marginal part of the Western Somali Basin than in the south, and more particularly in the Mozambique Basin (250 km vs. 50 km). In other words, the structures are less apparent in north Tanzania and Kenya magma-poor margin than in the south along the Mozambique margin volcanic margin. This difference is likely a result of the southward drift of the mid-ocean ridge along the DFZ throughout the Cretaceous. There is no active plate boundary in the north at the time of later transpressional events (*e.g.*, the formation of the large wedge along the DR, Fig. 8), whereas in the south the Davie Main Fault is the active plate boundary until ~125 Ma. The large wedge may, therefore, also be a result of increased cumulative strain in this area (the Davie transform system has been active for longer).

Further, the DFZ favors the localization of the deformation during and after its activity. Inversions are distributed along both the oceanic and continental-oceanic segments (Fig. 2). Interestingly, the strike of transform faults does not seem to influence the localization of deformation which occurs in the whole DFZ. These lithospheric- and/or crustal-scale structures, therefore, become future inheritance zone controlling the location of incoming structural events.

#### 6.1.1. Main segments

Based on our observations, three main segments defining the DFZ are recognized:

(i) The western segment, the Seagap (Fig. 1a) starts NNW-SSE where it joins a transfer zone in the margin between Pemba and Zanzibar islands and then runs N-S along the coast until the Rovuma delta in northern Mozambique. This intra-oceanic segment separates to the west a remnant of the early magma poor oceanic basin until 11°S. Interestingly, the Seagap Fault has a listric shape where it joins the Davie Main Fault in its southward termination at 11°S but on the convex side. This segment is still active.

(ii) The southern segment, the Davie Main Fault runs along the Mozambique Basin as the DR and corresponds to the main plate boundary (Fig. 1a). It is a sharp continent-ocean boundary between the Jurassic oceanic crust and continental crust made-up of a Proterozoic basement with local wedges of Karoo syn-rift deposits in Africa and Madagascar. From north to south: (1) It is mostly N-S as the boundary between the Somali Basin and the north Mozambique continental transform margin at 11°S (Fig. 1). (2) Southward, the segment runs along the east of the Lacerda trough and then along the DR with a strong normal component. It is mapped between the southern part of the Morondava basin where the ridge is close to the present-day Mozambique shelf break, to the North of the Angoche segment (Fig. 1). In the south, the structure finally formed a prominent N-S transpressive Neocomian ridge below the Aptian unconformity, corresponding to a narrow continent-ocean boundary between Mozambique basin and Madagascar (Fig. 8). Here, it is not covered and becomes a bathymetric relief south of 17°10'S, while it is deeply eroded by the Aptian wave-cut northward (calibrated by Cachalote well) which is collapsed allowing the development of the Lacerda trough north of 17°S.

(iii) The eastern segment, the Davie-Walu fault (Fig. 1a) splits off from the Davie Main Fault at 14°10'S. (1) In the south, it is an active segment, lined by fault scarps at seabed along the Kerimbas Neogene trough (Fig. 1b). At basement level, the segment is characterized by an N-S gravimetry anomaly along which volcanic centers are mapped. (2) In the north, the east-dipping boundary fault of the Anza half-graben extends offshore in the oceanic domain. The northern part of the segment is an east-dipping boundary fault located in the Anza half-graben which extends offshore in the oceanic domain. It is inverted in the Late Cretaceous – Paleogene (Fig. 4). This feature dies out in the WR where 3D seismic allows mapping an NW-SE trending horse-tail termination characterized by Neocomian thrusts affecting the oceanic crust, locally mostly made-up of mantle (Fig. 5). The northern segment is also characterized by Quaternary activity. (3) In between these both segments, inside the oceanic domain, it is trickier to map as a continuous fault (Fig. 1) even though a gravity high and localized inversion are observed (Fig. 3, Southern Kenya – Western Somali Basin cross-section). However, Lower Cretaceous transpressional structures are present.

### 6.1.2. Periods with a transpressional dominance

The transpressional events can be summarized following their timing (Fig. 9). The DFZ and some continental structures are inverted during Neocomian until Aptian, forming the horsetail structures along the WR, the IR, and the DR southward (Fig. 1). In detail, our data show that such transpressional ridges have been deeply eroded by waves (i) probably during the middle Lower Cretaceous in the southern Western Somali Basin and the Mozambique Basin (see Figs. 7 and 8) and (ii) during the Aptian time in the northern Western Somali Basin (Figs. 5 and 6). Interestingly, the Aptian unconformity related to the end of oceanic spreading in the Western Somali Basin is recorded in the whole area. Depending on the locality, this major unconformity seals the pre-Aptian to Aptian inversions observed along the WR and marked the end of the uplift forming the DR in the Mozambique Basin.

The most important transpressional event is recorded in the Mozambique Basin along the Davie Main Fault. This later appears less apparent in the north (*i.e.*, along the IR) than in the south (*i.e.*, along the DR) where the oceanic crust is involved highlighting an isostatic disparity between these places. It is interpreted as an effect of transpression that induces crustal thickening during the end of Jurassic and Neocomian. This narrow-elongated feature might be the longest marginal ridge consistent with the definition yielded by Lepinay et al. (2016) and Loncke et al. (2020). The absence of Moho constraints due to low seismic data quality here doesn't help to identify the major process controlling this morphology. We propose that this wedge results from the transform fault activity which is influenced by far-field compressional stresses related to plate kinematic reorganizations. The incipient subduction stage described by Intawong et al. (2019) may arise from this process and by differential thermal subsidence between the oceanic and continental lithospheres. Nonetheless, there is no clear evidence of magmatism related to this event and the negative buoyancy of this young oceanic lithosphere cannot provide the primary driving force for subduction.

The second significant event occurs during the end of the Cretaceous until Paleogene (Fig. 9), thus after the transform fault activity. Such compressional events are observed over the entire area. They are mainly recorded in the WR (*e.g.*, see the antiform in Fig. 5) and are also associated with gravity collapse cells gliding to the east along the south Somalia segment in the oceanic domain (Fig. 1b). Inversion is also observed along Central Tanzania – Western Somali Basin cross-section (Fig. 3). It is characterized by an anomalous relief of the basement (close to the Seagap Fault) which is more likely related to oblique-slip along the vertical plane (see Fig. 1b). Locally, small relays and one major N-S trending offshore inversion are observed along the Seagap Fault and in the line with the Pemba strait (Fig. 1b).

Finally, the latter major inversion is Neogene in age (Fig. 9). It is located on the west side of the Seagap Fault and northwest of the Kerimbas basin in the Jurassic oceanic domain (Fig. 1b).

### 6.1.3. Periods with a transtensional and extensional dominance

As previously mentioned, the structures related to the onset of the Davie transform system are less apparent in the north of Western Somali Basin than in the south along

Tanzania and north Mozambique segments. Here, faults trend NW-SE and become progressively N-S toward the Seagap Fault, implying a dextral shearing. These pull-apart structures separate the continental domain from the Jurassic oceanic one. During the Valanginian-Barremian, extension is mainly localized along the Kenya margin as attested by the presence of the Anza graben (onshore and offshore) whereas folding is recorded in the deeper layers (Fig. 4), witnessing a coexistence between extension and compression components. Similar features are reported along the DR during the Neocomian (Fig. 8). Indeed, transpression is recorded at the forefront of the DR whereas transtension occurs in the eastern part of the ridge. Locally, relays are observed along the Davie-Walu Fault (Fig. 1). Transtension is also recorded along the Lacerda and Kerimbas grabens during the Neogene (Figs. 1b and 9). The first graben corresponds to the collapse of the IR in the Mozambique Basin. The second one shows significant similarities with a pull-apart basin limited by the Seagap Fault and the Davie-Walu Fault.

## 6.2. Evolution of the DFZ

The northern proto-transform segments of the Davie transform system in the oldest oceanic domain, are broadly in the same trend that onshore major faults and lineaments (*e.g.*, Aswa shear zone that may continue into the Tombo fault in Madagascar, Collins and Windley, 2002; Reeves, 2014). A linkage to onshore tectonic features may thus be envisaged (Reeves and De Wit, 2000; Reeves et al., 2016; Sinha et al., 2019). Consequently, transfer faults may pass laterally into oceanic transform faults in this area and tectonic inheritance thus influenced the first stages of transform systems. Indeed, NW-SE trending structures are mainly reactivated during the rifting phase of the Western Somali Basin since the Early

Jurassic. Unfortunately, seismic is quite poor in the Kenyan margin and the Morondava basin to properly define the structure of the margin and early transform segments.

At ca. 166 Ma, the synchronous opening of the Western Somali Basin and the Mozambique Basin leads to the onset of the Davie transform system that will accommodate the southward drift of Madagascar and Antarctica (Figs. 9 and 10). In the Western Somali Basin, large pull-apart systems and a succession of rotated continental blocks with oblique components along the Tanzania segment (Sinha et al., 2019) and in the north of the Morondava Basin (Klimke et al., 2016), respectively, are described. These structures related to the early stages of spreading are interpreted in the context of NW-SE extension (*e.g.*, Reeves, 2017) as associated with pull-apart structures along en-échelon dextral strike-slip faults within a span of 10 Ma. The oldest oceanic basin formed in this context is preserved in the embayment west of the Seagap segment in north Tanzania and Kenya all along the Kenya-Somali margin (Fig. 1a). The embayment is floored mostly by the exhumed mantle with patches of magmatic rocks, a poorly magmatic oceanic basement considered to have formed in an ultra-slow spreading mode (Fig. 6) (Sauter et al., 2018). Conversely, the onset of rifting in the Mozambique Basin is characterized by a warmer thermal regime as attested by the presence of onshore Karoo magmatism (Rb/Sr age data at ca. 184 ± 15 Ma, Grantham et al., 2018), magmatic SDRs and the high velocity lower crustal body between the magnetic anomalies M38n and M33 (Mueller and Jokat, 2019) near the Angoche continental margin.

At around 155 Ma (Fig. 10), a regional change in kinematics (NW-SE to N-S) impacts the whole of eastern Africa (*e.g.*, the Mozambique Basin and Western Somali Basin, Mueller and Jokat, 2019). Such timing also corresponds to a progressive change in (i) spreading pattern (our study, Reeves et al., 2016; Sauter et al., 2018; Sinha et al., 2019) and (ii) flow line geometries (Müller et al., 2008) and (iii) structural pattern. Indeed, at ca. 155 Ma, the NW-SE trending proto-transform segments are cut by or give way to the major N-S transform segment – *i.e.*, the Davie Main segment – which separates the two newly formed oceanic basins where the oceanic domain was mapped and the continental domain. In other words, the new-formed transform fault joins into the older proto-transform segments due to plate kinematic reorganization. This major change in plate kinematics is not instantaneous; that is consistent with Sinha et al. (2019)'s observation based on the slow rate of spreading coupled with asymmetric extension. This large-scale kinematic change may be related to the onset of the south Atlantic rifting and opening well-recorded in the Outeniqua basins and northern Falkland during the Late Jurassic (*e.g.*, Schimschal and Jokat, 2019; Lovecchio et al., 2020).

Further, the initiation of this major transform segment is probably related to the connection of a series of discrete spreading centers irrespective of the influence of structural inheritance as suggested by numerical modeling (Gerya, 2013). Even though locally, this continent-ocean transform fault shows obliquity compared with the new-formed oceanic transform segments (see the changes NW-SE to N-S at 11°S and 14°S, Fig. 1). This change of trending may be explained by a pre-existing structuration resulting from (i) the onshore NW-SE structural trend delimiting the tectonic contact between the Neoproterozoic domain and overprinted Mesoproterozoic domain (Thompson et al., 2019) and (ii) the early basin formation which started to develop in the Middle Jurassic. In any case, the alignment of weak rifted margins, and young oceanic lithosphere, and the small distance between the two basins may have favored the location of the Davie transform system (Phethean, 2018). During this period, the oceanic spreading becomes more mature and controlled by asthenospheric mantle flows which favor the southwards drift of Madagascar and Antarctica. The Davie transform system is no longer influenced by the African inheritance. Interestingly, 3D thermo-mechanical modelings (Gerya, 2013; Le Pourhiet et al., 2017; Ammann et al., 2018) predict that initiation of transform faults occurs several million years after the break-up of the divergent segments. In detail, Le Pourhiet et al. (2017) showed that the delay between the break-up occurring along the divergent rift segment and the final oblique break-up increases from 6Myr for 100 km offset to 25Myr for a 300 km. But, in our case, the delay is around 10 Ma (if we consider a break-up age at 166 Ma) for 1000 km offset, which is very fast compared to the previous models.

Finally, the Aptian time (M0) roughly marks the end of spreading and of the Davie transform system activity in the Western Somali Basin (Fig. 10) whereas transform activity is still active in the Mozambique Basin until 96 Ma in the south (Bernard et al., 2005). Interestingly, during Aptian time, a series of successive islands might have existed in the Western Somali Basin and the Mozambique Basin (*e.g.*, IR, DR…), some floored by mantle rocks.

### 6.3. A major structure sensitive to far-field stresses

Both extension and compression were recorded along the margin in the continental and the oceanic domains along the trend of the DFZ during and after Western Somali Basin ocean spreading activity (*e.g.*, Figs. 5 and 8). The first inversion, Hauterivian-Barremian in age, is characterized by N-S to NW-SE reverse faults affecting the Late Jurassic oceanic crust along the wide sheared corridor of the DFZ. This inversion is more prominent in the DR as attested by the presence of a west-verging thrust wedge and associated foredeep basin, but occurs also along the IR. To the north, this deformation interferes with the Valanginian-Barremian NNW-SSE Anza half-graben (Fig. 1b): folding is recorded along inverted margin blocks in the middle of the actively subsiding graben. Here, we suggest that these inversions, a dominantly transpressional motion along the DR-IR and the thrusts in the WR (*e.g.*, Fig. 5) area may be related to the early stages of opening of the Indian Ocean between India and Antarctica at ca. 130 Ma (Fig. 9).

The Davie trend is once more reactivated in the Late Cretaceous-Paleogene mainly through (i) the inversion of the Anza graben to the north triggering gravity cells gliding to the east, (ii) uplift south of Zanzibar island, and local folding along south Tanzania transform margin (Fig. 1b). These inversions are extended in time and space and may be related to (i) the breakup between India and Madagascar during the Late Cretaceous (Fig. 9) (ca. 80 Ma, Seton et al., 2012) and/or (ii) the Himalayan collision which started during the Paleogene (55 Ma, Seton et al., 2012).

Oligocene inversion and gravity sliding are locally observed along the South Somalia segments (Fig. 1b). Here, deformation may be related to the rifting between Africa and Arabia and/or to the East African rifts system (Fig. 9).

In the Tertiary, mostly Miocene (Fig. 9), transtension is responsible for the subsidence of the Kerimbas basin in the fork between the Seagap and Davie-Walu segments. Continued subsidence occurs (Lacerda graben, Fig. 1b) in the south between the Davie-Main and the remaining relief of the DR-IR. Delayed subsidence of the continental margin also occurs in the troughs between the Tanzania islands of Mafia, Zanzibar, and Pemba and the coast (Fig. 1b). In these coastal troughs, a present-day activity characterized by an organized en-échelon system of normal faults continues throughout Neogene and is still active. It is compatible with a sinistral reactivation of the deep Jurassic faults. These activities delineate the eastern part of the Rovuma block (Calais et al., 2006; Kusky et al., 2010) and correspond to the southward extension of the Cenozoic East African Rift System (Franke et al., 2015). Locally, compressional structures are observed northwest of the Kerimbas graben and recent volcanoes develop along the DFZ suggesting that transform fault guide volcanic lavas to the surface (Fig. 1).

## 7. Conclusion

We used a high-resolution seismic dataset provided by the industry, to better understand the structure of a continental-ocean transform margin – the Davie transform system (Western Somali Basin and Mozambique Basin) – from rifting to post oceanic spreading. Results show that the DFZ offers great variability of structures ranging from en-échelon folds and faults to reverse faults associated either with transtension or transpression in both continental and oceanic domains during and after its main activity. This structure that allows the southward drift of Madagascar, is therefore very sensitive to regional/far-field stresses. In detail, we proposed:

1) a new detailed map of the basement showing the continental crust and two oceanic domains, which displays the COB farther inboard – *i.e.*, closer to the coast – than previous interpretations (*e.g.*, Sinha et al., 2019).
2) a series of cross-sections, dip and strike showing the main domains and the limits of the continental margin, which is most often narrow and abrupt (no distal margin setting with thin crust except on the W[illegible]). One of the major differences concerns the presence of the oceanic crust east of the Kerimbas basin.
3) A simplified kinematic evolution model of the DFZ based on a revised tectonic calendar. Findings show that the early basins related to the Middle Jurassic rifting event are influenced by the African crustal inheritance (NNE-SSW normal faults and NNW-SSE transfer zones). The oceanic spreading started at ca. 166 Ma within an oblique system forming pull-apart structures along the Kenyan and Tanzanian margins. At ca. 155 Ma, a kinematic reorganization (NNW-SSE to N-S) related to the South Atlantic opening occurs in the whole of eastern Africa. This latter is accompanied by a mature oceanic spreading and by the formation of the main transform segment of the Davie transform system (*i.e.*,

the Davie Main Fault) that corresponds to the plate boundary between, the mature Somali and Mozambique basins and adjacent north Mozambique-Tanzania and Madagascar continental margins. It was followed by several pulses of compression (Valanginian-Hauterivian) along the newly formed transform system while the Anza graben and its offshore extension subsided. Finally, the DFZ and some continental structures are rejuvenated (inversion and strike-slip) in Late Cretaceous-Cenozoic. Gravity tectonic systems form also in response to these inversions in association with deltas (*e.g.*, Rovuma, Anza).

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## Credit Author Statement

Vincent Roche: Conceptualization, Methodology, Writing- Original draft preparation. Jean-Claude Ringenbach: Methodology, Writing- Reviewing

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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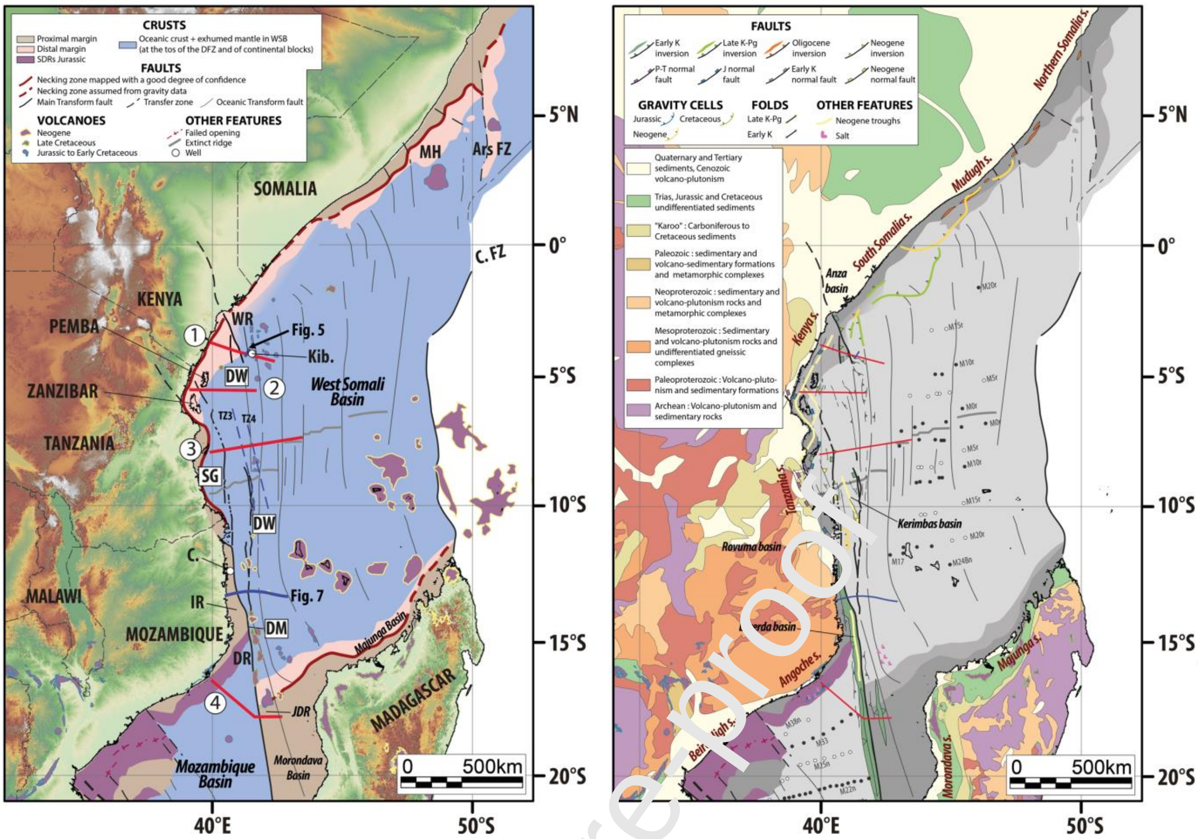

Figure 1: Simplified maps of the study area. (a) Map showing the crustal domains and the main segment of the DFZ. Red lines represent the necking zone based on our seismic observations and gravity data. Numbers correspond to the position of lithospheric cross-sections. Note also the location of Figures 5 and 7 and the two seismic lines - TZ3-1200 and TZ4-1275 - from ION used to map the oceanic domain. Ars FZ (Ars Fracture Zone), C. (Cachalote-1), C. FZ (Carlsberg Fracture Zone), DM (Davie Main), DR (Davie Ridge), DW (Davie-Walu), IR (Ibo Ridge), JDR (Juan de Nova Ridge), Kib. (Kiboko-1), SG (Seagap), MH (Mudugh High), WR (Walu Ridge). (b) Map showing the main compressional and transtentional events. Note also the presence of gravity cells and Neogene troughs. Magnetic anomaly identifications in the Western Somali Basin and the Mozambique Basin are after Davis et al. (2016) – Vormann et al. (2020) and Mueller and Jokat (2019), respectively. Segment (s) indicates along-strike segmentation observed along the continental margins offshore, and thus the structural complexity.

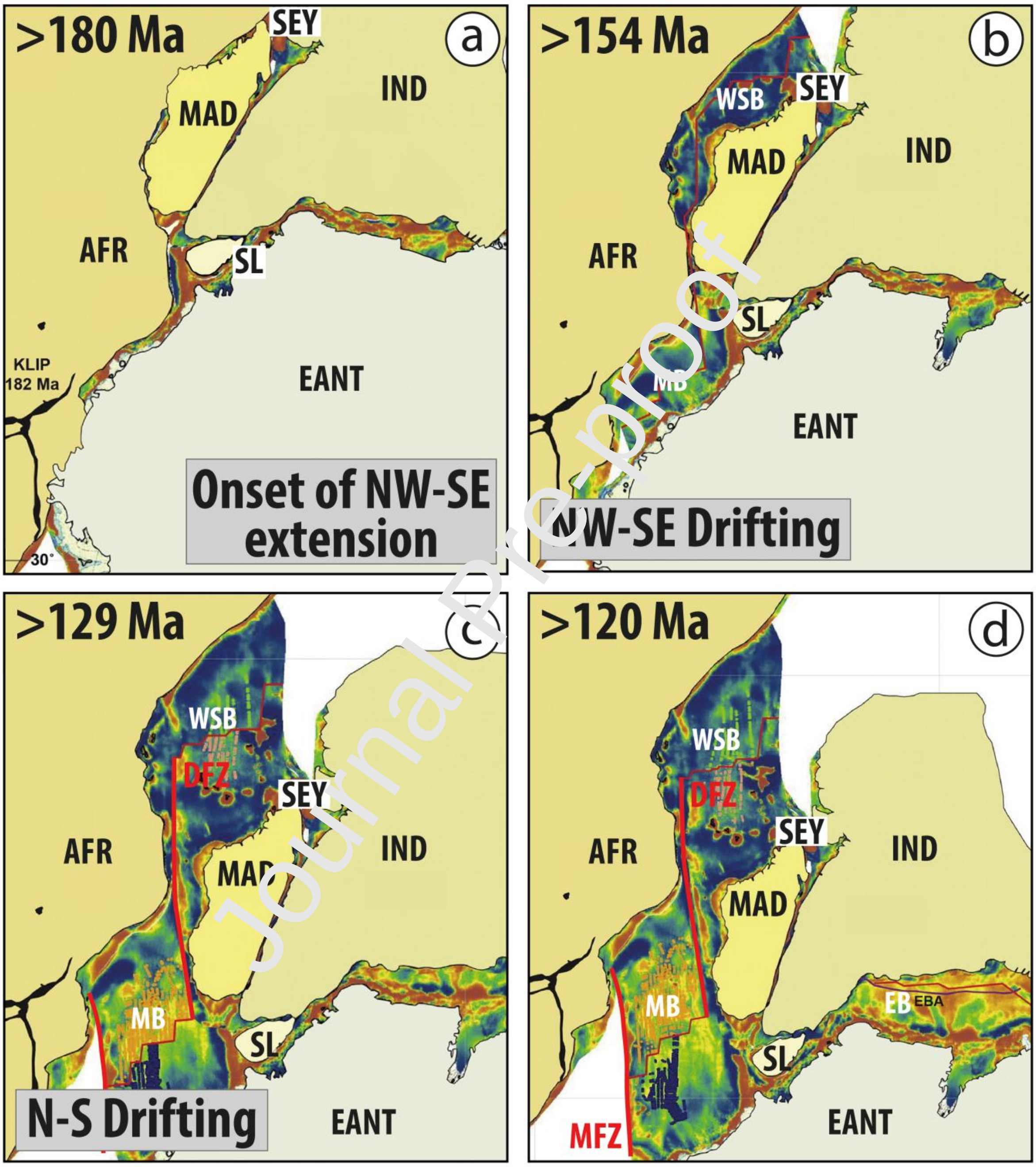

Figure 2: East Gondwana evolution modified from Davis et al. (2016) showing at different time-scale the break-up between the different tectonic plates. Note that this model is mainly focused on the Western Somali Basin and is based on offshore geophysical interpretations. (a) Gondwana fit. (b) Seafloor spreading in the Western Somali Basin and the Mozambique

Basin related to NW-SE opening. (c) Seafloor spreading in the Western Somali Basin and the Mozambique Basin related to N-S opening. Note also that the breakup between the Madagascar/India and East Antarctica plates begins after M15n. (d) Ending of spreading in the Western Somali Basin, whereas it is ongoing in the Mozambique Basin and Enderby Basin, out to the Enderby Basin Anomaly (EBA; thick purple line). Abbreviations are: AFR = African plate, DFZ = Davie Fracture Zone, EANT = East Antarctic plate, EB = Enderby Basin, EGD = East Gondwana plate, IND = Indian plate, KLIP = Karoo Large Igneous Province, MAD = Madagascar, MB = Mozambique Basin, MFZ = Mozambique Fracture Zone, SEY = Seychelles, SL = Sri Lanka, WSB = Western Somali Basin.

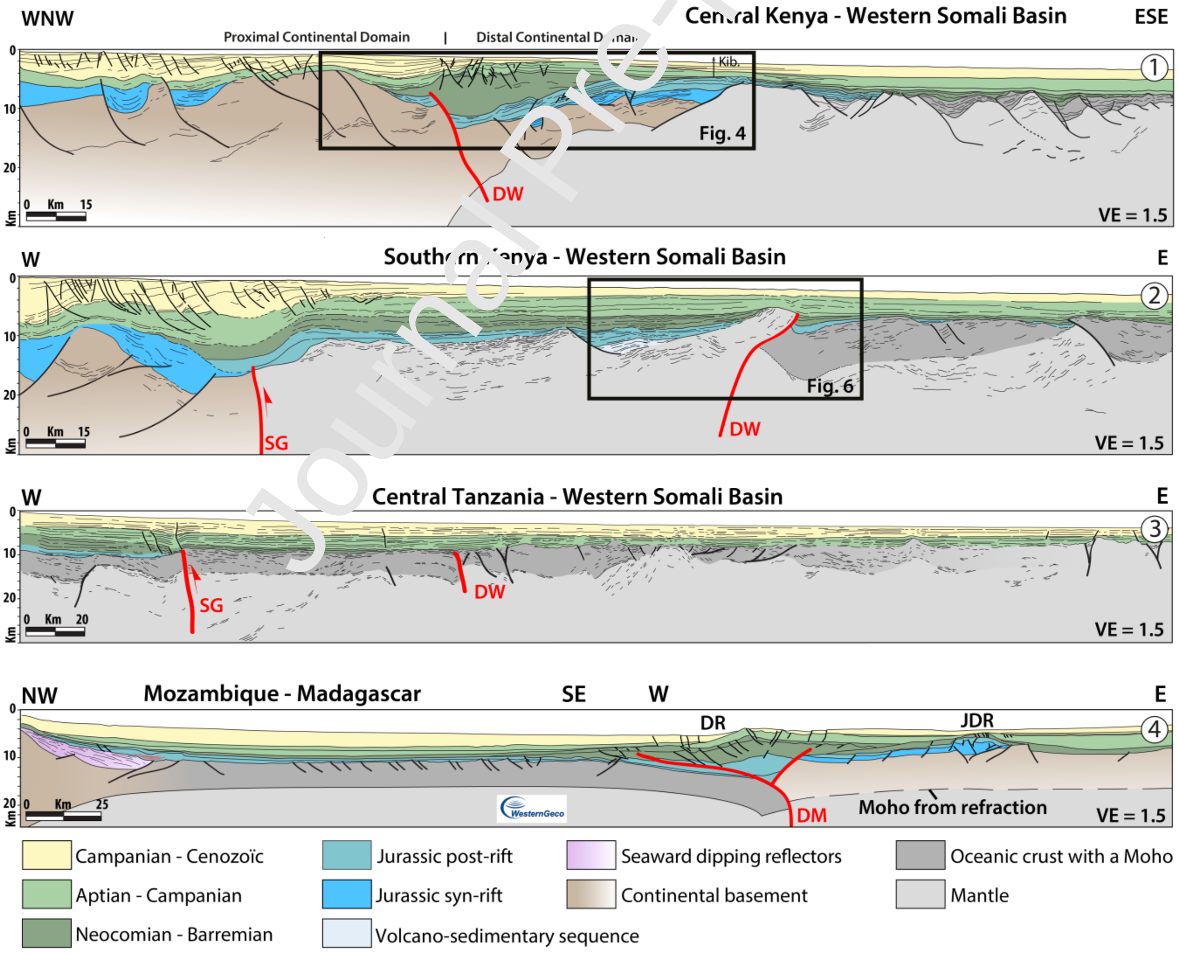

Figure 3: Simplified cross-sections based on seismic lines through the study area showing the main crustal structures. Note that the boundary between proximal and distal continental

domains is defined by a major fault favoring a radical thinning of the continental crust in Central Kenya – Western Somali Basin cross-section. In addition, the depth of the continental Moho along the Mozambique – Madagascar cross-section is from Vormann et al. (2020). Note that some parts of these cross-sections correspond to seismic profiles shown in this study. The location of these cross-sections is indicated in Figure 1. Davie Main (DM), Davie Ridge (DR), Davie-Walu (DW), Juan de Nova Ridge (JDR), Kiboko-1 (Kib.), Seagap (SG), Vertical Exaggeration (VE).

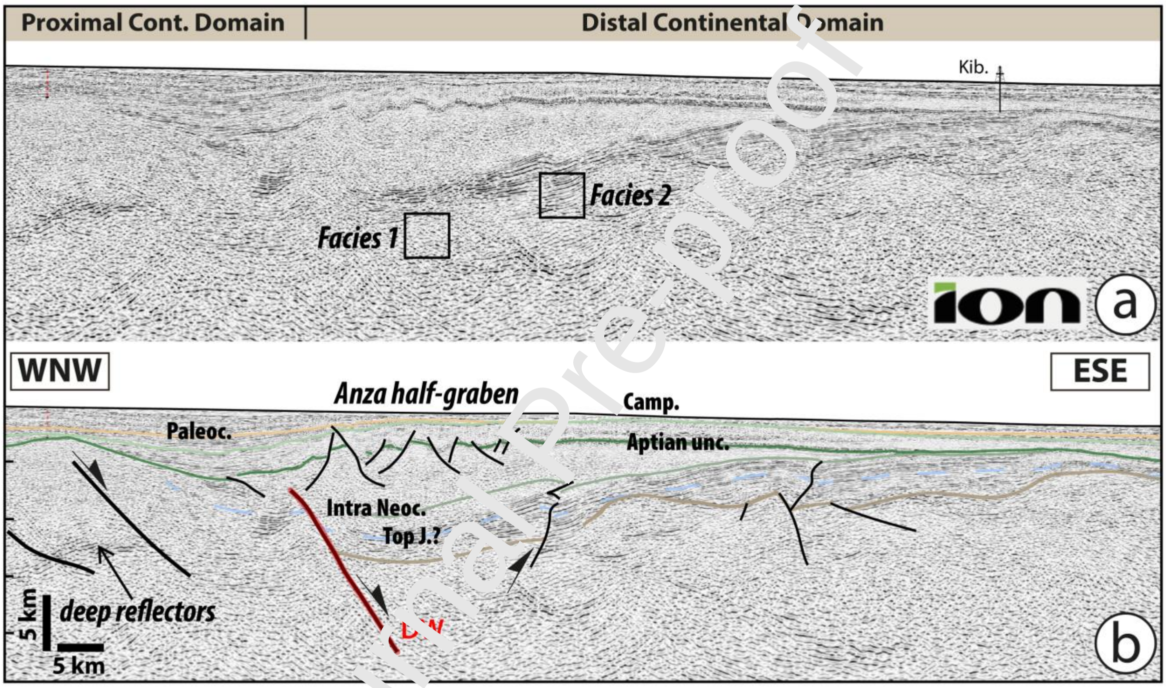

Figure 4: Inversion in the continental crust. (a) WNW-ESE trending offshore seismic profile ION – KE1000. (b) Line drawing and interpretation of basement structures observed. Note that the distinct domain is identified above the seismic profile. The red line indicates the position of the Davie-Walu Fault. Note that the distinct domain is identified above the seismic profile. See Figure 3 for the location. See text for explanations. Paleocene (Paleoc.), Campanian (Camp.), Neocomian (Neoc.), Jurassic (J.), Unconformity (unc.), Davie-Walu (DW), Kiboko-1 (Kib.).

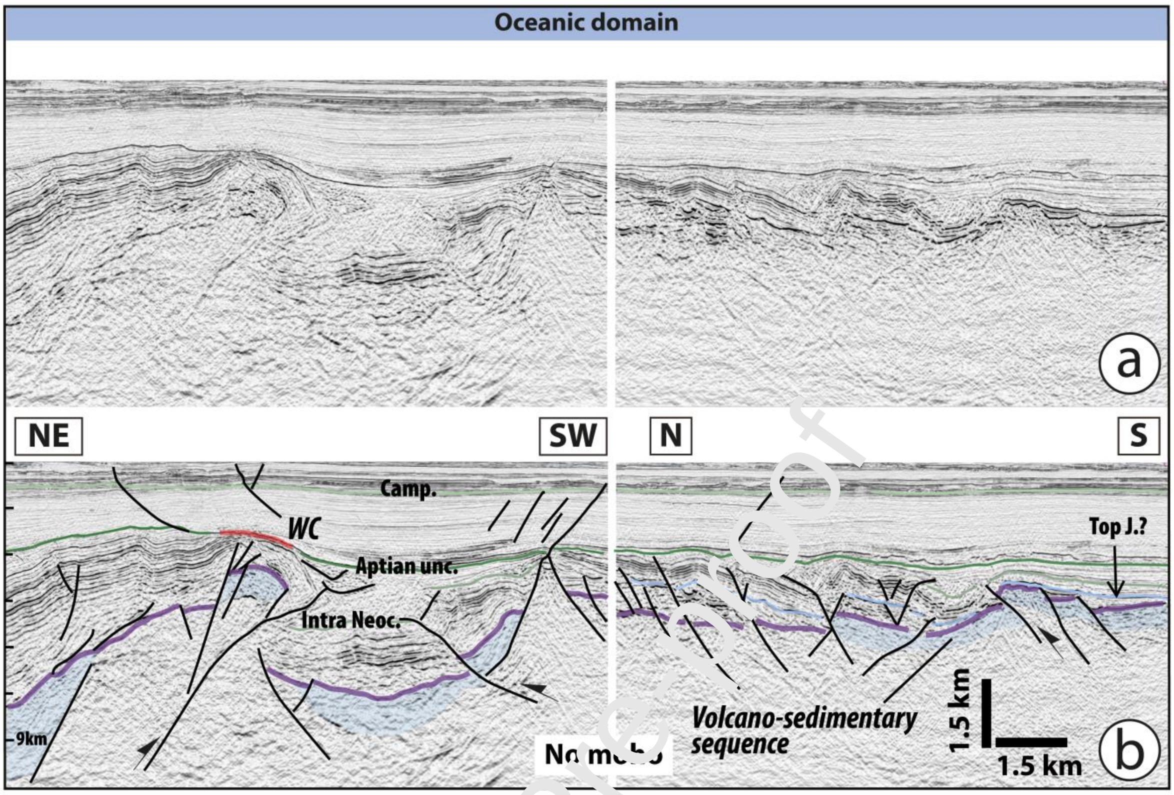

Figure 5: Inversion in the oceanic crust. (a) Offshore 3D seismic profiles with (b) line drawing and interpretation. Note that the distinct domain is identified above the seismic profile. See Figure 1 for the location. See text for explanations. Campanian (Camp.), Neocomian (Neoc.), Jurassic (J.), Unconformity (unc.), Wave-cut (WC).

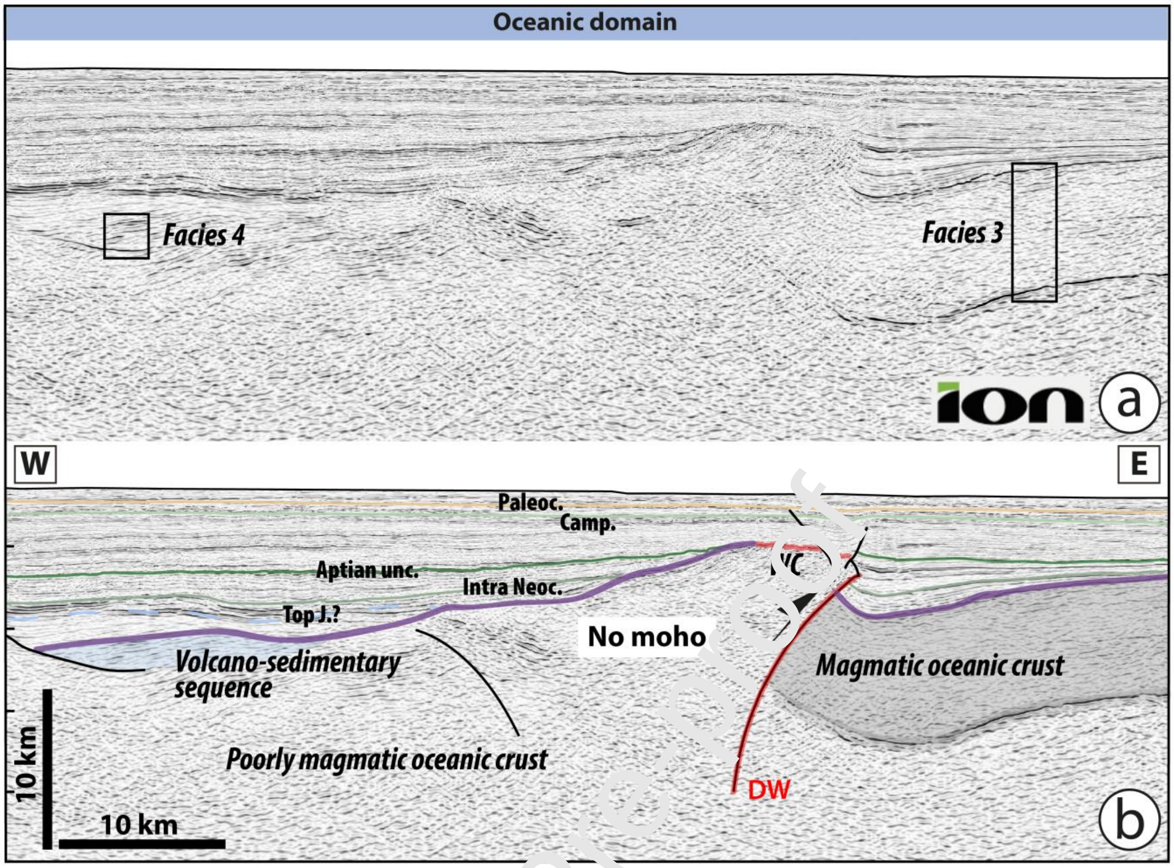

Figure 6: Inversion in the oceanic crust. (a) W-S trending offshore seismic profile. (b) Line drawing and interpretation of basement structures observed. The sub-vertical red line indicates a reverse fault that corresponds to the Davie-Walu Fault. Note that the distinct domain is identified above the seismic profile. See Figure 3 for the location. See text for explanations. Paleocene (P.), Campanian (Camp.), Neocomian (Neoc.), Jurassic (J.), Unconformity (unc.), Davie-Walu (DW), Wave-cut (WC).

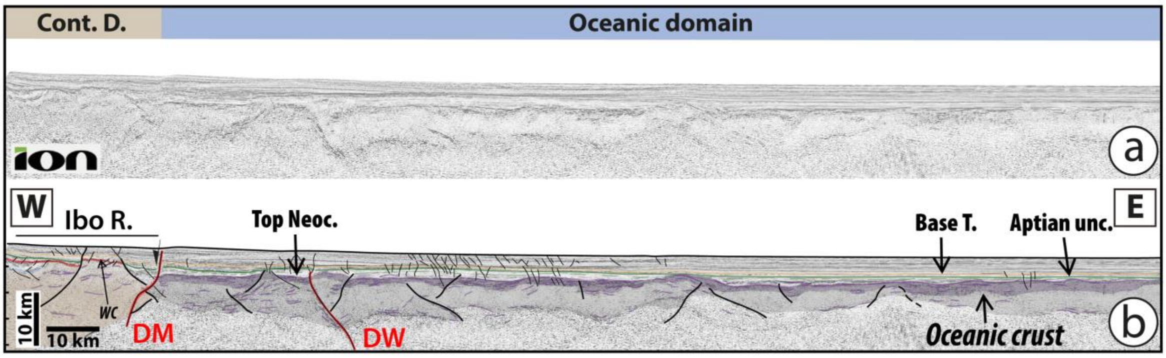

Figure 7: Localized inversion at the boundary between the oceanic and continental domains in profile ION – MZ1-7500. (a) W-E trending offshore seismic profile. (b) Line drawing and interpretation of basement structures observed. Red lines indicate major faults, *i.e.*, the Davie Main and Davie-Walu faults. Note that the distinct domains are identified above the seismic profile. The blue line corresponds to the Jurassic horizon. See Figure 1 for the location. See text for explanations. Tertiary (T.), Neocomian (Neoc.), Unconformity (unc.), Davie Main (DM), Davie-Walu (DW), Ibo Ridge (Ibo R.), Wave-cut (WC).

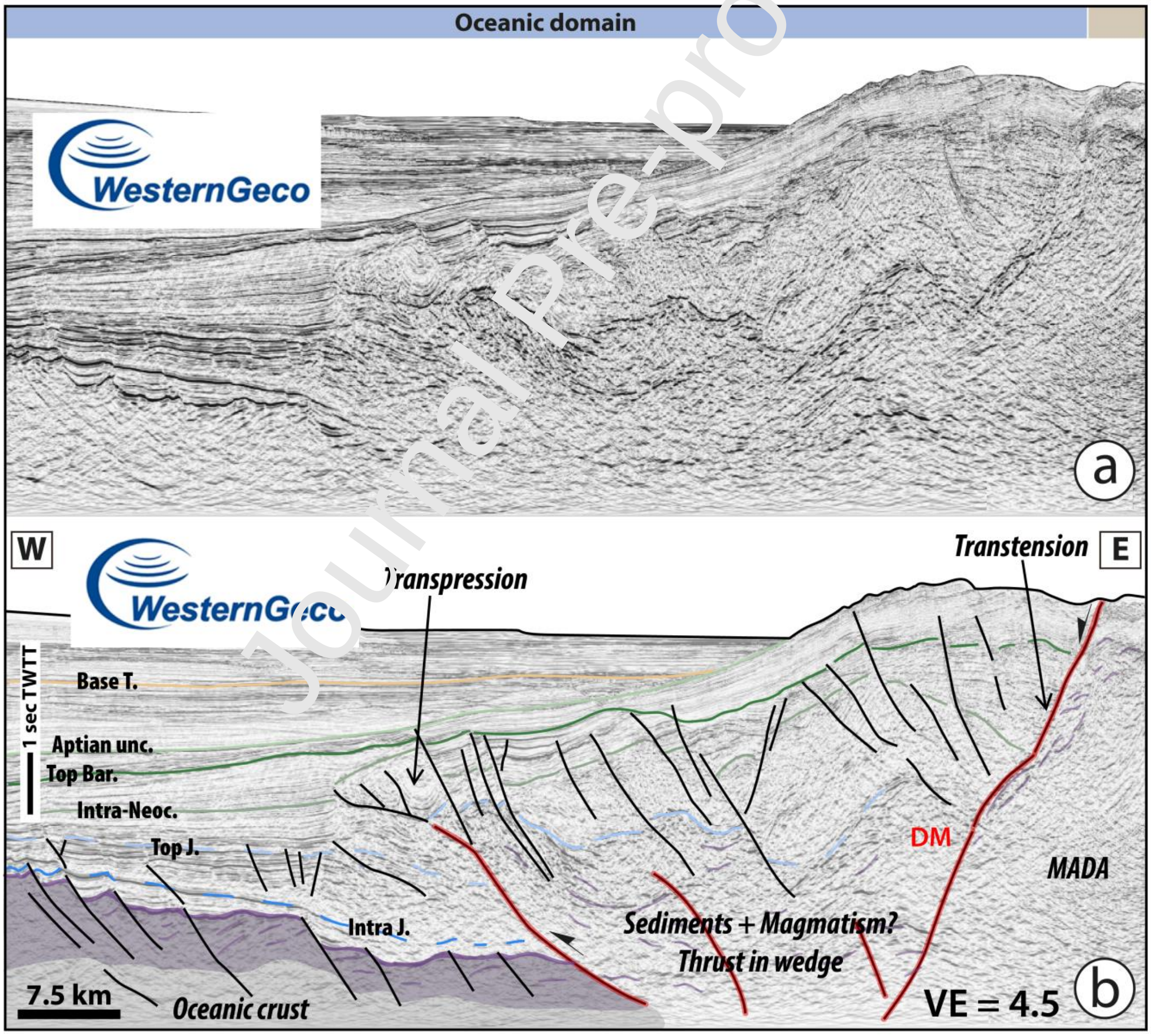

Figure 8: Inversion at the edge of the continental domain along the WesternGeco seismic profile (brown color on the top right corner of the figure). (a) Offshore seismic profile with

(b) line drawing and interpretation. Note that the distinct domain is identified above the seismic profile. Red lines indicate major faults defining the Davie Main Fault. Vertical exaggeration (VE) is estimated at around ~ 4.5 based on velocity in the sediment column. This seismic line is located north of the Mozambique – Madagascar cross-section, between the Figs. 2a and 2b of the study of Mahanjane et al. (2014). For confidentiality issues, the exact location of this seismic profile is not indicated in Figure 1. Data is courtesy WesternGeco and INP. See text for explanations. Tertiary (T.), Barremian (Bar.), Neocomian (Neoc.), Jurassic (J.), Unconformity (unc.), DM (Davie-Main), Madagascar (MADA), Two-way Travel Time (TWTT).

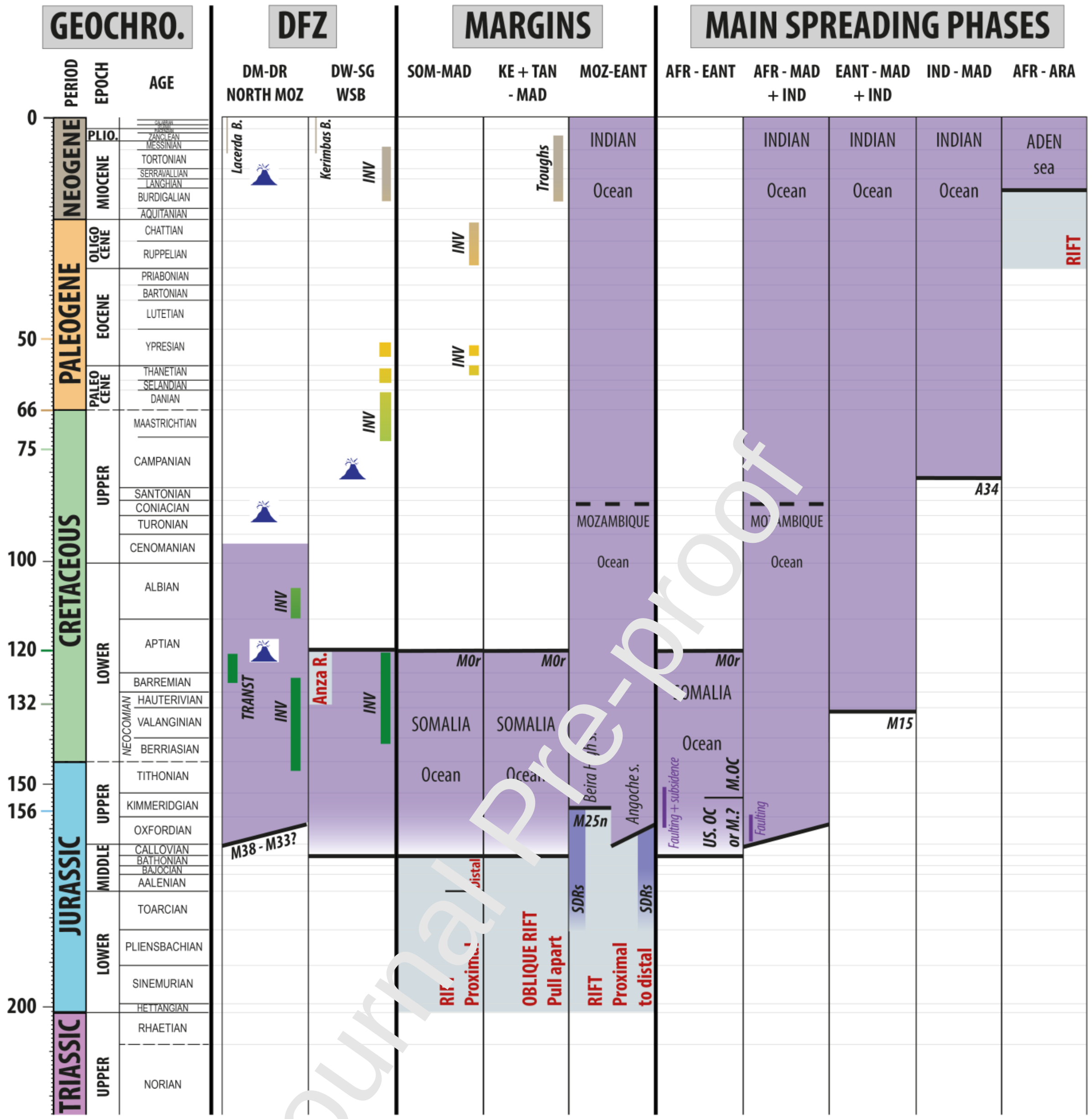

Figure 9: Simplified geodynamic chart covering all important tectonic and magmatic features associated with rifting and oceanic spreading in the Western Somali Basin and eastern Mozambique Basin. Most of these observations come from our study, from the references therein, from Leroy et al. (2012) for the Gulf of Aden and Seton et al. (2012) for the India-Madagascar opening. Abbreviations are: AFR = African plate, EANT = East Antarctic plate, EGD = East Gondwana plate, Davie Fracture Zone (DFZ), Davie Main (DM), Davie Ridge (DR), Davie-Walu (DW), IND = Indian plate, KE = Kenya, MAD = Madagascar, MOZ = Mozambique, TAN = Tanzania, Seagap (SG), SOM = Somalia.

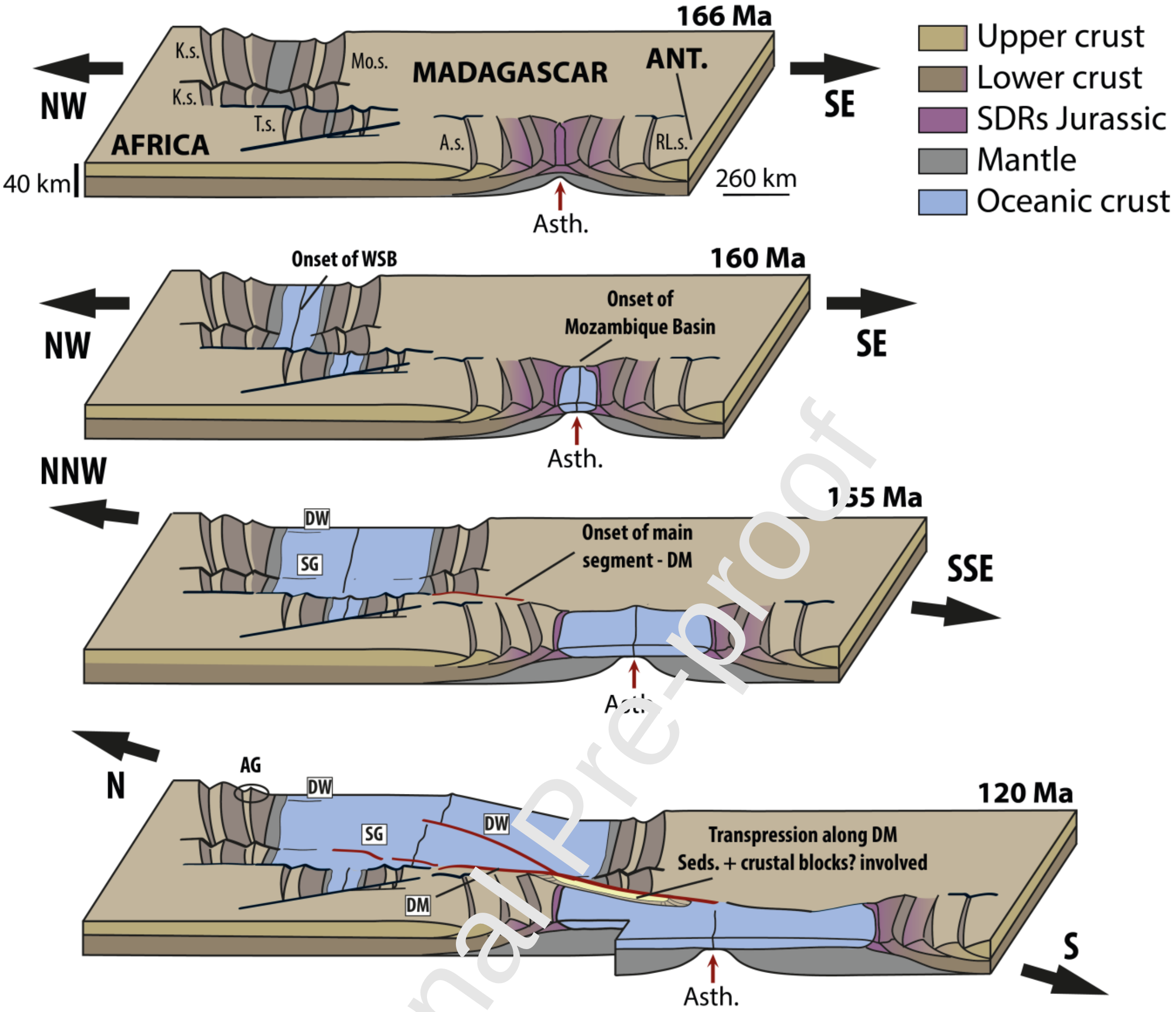

Figure 10: Conceptual 3D model of the geodynamic evolution from the magma-poor continental rifting of the Western Somali Basin and magma-rich one of the Mozambique Basin to oceanic spreading. The segments of the Western Somali Basin are characterized by the hyperextension of the upper continental and mantle exhumation whereas the Angoche segment of the Mozambique Basin is made of SDRs (Senkans et al., 2019) and intrusion that consists of mafic underplating (*e.g.*, Mueller and Jokat (2017)). Black arrows represent relative movements of the continental plates before the continental rupture and the main direction after the oceanic spreading. Note the rotation that occurs at around 155 Ma. Angoche segment (A.s.), Antarctica (ANT.), Asthenosphere (Asth.), Davie Main (DM),

Davie-Walu (DW), Kenya segment (K.s.), Morondava segment (Mo.s.), Riiser-Larsen segment (RL.s.), Seagap (SG), Tanzania segment (T.s.).

Highlights

- The Davie Fracture Zone shows a large variability of vertical displacements due to its composite origin and its long-lived evolution
- The Davie transform system started at ca. 166Ma along discrete NW-SE trending segments and then became a N-S mature segment at ca. 155Ma
- Transform boundaries are lithospheric-scale structures sensitive to kinematic changes