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South and East African Fracture Zones: a long lifespan since the breakup of Gondwana

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Abstract

Gondwana started to split up during the Early Jurassic (ca. 180 Ma) with the separation of Antarctica and Madagascar from Africa/South America, followed by the separation of South America and Africa during the Early Cretaceous. Thanks to recent seismic profiles, the architecture of rifted margins and the transform faults zones, which developed as a result of the relative motion between tectonic plates, have been recently evidenced and studied along the whole eastern and southeastern Africa margins (*i.e.*, in the Western Somali Basin, the Mozambique Basin, the Natal Basin, and the Outeniqua Basin). Yet, the structure and overall kinematic evolution of the three major transform faults zones together – *i.e.*, the Agulhas, the Davie, and the Limpopo Fracture Zones (FZ) – that control the opening of major oceanic basins (Antarctic Ocean, Weddell Sea and Austral South Atlantic) remain poorly studied. The interpretation of an extensive regional multichannel seismic dataset coupled with recent studies allows us to propose a detailed regional synthesis of the crustal domains and major structural elements of the rifted margins along the whole eastern and south-eastern Africa. We provide new constraints on the structure and evolution of these three transform systems. Although our findings indicate common features in transform style (*e.g.*, a right-lateral

transform system, a wide sheared corridor), the deformation and magmatism along these systems appear quite different. In particular, our results show that the Davie and Agulhas transforms faults postdate the development of the rift zone-controlling faults whereas the Limpopo margin seems to be a simple intra-continental transform. Moreover, the Davie and Agulhas FZ recorded spectacular inversions during the transform stage whereas transtensional deformation is developed along the Limpopo FZ. This different style of deformation may be explained by two main forcing parameters: (i) the far-field forces that may induce a rapid change of regional tectonic stress, and (ii) the magmatic additions that may compensate a part of the displacement and modify the structural style. In the post-drift history, several reactivations of transform fault zone are recorded implying that some transform margins are excellent recorders of large plate kinematic changes. Such reactivations can serve also as drains for magmatic fluids in the vicinity of hotspots emplacement.

1. Introduction

Transform margins, also called sheared margins (Rabinowitz and Labrecque 1979; Scrutton 1979) or strike-slip margins (Nagel *et al.* 1986), develop mainly as a result of the relative motion between two tectonic plates. Although they represent around 16% of the cumulative world-wide length of continental margin (Mercier de Lépinay *et al.* 2016), they are still poorly studied compared with rifted margins. Accordingly, some important issues are still controversial (*e.g.*, initiation of transform fault, crustal structure, vertical displacement), and there are too few cross-sections across transform margins to resolve these questions. Despite all, a common kinematic model of transform fault zones is often considered with three successive stages of evolution: (i) intra-continental transform faulting, (ii) active

transform margin characterised by the migration of the oceanic accretion axis along the continental domain, and (iii) passive transform margin (*e.g.*, Mascle and Blarez 1987; Basile 2015; Mercier de Lépinay *et al.* 2016). Although these three stages are recorded along a transform margin, the duration of each stage varies (Basile 2015) depends on the extensional rates during rifting and spreading, and the spacing between the two spreading centres.

The Gondwana breakup led to the formation of several major fracture zones which accommodated the oceanic opening since the Jurassic. In particular, the South and East African Margin (SEAM) system – the Agulhas, the Davie, and the Limpopo Fracture Zones (FZ) (Fig. 1) – offers the opportunity to study three FZ which recorded different evolutions since their initiation. For instance, recent seismic reflection data along the Davie FZ show mainly transpressional structures during transform activity (*e.g.*, Mahanjane *et al.* 2014; Roche and Ringenbach 2021) whereas the Limpopo case is characterised by a dextral strike-slip to transtensional system (Roche *et al.* 2021). Unfortunately, the low-resolution seismic imaging published along the Agulhas FZ does not allow to identify in detail the structures related to transform motion, even though few studies have reported several segments with distinct geometries (*e.g.*, Ben-Avraham *et al.* 1997).

In this study, we investigate these three major fracture zones to draw a first synthesis of what we know about transform structures (*e.g.*, their nature and their evolution through time). We used new and published high-quality multichannel seismic lines combined with wells available in TotalEnergies' database to attempt to solve some controversies regarding transform margins. We first propose a compiled offshore geological and structural map, and then we provide new constraints on their dynamic development from their initiation to post-transform evolutions. Results allow us to discuss the possible role of pre-existing crustal structures, magmatic activity, and superimposed tectonic phases.

2. Geological background

2.1. Geodynamic evolution of East and South Gondwana

Pangea, and more particularly Gondwana (Figs. 1a and 1b) are composed of an assemblage of Archean and Paleoproterozoic cratons, Meso- to Neoproterozoic metamorphic belts and terranes accreted during several orogenic events related to the Panthalassic subduction dynamics (*e.g.*, Ring *et al.* 2002; Jacobs and Thomas 2004; Collins and Pisarevsky 2005; Cawood and Buchan 2007; Suarez *et al.* 2019) and Panafrican aggregation. The amalgamation was completed in the Late Paleozoic (Riel *et al.* 2018) with the accretion of Patagonia leading to the formation of the Gondwanides orogen (*e.g.*, Ramos 2008). The onset of extensional tectonics (Karoo rifts) was mainly active in Triassic during the main Karoo rifting phase (*e.g.*, Catuneanu *et al.* 2005; Davison and Steel 2018). It is present in the whole of Africa and South America along variable trends from E-W to NNW-SSE at a regional scale (Zerfass *et al.* 2004; Catuneanu *et al.* 2005; Davison and Steel 2018; Lovecchio *et al.* 2020). Interestingly, these trends are controlled by ancient crustal shear zones, implying that basement structural inheritance has played a key role in the Triassic rifting spatial development (*e.g.*, Daly *et al.* 1989; Castaing 1991; Macgregor 2018; Lovecchio *et al.* 2020). The first rifting phase ends in the Early Jurassic at ca. 195 Ma (Davison and Steel 2018) suggesting aggregation of several rifting events during throughout the Triassic. Such rifting dynamics may be partly explained by the rollback of the slab along the west Gondwana margins (Bercovici and Long 2014; Frizon de Lamotte *et al.* 2015; Lovecchio *et al.* 2020).

The Early to Middle Jurassic rifting phase along the future SEAM was coeval with three Large Igneous Provinces (LIP) that emplaced at ca. 180 Ma (Fig. 1a) (*e.g.*, Karoo volcanic province in South Africa, Riley *et al.* 2004; Jourdan *et al.* 2007; Svensen *et al.* 2012; Ferrar volcanic province in Antarctica, Encarnación *et al.* 1989; Chon Aike volcanic province in South America, Kay *et al.* 1989;

Pankhurst *et al.* 2000). Even though the initial fit positions of Gondwana remain contentious (*e.g.*, Seton *et al.* 2012; Torsvik *et al.* 2012; Thompson *et al.* 2019), the trend of continental rift zones seems to be NE-SW along the East African margins (EAM) (*e.g.*, Senkans *et al.* 2019; Sinha *et al.* 2019; Roche and Ringenbach 2021) separated by transfer and transform zones that accommodate the possible regional NW-SE extensional kinematic movement (*e.g.*, Cox 1992; Nguyen *et al.* 2016; Reeves 2018; Klimke *et al.* 2018; Senkans *et al.* 2019). The continental breakup occurred at a disparate age depending on the localities because the transition from syn- to post-rift sedimentation is not always easy to determine and is not calibrated by boreholes in the distal domains. From north to south, the onset of oceanic spreading probably initiated at:

- (1) ca. 165 Ma along the Somali margins (*e.g.*, Papini and Benvenuti 2008; Sinha *et al.* 2019; Roche and Ringenbach 2021);
- (2) ca. 165 Ma (just before chron M38n.2n, Mueller and Jokat 2019) or ca. 161 Ma (chron M33, Senkans *et al.* 2019) along the Angoche segment considering that chron M38n.2n is associated with emplacement of seaward dipping reflectors (SDR);
- (3) ca. 156 Ma along the Beira High segment (chron M25, Mueller and Jokat 2019; Senkans *et al.* 2019; Roche *et al.* 2021) whereas it appears poorly constrained along the Natal margin.

Consequently, the youngest post-rift sediments on the margins and the oldest sediments on the oceanic crust change accordingly with the margin location: they are estimated of Middle to Late Jurassic age in the Western Somali Basin and the Mozambique Basin.

The trend of continental rift zones along the South African margins (SAM) changed during the Jurassic, and rift zones seem to be located in a back-arc basin induced by subduction rollback (*e.g.*, Elliot and Fleming 2000; Martin 2007). The extension starts to localize along southern Africa during the latest Jurassic forming several rift basins such as the Outeniqua and Pletmos basins (Broad *et al.*

2012; Baby *et al.* 2018). Lithospheric breakup occurs in the Early Cretaceous marked by a Hauterivian breakup unconformity (Broad *et al.* 2012) which is consistent with the first oceanic magnetic anomaly – chron M10 (134 Ma) – recorded in the southern Natal Valley (*e.g.*, Goodlad *et al.* 1982; Martin 1984; Gradstein *et al.* 2012) and Cape Basin (Hall *et al.* 2018). Further, the case of the Falkland Islands microplate is particularly debated, and the age of break-up remains contentious (*e.g.*, Schimschal and Jokat 2019; Stanca *et al.* 2021). Some studies have suggested that extension is coeval with the opening of the South Atlantic (*e.g.*, Lovecchio *et al.* 2019) even though oceanic spreading may start around 162 Ma and end before 152 Ma between Falkland Islands (Fig. 1b) and the Maurice Ewing Bank (Schimschal and Jokat 2018; 2019). Others have proposed that the Falkland Islands microplate represents the conjugate to the Weddell Sea, and thus undergoes extension related to the Antarctic plate movement (Eagles and Vaughan 2009; Eagles and Eisermann 2020). This implies that Falkland Islands microplate recorded a polyphase history of rifting (Stanca *et al.* 2021). Similar ages are reported for the opening of the Weddell Sea (*e.g.*, König and Jokat, 2006; Jordan *et al.* 2017; Bastias *et al.* 2021) located to the east of the Antarctica Peninsula. Back-arc extension started around 178 Ma with the emplacement of mafic-intermediate magmatism (Riley *et al.* 2020) and was characterised by N-S trending structures (Jordan *et al.* 2017). This extensional pattern was then overprinted by N-S extension leading to the formation of NE-SW trending structures until breakup (Jordan *et al.* 2017), which seems to occur at around 145 Ma (Bastias *et al.* 2021).

Wide areas of the SEAM are influenced by magmatism from the onset of rifting (*i.e.*, around 180 Ma) to oceanic spreading. As an example, south-eastern Africa was characterised by several magmatic events whose origins are still debated (*e.g.*, Cox 1992; White 1997; Jourdan *et al.* 2007; Hastie *et al.* 2014): (1) 184 – 176 Ma, the Karoo Magmatic Province (Fig. 1a) (Duncan *et al.* 1997; Jourdan *et al.* 2008; Svensen *et al.* 2012); (2) 145 – 133 Ma, the Bumbeni-Movene volcanic system (Allsopp *et al.* 1984; Saggerson and Bristow 1983); (3) 140 – 122 Ma, the Mozambique ridge volcanic system (Gohl *et al.* 2011; Fischer *et al.* 2016; Jacques *et al.* 2019); (4) 135 – 105 Ma, the Chilwa

Alkaline Province (Woolley 1991; Eby *et al.* 1995) and (5) 105 – 80 Ma, the Upper Cretaceous Kimberlite Province (Jelsma *et al.* 2004) combined with the oceanic Agulhas Plateau formation (Gohl and Uenzelmann-Neben 2001) related to the Bouvet hotspot passage at 80-100 Ma (*e.g.*, Martin 1987).

2.2. Fracture Zones: main characteristics

Along the SEAM, three major fracture zones have been recognized as a result of the Gondwana breakup. From north to south, we identified the Davie, the Limpopo, and the Agulhas FZ (Fig. 1).

2.2.1. The Davie Fracture Zone

The Davie FZ separates the western part of the Western Somali Basin and the eastern part of the Mozambique Basin (Fig. 1). This system accommodated the southward drift of Madagascar since the onset of oceanic seafloor spreading in the Late Jurassic (at ca. 155 Ma) (Roche and Ringenbach 2021) forming a N-S kinematic linkage between two extensional margins whose breakup occurred in Middle Jurassic (Sinha *et al.* 2019). Deformation is mainly transpressional along the main transform segment (the Davie Main). According to different studies, this event is sealed either by a top Jurassic unconformity (Mahanjane 2014; Mahanjane *et al.* 2014; Franke *et al.* 2015) or by a top Neocomian unconformity (Roche and Ringenbach 2021). The latter interpretation is based on new well calibration, and thus seems to be the most accurate. This transpressional event is followed by transtensional deformation sealed by the Aptian unconformity (Roche and Ringenbach 2021), which marks the end of oceanic spreading at ~120 Ma in the whole Somali Basin (Sauter *et al.* 2018). In addition, the whole corridor of the Davie FZ (2°S to 22°S) has experienced various post-transform

tectonic reactivations characterised by extensional and compressional structures as well as vertical movements. These main phases of reactivation are interpreted as a consequence of plate scale kinematic reorganizations (Roche and Ringenbach 2021).

2.2.2. The Limpopo Fracture Zone

The nature of the crust below the South Mozambique Coastal Plain (SMCP) and the Natal Valley has been controversial for decades: continental (*e.g.*, Dingle and Scrutton 1974; Raillard 1990; Goodlad 1986; Hanyu *et al.* 2017) or oceanic (*e.g.*, Martin and Hartnady 1986; Tikku *et al.* 2002; Leinweber and Jokat 2011). Recent seismic studies argue for a continental affinity using (i) P-waves velocity models from refraction profiles (Moulin *et al.* 2020; Leprêtre *et al.* 2021; Evain *et al.* 2021; Watremez *et al.* 2021) and (ii) seismic reflection profiles (Li *et al.* 2021; Roche *et al.* 2021). According to the refraction studies, the crust reaches 40 km in thickness and becomes thinner eastward of 36 degrees. The first oceanic magnetic anomaly is recognized east of the SMCP (Mueller and Jokat 2019) at 37°E, implying that the Limpopo margin is considered as a transform margin. In particular, this margin is characterised by a sharp continent-ocean transition between a thinned anomalous continental crust (Moulin *et al.* 2020; Evain *et al.* 2021; Watremez *et al.* 2021) and an oceanic crust showing locally strong crustal thickness variation due to high syn-spreading magmatic supply (8 to 14.5 km at the east of the SMCP, Watremez *et al.* 2021).

This system accommodated the southward drift of Antarctica since the onset of oceanic seafloor spreading. Recently, Roche *et al.* (2021) showed that the intra-continental transform faulting stage starts at around 180 Ma, contemporaneous with the onset of the plume and activity of rifted segments (*i.e.*, the Beira-High and Natal segments). This intra-continental stage is mainly characterised by N-S trending normal to strike-slip faults as attested by the

presence of several pre-Neocomian/Valanginian basaltic and sedimentary wedges (Moulin *et al.* 2020; Leprêtre *et al.* 2021; Evain *et al.* 2021; Li *et al.* 2021; Roche *et al.* 2021) tilted toward the continent and the ocean. Roche *et al.* (2021) also suggest that some of wedges (mainly located in the SMCP and close to the Lebombo) are Early Jurassic in age which would be consistent with the age of the rocks from the Karoo LIP. The active transform stage starts in the north of the SMCP with the first oceanic accretion dated around M25 (*i.e.*, 156 Ma – Mueller and Jokat 2019) and ends during the Aptian in the southern Natal Valley (32°S) according to the geodynamic model of Roche *et al.* (2022).

2.2.3. The Agulhas Fracture Zone

The Agulhas FZ is a nearly 1500 km-long transform segment bounding the southern tip of Africa (from 28°S to 33°S) that separated the South American continental plate from the Africa plate (Fig. 1). The active transform stage starts in the northern Natal Valley at magnetic anomalies M10Nr (133.58 – Martin 1984; Gradstein *et al.* 2012; Hall *et al.* 2018). Depending on the kinematic models, the end of the continental transform activity that corresponds to the passage of the mid-ocean oceanic spreading centre along the southern tip of Africa is estimated between 90 Ma and 84 Ma as it is slightly younger than the chron C34n (84 Ma) identified west of the tip of the Agulhas Arch (Reeves 2018). The Agulhas FZ is characterised by strike-slip structures (Baby *et al.* 2018; Paton *et al.* 2021) that cross-cut a major Paleozoic structure, the Cape Fold belt. It truncated pre-existing structural trends such as the Jurassic to Early Cretaceous Outeniqua Basin (Broad *et al.* 2012). This implies that deformation related to the transform motion occurred after the rifting period – *i.e.*, during the oceanic spreading. Nonetheless, Stanca *et al.* (2021) proposed that deformation in the Falkland Islands microplate is already influenced by the movement of the Agulhas FZ during the Middle to Upper Jurassic.

3. Methods

3.1. Seismic data

We used an extensive set of 2D multi-channel seismic reflection profiles from WesternGeco, PGS, and ION to provide new constraints on the three transform systems from their initiation to post-transform evolution. Interestingly, some seismic lines have been chosen close to wide-angle seismic datasets from previous studies (Moulin *et al.* 2020; Vormann *et al.* 2020; Watremez *et al.* 2021; Vormann and Jokat 2021) providing some information about the deeper crustal structures. Note that most of the seismic lines presented here have never been published, particularly for the Agulhas FZ and the Davie FZ. Both systems are also covered by more extensive seismic imaging than in the Limpopo FZ. However, these data are necessary to show and discuss the evolution of this transform zone. All studied seismic lines are roughly perpendicular to the oceanic spreading direction, and thus parallel the transform direction. As far as possible, they cross-cut the SEAM at different places covering the whole transform fault zone. Note also that our interpretations depend mainly on the seismic resolution of different datasets.

3.2. Well control and geological age constraints

Published stratigraphic syntheses are used (*e.g.*, Salman and Abdula 1995; Mahanjane 2012, 2014; Franke *et al.* 2015; Castelino *et al.* 2015; Klimke *et al.* 2016, 2018; Ponte *et al.* 2018; Baby *et al.* 2018; Roche *et al.* 2021, 2022; Roche and Ringenbach 2021) and integrated into our interpretations (Fig. 2). Our seismic is tied to the wells available in the TotalEnergies' database. Briefly, from north to south, we used some onshore and offshore

wells (Fig. 3) and identified several key horizons that derived from the exploration wells for the post-rift time interval (Fig. 2).

Along the Western Somali margins, well calibrations are sparse, and they do not reach the Jurassic. In addition, most wells are located on the proximal margins in shallow water domains or onshore but far from the Davie Ridge system. We used mostly the offshore wells Cachalote-1 (Fig. 3) that calibrates the stratigraphy down to Barremian-Aptian (Fig. 2) and Kiboko well further north in Kenya that calibrates the stratigraphy down to Hauterivian. From oldest to youngest, we correlated the following horizons (1) the top Jurassic (estimated), (2) the top Neocomian, (3) the Aptian unconformity, and (4) the base Tertiary along the Pemba and Morondava transform margins (Fig. 2).

Along the Limpopo transform margin, several offshore wells (Savane-1, Sangussi-Marine-1, Zambesi-3, Funhalouro, and Nhachengue in the SMCP and Zululand-1 well in the Natal Valley, Fig. 3) have been used to calibrate the main seismic horizons. Interestingly, Roche *et al.* (2021; 2022) reported new $^{40}\text{Ar}/^{39}\text{Ar}$ ages using cuttings from the Funhalouro and Zululand wells to provide a possible age range for volcanic formations described below the sediments. They show for the first time that samples are Early Jurassic in age which is consistent with the age of the rocks from the Karoo LIP. Above these volcanic formations, sediments start with Valanginian thin continental sandy red beds (Baby *et al.* 2018), highlighting a likely continental hiatus from Early Jurassic to Valanginian times. The top Neocomian, the top Cenomanian, and the base of Tertiary horizons have been mapped over the area (Fig. 2).

Along the Agulhas transform segment, well calibrations are even sparser. The most distal wells are the Brulpadda and Luiperd wells that reached the Aptian but are still located within the Outeniqua Basin (Fig. 3), within the continental domain. No wells were drilled over the oceanic domain south of the Agulhas FZ. However, in the proximal domain, the

whole basin stratigraphic record has been sampled down to the Jurassic (Kimmeridgian-Oxfordian), which are the oldest Mesozoic sediments postdating the Gondwanides Orogeny. Well penetration even reached the basement of the basin composed of folded Paleozoic sediments of the Cape Foldbelt. From oldest to youngest, our markers are (1) the top Paleozoic, (2) the top Jurassic, (3) the top Aptian, and (4) the base of Tertiary.

4. Results and interpretations

In the following section, we first present briefly a large-scale description of the main crustal domains that compose the offshore map (Fig. 3). Based on a thorough interpretation of seismic data complemented by gravity data performed by Explo teams in TotalEnergies and PASSive Margin Exploration LABORATORIES project (some of them already published, Chauvet *et al.* 2021; Roche and Ringenbach 2021; Watremez *et al.* 2021; Roche *et al.* 2021; Roche *et al.* 2022), this large map combines temporal, tectonics and thermal constraints useful for understanding the evolution of the three transform systems. In addition, two simplified regional maps are also proposed along the Agulhas FZ and Davie FZ that are covered by more extensive seismic imaging than the Limpopo FZ. Then, we present the general structure of the margins from selected seismic profiles. Below, results start with the Agulhas FZ and end with the Limpopo FZ for which a single new seismic profile is presented.

4.1. Mapping of crustal domains

The oceanic domain is the easiest to identify. It is mostly characterised by a normal oceanic crust with an average crustal thickness of 6-7 km, where oceanic magnetic anomalies are identified (since approximately M25 and younger, Fig. 3). Locally, the oceanic crust may be rugged and devoid of Moho; it is interpreted as the result of ultra-slow spreading, often during the early stages of

oceanic seafloor spreading (Sauter *et al.* 2018). This is the case in the Western Somali Basin along the Somalian margins. Here, in some locations, near the distal margin (*e.g.*, Tembo High), doubts can be raised about the straightforward interpretation of this domain: either a poorly magmatic oceanic crust or an exhumed sub-continental mantle (*e.g.*, Roche and Ringenbach 2021).

The West Somali Basin rifted margins are magma-poor (*e.g.*, Sapin *et al.* 2021; Roche and Ringenbach 2021). They are characterised by a necking zone observed on seismic lines and gravity data, between a proximal margin, dominantly onshore, and a generally poorly imaged distal margin. It is generally characterised by poorly visible shallowing continental Moho and rifted blocks probably associated with Liassic to Middle Jurassic syn-rift sedimentary sequences.

The continental domain of Mozambique and South Africa rifted margins is strongly affected by magmatism since the Early Jurassic (Fig. 3). In this case, the necking zone is difficult to map, and SDR may be observed. The image of Moho is blurred by complex reflections due to the presence of these lava flows. Like for the Somalian margins, rifted continental blocks are observed in various divergent segments but syn-rift units are made of volcano-sedimentary sequences (VSS) and/or SDR (around 180 Ma to 135 Ma in age, depending on the areas). They entirely capped the continental crust, reaching locally several kilometres of thickness. These observations are typical of volcanic margins (*e.g.*, White and McKenzie 1989; Sapin *et al.* 2021; Chauvet *et al.* 2021).

4.2. The Agulhas Fracture Zone

The Outeniqua margin in South Africa (Fig. 4) shows both rifted and transform segments. At first glance, the margin shows several structures such as Late Jurassic to Early Cretaceous depocentres controlled by large normal faults (*e.g.*, Bredasdorp Basin among others, Fig. 4c), a structural high (Diaz Marginal Ridge, DMR in Fig. 4c), and a sharp continent-ocean transition between an already thinned continental crust and the oceanic crust.

In the northern part of the general cross-section (Fig. 4c), pre-rift units consist mainly of Paleozoic strata (Paton *et al.* 2006). Syn-rift units have been previously described by Broad *et al.* (2012), Paton *et al.* (2006), and Baby *et al.* (2018) as growth wedge structures related to the intra-continental rifting stage that occurred in the Gondwana during the Kimmeridgian - Valanginian. These faults trend NW-SE but their orientation is strongly controlled by the pre-existing Cape Foldbelt structural trends. They exhibit important syn-tectonic activity recorded by thick syn-rift infill. Interestingly, this activity is preserved or remains along some of the main structures in the transform continental-oceanic period which started at around 135 Ma (Paton *et al.* 2021). This suggests that deformation is not purely strike-slip and that vertical movement is related to the fault activity. This is also well observed in the southern part of the cross-section in the Outeniqua Basin (Fig. 4c). Here, the faults trend NE-SW and truncate pre-existing structural fabric related to syn-rift structures. One of these faults marks the southward termination of the Outeniqua Basin and controls the structural position of the DMR that forms an outboard isolated crustal high. The top of the DMR has a horizontal to shallow-dipping southeast limb. The north-western part is overlapped by the Campanian unconformity whereas the south-eastern part is cut by NE-SW Neocomian trending faults. This geometry and sedimentary infilling may be attributed to the transform activity. The DMR is then separated from the oceanic crust by a major transform fault that shows a flower geometry. Such structure suggests a clear strike-slip component. Later volcanic activity is also observed along the transform segment and may be related to the formation of the Agulhas magmatic plateau further south (Fig. 4c) during the Late Cretaceous (140 – 122 Ma, Gohl *et al.* 2011; Fischer *et al.* 2016).

The Agulhas FZ is an elongated linear fracture zone, which can be divided into three major subsegments, from east to west: the Transkei, Outeniqua, and Mallory Segments.

(i) The Transkei segment (Fig. 5a) exhibits a barely thinned continental crust in the proximal domain followed by a narrow (~10 km) necking domain and a preserved distal margin (15 to 20 km wide). Southward, the main Agulhas fault separates the continental and oceanic crusts.

(ii) The Outeniqua segment is characterised by the presence of the rifted Outeniqua Basin and the DMR (Fig. 5b). The DMR presents several structures from the Late Jurassic/Early Cretaceous rifting and associated depocentres. Some of these features are inverted (Fig. 5b, insert 5b-1) but the exact age of the inversion is difficult to calibrate due to strong erosion which obscures the top of the DMR. However, inversion seems to be pre-1At1 (137 Ma). Along the western part of the Outeniqua subsegment, a wedge of deformed sediments can be observed with major compressional structures (Fig. 5b, insert 5b-2). Again, the age of the deformed sediments, as well as the age of the deformation, are uncalibrated. They both seem to be post-syn-rift and we choose to attribute both of them to the 137-120 Ma interval to be consistent with regional knowledge and recent dating in the Outeniqua Basin (Brulpadda and Luiperd wells). The wedge is cross-cut by the Agulhas FZ forming a major escarpment.

(iii) The westernmost part of the Agulhas FZ, the Mallory subsegment, is characterised by the presence of a preserved extensional basin floored by either exhumed mantle or strongly deformed oceanic crust (Fig. 6a). The initial continental crust is thick, forming the Agulhas Arch (Fig. 6a), and thins rapidly toward the Mallory basin (~30 km). The earliest part of the Mallory basin is suspected to have formed during the 137-120 Ma interval but again we lack dating in this area. This extensional episode is followed by a clear compressional event forming a small accretionary wedge involving early post-rift sediments and basement (exhumed mantle or strongly structured oceanic crust) (Fig. 6b). The age of the sediments involved and the age of the deformation are unknown, but they predate the final emplacement of the Agulhas FZ slightly before the C34n magnetic anomaly.

It is difficult to know whether the inversions are related to the dynamic of the secondary strand of the Agulhas FZ in the Outeniqua basin or the main branch. But compressional structures

(*i.e.*, inversions and accretionary wedges) are only observed in the western part of the Agulhas FZ. This would suggest that they developed during the formation of the Agulhas FZ in the east and could be related to a major change in the pole of rotation between Africa and South America. It is possible that the event dated somewhere between the M7r and M4n magnetic anomalies was responsible, event during which most of the Austral South Atlantic broke up (Chauvet *et al.* 2021) and the spreading rate in the Cape basin slowed down from 45 mm/yr to 29 mm/yr (half spreading rates) around 130 Ma (M4n, Hall *et al.* 2018). The compressional event would therefore begin in the eastern area (Outeniqua subsegment) around 130 Ma and end around 100 Ma in the western area (Mallory subsegment). As most of the Agulhas FZ developed during the Cretaceous magnetic quiet zone, it is difficult to propose an age for the onset of oceanic transform in the two western subsegments.

4.3. The Davie Fracture Zone

In the western part of the Western Somali Basin and the Mozambique Basin, the EAM shows mainly transform segments with relays that record variable extensional or compressional components through time during and after transform fault activity (Figs. 7, 8 and 9). Roche and Ringenbach (2021) recognized three main segments defining the Davie FZ based on seismic observations: the Seagap, the Davie Main, and the Davie-Walu Segments (Fig. 7b). In the following, we focus mainly on (i) the major transform segment – *i.e.* the Davie Main (the main plate boundary), which links the two oceanic basins and shows a spectacular inversion (Fig. 7b), and on (ii) the Davie-Walu segment which shows Neogene reactivations.

The North Mozambique section (located in Fig. 7a) exhibits a faulted and thinned oceanic crust (Fig. 8a). Here, the main fault zone corresponds to the Davie-Walu segment, and the main plate boundary is not observed. These faults trend N-S and develop during the oceanic spreading as attesting the thick syn-transform infilling (see the Hauterivian – Aptian horizons, Fig. 8a).

Interestingly, Cenozoic reactivations are observed along the transform system. This new set of faults tends to join downward onto a single strand in oceanic crust suggesting a hybrid flower structure with an anticline shape. It is characterized by several normal faults and localized fault-bend folds (along the western segment) implying a synchronous presence of compressional and extensional deformation in the same place (*e.g.*, Huang and Liu 2017). This wrench fault zone corresponds to the southern end of the Kerimbas basin.

The Central Mozambique section (located in Fig. 7a) shows a thinned continental crust in the proximal domain before the main fault that separates the continental and oceanic crusts (Fig. 8b). Here, the margin is characterised by 25 km-thick pre-rift continental crust (Roche and Ringenbach 2021). Syn-rift units are probably Early Jurassic in age (Key *et al.* 2008) that is consistent with the history of rifting prior to the breakup in the Western Somali Basin. Strike-slip faults are mainly active during the transform continental–oceanic stage as attesting the thick syn-transform infilling (see the Hauterivian – Aptian horizons, Fig. 8b). A clear reactivation with a normal component is also observed during the Tertiary (Lacerda active graben, Fig. 8b).

The southern section (located in Fig. 7a) shows the Angoche volcanic margin which is characterised by SDR (Fig. 9a; Senkans *et al.* 2019) and by a Jurassic 10 km-thick oceanic crust based on refraction data (*e.g.*, Mueller and Jokat 2017). The latter is covered by a thin layer of upper Jurassic which seems to thicken towards the Davie Ridge in the east. Interestingly, the base of the oceanic crust is underlain by a high-velocity anomaly (7.3 km/s, Vormann *et al.* 2020). Above the oceanic crust, a large and thick wedge is observed. Previously described by Mahanjane (2014) and Mahanjane *et al.* (2014), this wedge is made of Neocomian sediments and shows two main deformation stages below the Aptian unconformity (Fig. 9a). The first one is transpressional and starts probably during the end of the Jurassic as attested by the growth strata in-between the top of the oceanic crust and the top Jurassic, which indicates syn-tectonic deposition in a foredeep basin. This transpressional event is still active during Lower Neocomian and it is sealed by the top

Neocomian unconformity (the frontal fold is locally cut by this unconformity, Fig. 9b). The transtensional structures in the wedge develop mainly during the Albo-Aptian period and explain the steep east limb asymmetry of the wedge. Figure 9 shows also a clear reactivation with a strong normal component during the Tertiary (Lacerda active graben). This active graben is observed above the prominent N-S transpressive Neocomian ridge and is mapped between the southern part of the Morondava basin where the ridge is close to the present-day Mozambique shelf break, to 21°S (Fig. 7). Interestingly, a local bulge affecting the whole Cenozoic cover is observed at the foot of the volcano (Fig. 9b). This localized uplift seems to be related to magmatic intrusions (laccolith?) evidencing a recent magmatic activity. Finally, a differential passive subsidence between the oldest part of the Mozambique Basin and the continental margin of Morondava is observed during the Late Cretaceous-Cenozoic (Fig. 9a).

4.4. The Limpopo Fracture Zone

The Limpopo margin located along the SMCP and the Natal Valley (Fig. 3) shows both rifted and transform segments. As a whole, the margin is characterised by (i) several syn-rift depocentres filled by large-volume of pre-Neocomian/Valanginian basaltic and sedimentary deposits controlled by two sets of faults (N-S trending in the SMCP and NE-SW in the southern part of the Natal Valley, Roche *et al.* 2021; 2022) and (ii) a sharp continent-ocean transition between a thinned anomalous continental crust and an oceanic crust based on refraction data (Moulin *et al.* 2020; Evain *et al.* 2021; Watremez *et al.* 2021).

Three seismic profiles across the transform margin provide useful information on its structuration (Figs. 10 and 11). In particular, the northern and central SMCP profiles (see Fig. 3 for location) exhibit volcano-sedimentary wedges only observed westward of the Limpopo FZ. Based on new absolute age constraints, Roche *et al.* (2021) proposed an Early Jurassic age for the top of the wedges. Therefore, these geometries may be related to the intra-continental rifting stage occurring

in the whole Gondwana, implying a pre-structuration before transform motion. Eastwards, the northern part of the continental margin is bounded by a major strike-slip fault with a normal component that separates the oceanic crust (Fig. 10a). The associated sedimentary infill is thin and a syn-tectonic sequence with sediment wedging towards the fault seems to be observed until the end of Neocomian (Fig. 10a). In Figure 10b, this limit seems to be shifted to the east according to the refraction data (see Watremez *et al.* 2021) whereas another strike-slip fault is observed westwards in the continental domain. This latter is again still active during the Neocomian (Fig. 10b). In-between these two faults, the top of the crust shows a strong, continuous, and smooth top reflection lying deeper than the adjacent continental crust and oceanic crust (see the top magmatic basement in Fig. 10c). Intra-basement reflections are discontinuous and are interpreted as volcano-sedimentary sequences and/or lava flows. The base of these seismic units is not identified due to a lack of contrast between the basement and the overlying series. The eastern part of the section which corresponds to our identified oceanic domain is characterised by a series of faults controlling magmatic feeding and infilling during the transform evolution stage (Fig. 10c, see red arrows that correspond to toplaps). Because the oceanic spreading axis is approximately ENE-WSW trending, these N-S trending faults with a clear normal component have also certainly a strike-slip component implying a transtensional deformation. Such a hypothesis is reinforced by the presence of a huge quantity of magma that needs space to emplace.

The southern profile – *i.e.* the Natal section – located at around 27°S in the Natal valley (Fig. 3) cross-cuts the rifted basins and shows the Limpopo trough that corresponds to the transform zone (Fig. 11). The western part of the profile exhibits the rifted basins (Figs. 11a and b). They are observed below the top acoustic basement and filled by VSS (Fig. 11b, Moulin *et al.* 2020; Leprêtre *et al.* 2021; Li *et al.* 2021) interpreted as SDR by Roche *et al.* (2022). Eastwards, these deposits are cross-cut by a major sub-vertical strike-slip fault that corresponds to the onset of the transform fault zone. This domain recorded important subsidence since ca. 100 Ma and several volcanic sequences below the top acoustic basement are observed (Figs. 11b and 11c; see also the seismic line in Li *et al.*

(2021)). Toplaps are also commonly observed within these units and some of them are controlled by faults (Fig. 11c). These units show wedge geometries and are interpreted as VSS. In addition, the sedimentary sequence observed just above exhibits also a syn-tectonic sequence with sediment wedging towards the fault, implying that fault is still active during Neocomian (Fig. 11c). According to the refraction data in this area (Moulin *et al.* 2020), this domain corresponds to the thinned anomalous crust, which is also reported northward. It is separated from the oceanic domain by a second major strike-slip fault. Interestingly, a volcano is observed along this fault (Fig. 11a).

It is difficult to know the age of deformation along the Limpopo margin because there is (i) an important hiatus from Early Jurassic to Valanginian times over the SMCP (Baby *et al.* 2018; Roche *et al.* 2021), and (ii) an absence of good calibration along the southern part of the Limpopo FZ. In agreement with most studies (*e.g.*, Gaina *et al.* 2013; Reeves *et al.* 2016; Roche *et al.* 2021) extension in this area results from the regional NW-SE extensional kinematic movement and started at ca. 180 Ma coeval with the Karoo LIP emplacement (*e.g.*, Riley *et al.* 2004; Jourdan *et al.* 2007; Svensen *et al.* 2012). This suggests that N-S trending faults in the western part of the seismic section (Fig. 10a) developed during the rifting period. This oblique structural trend may have a strike-slip component to be consistent with the global kinematic movement. Deformation related to the transform fault zone is mainly characterised by two N-S trending sub-segments. The interpretation of seismic imagery in the Natal rift zone linked via the Limpopo FZ seems to indicate that the western trans-crustal fault that cuts the basement, postdates the development of the rift zone-controlling faults (Fig. 11). This fault seems to be prolonged northwards and developed during the formation of the Limpopo FZ. It was active until the end of Neocomian. The eastern segment identified in Figure 11 corresponds to the Limpopo fault, which separates the thinned anomalous magmatic crust from the oceanic one (Moulin *et al.* 2020). It can be extended to the north even though the fault is less marked in the central SMCP profile (Fig. 10b). In-between these two faults, minor faults, and wedges are observed with opposite dipping (Figs. 10c and 11c). A good candidate would be an event dated somewhere between 180 Ma and M25 (156 Ma) magnetic anomaly in the

north of the SMCP to the M10n (134 Ma) magnetic anomaly in the south. In that sense, a pre-structuration before the active continental–oceanic transform stage may be preserved. However, the simplest solution is to associate the age of the series and the deformation to the oceanic spreading.

5. Discussion

5.1. Structural architectures of transform fault zones along the SEAM

The three transform margins are characterised by submarine plateaus forming bathymetric highs at continent-ocean transitions showing lateral and longitudinal variations. Such morphological features act as sediment dams (Fig. 6b) and favour the formation of specific sedimentary processes such as the contourites. Our study shows that these three fracture zones share numerous characteristics. In particular, they mainly consist of (i) continental rifted fragments detached from continents remaining along the transform (Agulhas and Limpopo cases) and (ii) sediments accreted during the transform motion into a transpressive wedge (Davie and Agulhas cases). These systems are also characterised by a major and strongly localized ocean-continent boundary fault associated with a set of strike to oblique-slip faults accommodating part of the transform motion inside the continental and oceanic crusts. The faults observed in these corridors through time record the full range of motions from pure strike-slip to normal and reverse slip whether the activity is more transtensional or transpressional. The width of the entire fault array associated with the transform fault zone varies from a few km to less than 100 km depending on the area.

Even though the timing and rifting direction are not the same as well as the quantity of magmatic material before, during and after the transform activity, many similarities allow us to discuss the structural evolution of transform margins across three main stages: (1) the active intra-

continental stage, (2) the active continental – oceanic stage and (3) the passive margin stage (Fig. 12).

5.1.1. Structures observed/preserved during the intra-continental stage

As previously mentioned, the initiation of transform margin differs depending on the study areas. First, the record of the intra-continental transform stage along the Davie FZ is not observed/preserved on seismic whereas it can be discussed for the Agulhas and Limpopo FZ (Figs. 12 and 13). In the case of the Agulhas system, the recent study of Stanca *et al.* (2021) showed that deformation in the Falkland may be already influenced by the movement of the Agulhas FZ during the Middle to Late Jurassic while breakup occurred during Valanginian. It implies that this predominantly extensional setting favoured the location of the future Agulhas FZ, and thus facilitated the early fragmentation of south-western Gondwana. Nonetheless, our seismic data along the Outeniqua margin shows that the important syn-tectonic activity related to thick syn-rift infilling is cross-cut by the NE-SW trending faults which developed at around 135 Ma, simultaneously with the emplacement of the two spreading centres at both ends of the transform zone. This observation, therefore, minimizes the role of the intra-continental transform stage as previously mentioned. In addition, the initial break-up at around 162 Ma along the Outeniqua margin forming the oceanic crust between Falkland Islands and the Maurice Ewing Bank (Schimschal and Jokat 2018; 2019) cannot be confirmed. Indeed, the NE-SW trending faults cross-cut all the previous rifted structures of the last Jurassic.

The intra-continental transform stage seems only preserved and observed along the Limpopo transform margin as attested by the presence of N-S trending grabens filled by Early Jurassic volcanic rocks in the SMCP (Figs. 12 and 13) (Roche *et al.* 2021). This implies that these grabens are contemporaneous with the first syn-rift sequences described in the Central Mozambique margins (*e.g.*, Mahanjane 2012; Senkans *et al.* 2019) and in the Natal rifted margin (Roche *et al.* 2022). Thus,

this example could document the development of accommodation zones, coevally with the propagation of the rift bounding faults, implying a pre-structuration before the active continental–oceanic transform stage. These N-S trending structures along the SMCP are parallel to the future transform zone. This observation differs from 3D thermo-mechanical numerical modelling (*e.g.*, Gerya 2013; Le Pourhiet *et al.* 2017; Jourdon *et al.* 2021) predicting the formation of small basins, perpendicular to oblique to the future transform zone. This particular trend along the SMCP may be explained by a strong tectonic inheritance (*e.g.*, Permo-Triassic structures have been supposed in this area, Roche *et al.* 2021) or by the influence of the remaining hotspot in the area that controls rapid ridge shifts, and therefore transform location in strongly magmatic domains (Iceland case, Foulger and Anderson 2005).

To sum up, it is important to note that the early stages are illegible in most of our seismic data challenging the intra-continental transform stage. In addition, the earlier history of transform fault zone may be masked and/or overprinted, and only suppositions can be made, based on kinematic models and geological structure of the adjacent continental domains. This idea was recently supported by Farangitakis *et al.* (2019) through recent analogue modelling of plate rotation effects along transform margins. They showed that oblique deformation related to the simulation of changing plate motions reactivates and overprints earlier orthogonal structures. In all cases, a minimum of several Ma is required to establish a complete kinematic linkage between the two active spreading centres. This delay in the formation of active transform fault was also reported for other transforms systems (*e.g.*, Romanche, Wallaby–Zenith, Nemčok *et al.* 2016). During this period, the rifted segments opening possibly triggered rift-parallel mantle flow, which progressively favours the decoupling in-between the continental domain and the future oceanic domain.

5.1.2. Compression and extension during the transform activity

Transpression is observed along the Davie FZ and the Agulhas FZ (Fig. 13) and is evidenced by two accretionary wedges that formed approximately during the same period, between the end of the Jurassic and the Albo-Aptian (Fig. 12). The transpressional wedge is localized along the boundary between the Mozambique Basin and the Morondava margin in the Davie case. After the NW-SE opening of two large-scale pull-apart systems possibly influenced by the pre-Jurassic African inheritance (Sinha *et al.* 2019; Roche and Ringenbach 2021), the major N-S trending transform fault connecting both basins developed at around 156 Ma and records transpression which initiation is attested by the beginning of the foredeep activity. The initiation of the transform fault is favoured by the proximity and the alignment of weak rifted margins coupled with young oceanic lithosphere which act as pre-transform structures (Phethean 2018; Roche and Ringenbach 2021). The kinematic change during the Late Jurassic (NW-SE to N-S) is recorded by an uncalibrated seismic marker (Fig. 9), and it is tentatively correlated with the global kinematic reorganisation (*e.g.*, Reeves *et al.* 2016; Reeves 2018; Roche and Ringenbach 2021). This event ended in the Hauterivian as attested by the major unconformity (Fig. 9). In the south, the Davie Ridge is still a bathymetric high, while thrusts are visible northward till the Rovuma area along the Ibo High, which is the continuation of the Davie Ridge eroded by a marked wave-cut surface (Fig. 8b).

Along the Agulhas FZ, despite a short period of transtensional deformation, this transform system recorded a major compressional event (Figs. 5b and 6b) involving early post-rift sediments and the basement. It is only observed along the central and western segments whereas the eastern Transkei segment seems to be free of any compressional structures. As there are no wells to calibrate the series south of the Agulhas FZ in the oceanic basins, horizons ages are only based on the magnetic anomalies and reconstructions associated. The oceanic domain along the Transkei Basin is produced between 137 and 126 Ma. This would suggest a pure strike-slip motion along this segment during this time. From 126 to 103 Ma, the passage of the Maurice Ewing Bank along the Central and Western segments (Outeniqua and Mallory Segments), in association with a slight change of rotation between Africa and South America may have induced a transpressional event

along these two segments that began globally during the same time but ended earlier in the Central segment as the continental transform activity stopped. This is in line with the recent interpretation of Paton *et al.* (2021) that explained the global inversion by rotations and motions along the Agulhas FZ.

The Limpopo FZ recorded strike-slip to transtensional motion coupled with magmatic feeding and infilling during the transform activity (Fig. 13), which started at around 156 Ma (Fig. 12), contemporaneous with the onset of the main segment of the Davie FZ. Indeed, volcanic rocks of known (based on the magnetic anomalies in the oceanic domain) and unknown ages showing wedge-shaped geometries are observed along the entire transform fault zone. A huge quantity of magma was also reported in the oceanic domain as attesting to the thickened oceanic crust (14.5 km at the east of the SMCP, Watremez *et al.* 2021). We propose here that oceanic seafloor spreading dynamics is modified by the transform motion, disturbing the oceanic lithosphere pattern. Such high magmatic supply may be favoured by transtensional motion which creates opening areas allowing adiabatic melting. Southwards, deformation appears more localized than previously, as attested by the sharp continent-ocean transition between an already thinned crust and the oceanic crust (Fig. 11). This would suggest a pure strike-slip motion along this segment during Middle Cretaceous based on the magnetic anomalies and reconstructions associated.

5.1.3. Post-transform activity reactivations

Extension and compression after the transform activity are mainly observed along the Davie FZ as presented in the recent study of Roche and Ringenbach (2021) (Fig. 12). They showed several reactivations ranging from Late Cretaceous-Paleogene (*e.g.*, the inversion of the Anza graben) to Miocene (*e.g.*, the Kerimbass basin), mostly. These main phases of reactivation are interpreted as a consequence of plate scale kinematic reorganizations, especially during the Cretaceous – Tertiary with the separation of India from Madagascar. Our seismic interpretations additionally show

Neogene reactivations including the continent-ocean transform boundary between the Western Somali Basin and the Morondava margin as well as oceanic transform faults (Figs. 8 and 9). These reactivations are compatible with earthquake focal mechanisms (*e.g.*, see recent compilation in Famin *et al.* (2020) and Bertil *et al.* (2020)). Deformation is mostly made of normal to strike-slip faults compatible with E-W extension even though reverse faults are locally observed (Fig. 8a). In agreement with the study of Franke *et al.* (2015), our seismic data and mapping show that the deformation zone at 10 to 12°S is wide and continues over a large distance whereas it becomes narrow southwards along the Mozambique margin (Fig. 7). A good candidate to explain this southward migration would be the propagation of the East African Rift System (EARS) in Mozambique (*e.g.*, Franke *et al.* 2015; Vormann and Jokat 2021). The localized uplift that seems to be related to a recent magmatic activity (Fig. 9b) also suggests that the offshore portion of the EARS may be magma-rich similar to the onshore eastern branch. This is reinforced by prior studies which proposed that this offshore portion is underlain by particularly slow upper mantle velocities (*e.g.*, Emry *et al.* 2019) and by lower crust underplating interpreted as a young feature (Vormann *et al.* 2020; Vormann and Jokat 2021). Therefore, the Davie FZ is considered as an area of weakness controlling the location of incoming structural events such as the EARS. It was recently interpreted as a limit between Rovuma and Somalia/Lwandle plates (*e.g.*, Saria *et al.* 2014, Famin *et al.* 2020). Further, strike-slip faults with normal components are also present along the Limpopo margin (Fig. 10b). They are still active during Neocomian and/or develop at this period along the pre-existing transform segments implying a continuum of deformation after the passage of the oceanic accretion axis. This activity, particularly recorded along the western major fault (Figs. 10b and 11), may be related to the early stages of rifting between India and Antarctica and/or to the asymmetric opening of the Austral South Atlantic, which ends at Barremian (Lovecchio *et al.* 2020; Chauvet *et al.* 2021).

5.1.4. Margin morphology and tectonic activity

In our interpretation, the tectonic activity during the transform motion plays a key role to explain vertical displacement compared to other processes such as the flexural behaviour of the lithosphere (Basile and Lallemand 2002) and the thermal exchanges between the oceanic and continental lithospheres across the transform fault (*e.g.*, Gadd and Scrutton 1997; Nemčok *et al.* 2012). However, other second-order processes may be invoked to explain some bathymetric reliefs. For example, in the Agulhas case, the crust and pre-rift sediments from the DMR show an isolated crustal high, and the overlying sediments are very thin (less than a few km, Fig. 5b). This particular morphology may be associated with a delayed cooling of the lithospheric mantle due to lateral heat transfer from the passing oceanic spreading centre (Parsieglia *et al.* 2009) and/or the formation of the Agulhas magmatic plateau during the Late Cretaceous (Gohl *et al.* 2011; Fischer *et al.* 2016). Nonetheless, Paton *et al.* (2021) challenged these hypotheses and proposed that the DMR results from the structural inversion of a Jurassic rift basin during transform development.

At the margin-scale, and more particularly during the post-transform activity, the relief is mainly controlled by differential passive subsidence (isostasy) between the oceanic domain and the continental margin. The transform margins may also record periods of uplift associated with mantle dynamic during the post-transform stage. This is the case of the Outeniqua margin (see Braun *et al.* 2014) which underwent several periods of uplifts during the end of Cretaceous and the Cenozoic (Baby *et al.* 2018).

5.2. Transform fault zones and kinematic changes during transform activity

Looking at the three transform systems studied here, three major global events can be identified (Fig. 12):

(i) Oxfordian: During this period, only the Davie FZ is active. The motion seems only transpressional along the main fault and the initial strike-slip regime was not observed in our seismic data.

(ii) Late Jurassic to Barremian: The Davie FZ continues to record the transpressional event while deformation in the Limpopo FZ is more purely strike-slip to slightly transtensional explaining the large emplacement of volcanic rocks. The activity along the Agulhas FZ began during this period around 137 Ma. After a short period of transtensional deformation, this transform system recorded a compressional event.

(iii) Aptian to Cenomanian: The Davie FZ activity ended around 126 Ma and various reactivations are observed along this system. No peculiar change of activity is observed along the Limpopo FZ. However, strong transpressional events are still observed along the Agulhas FZ.

Even though pre-existing crustal and thermal features (*e.g.*, plume activity) influence the formation and evolution of the transform fault zone, we think that the global kinematic reorganisation which is mainly controlled by the underlying asthenospheric mantle flows plays a first-order role in transform boundaries activity (Fig. 13). In that sense, we propose here that the main periods with transpressional and transtensional components may be related to major plate kinematic changes during the fragmentation of the Gondwana. This is particularly well illustrated in the Davie case, where the N-S transform fault bounds southward displacement of Madagascar. Similar results are recently reported based on global mantle convection (Langemeyer *et al.* 2021) and numerical modelling (Farangitakis *et al.* 2020). The first event is related to the motion between Africa and Madagascar/India/Antarctica Plates. The second event records the gradual change of motion of Africa associated with the south to the north propagating opening of the Austral South Atlantic from Kimmeridgian to Barremian (Lovecchio *et al.* 2020; Chauvet *et al.* 2021). This period is also contemporaneous with the early stages of rifting between India and Antarctica, where breakup occurred at around Valanginian time (*e.g.*, Reeves 2018). The third stage is coeval with the linkage of Central and Austral South Atlantic oceans that induces a large reorganization of African Plate motion. Coevally, the spreading within the Somali Basin stopped and jumped east of Madagascar separating it from India.

5.3. Magmatic activity and transform margin formation.

The previous part exhibited how global kinematic changes due to plates fragmentation are influencing changes of activity along a transform margin while it is active. In the three examples shown, the Limpopo FZ seems quite peculiar as it never recorded any of these compressional events related to plate reorganizations. While the deformation is synchronous with the Davie case and follows the same trend, its motion seems always purely strike-slip to slightly transtensional. The other peculiarity of this fault zone is that is initiated coevally to the formation of a large magmatic province during the Early Jurassic and important magmatic activity remained until the Early Cretaceous (*e.g.*, Fischer *et al.* 2016; Roche *et al.* 2021; Watremez *et al.* 2021). These activities support magmatic underplating at the base of the crust across the entire region (Moulin *et al.* 2020; Leprêtre *et al.* 2021; Watremez *et al.* 2021).

Like rifted margins, successive SDR and landward dipping reflectors wedges grow from the interpreted thinned anomalous continental crust (Moulin *et al.* 2020; Evain *et al.* 2021; Watremez *et al.* 2021) to ocean. The first group seems only observed west of the major continental-ocean transform fault which appears less marked to the north. Unfortunately, seismic data do not allow us to identify the deeper geometries of these seismic packages. This group may develop during the intra-continental transform stage along a narrow zone that corresponds to the thinned anomalous continental crust. This suggestion matches with a recent 3D thermo-mechanical numerical modeling study showing that the formation of transform continental margins follows a thinning phase during which the lithosphere is thermally and mechanically weakened (Jourdon *et al.* 2021). The second group is mainly observed in the northern and distal part of the Limpopo margin. These SDR are associated with a high-velocity magmatic crust (Watremez *et al.* 2021), which is thicker than average oceanic crust (6 km, Christeson *et al.* 2019).

All these observations may suggest that the presence of a large quantity of magma and a very hot lithospheric mantle associated with mantle plume emplacement forced the transform margin to act similarly to an intra-oceanic transform fault linking two spreading centres. In addition, the plume influence is probably under-estimated during the end of Lower Jurassic. The presence of the Lebombo and Matake-Sabi Monoclines cropping out around the SMCP contemporaneous with the onset of the LIP emplacement (*e.g.*, Klausen, 2009; Melluso *et al.* 2008) may correspond to a first successful breakup event characterized by regional variation in the spreading direction (Fig. 13, see the question mark). Similar to the Iceland case (Foulger and Anderson 2005), the result of the plume activity may induce an unstable tectonic involving microplates and various ridges. Further, magmatism along the transform fault zone may be also favoured by the intersection between the transform fault and the opposing ridge axis in this area (*e.g.*, the Mozambique Ridge that shows large volume of magmatism, Fischer *et al.* 2016; Jacques *et al.* 2019). More generally, the interaction of a plume with a transform boundary modifies the structural evolution of the margin and may locally favour the formation of transtensional structures that may also depend on the plate motion (*e.g.*, Farangitakis *et al.* 2019).

6. Conclusion

We used high-resolution industrial seismic data calibrated by a few deep wells to better understand the structure and evolution of transform margins through three major examples – the Davie FZ, the Limpopo FZ, and the Agulhas FZ, which are a lithospheric-scale dextral strike-slip system – from rifting to oceanic spreading. We proposed (1) a fairly comprehensive structural view of the transform systems along South and East African Margins (SEAM) and (2) a tectonic evolution of each margin.

- (1) The transform systems along the SEAM are characterised by a set of strike- to oblique-slip faults accommodating:

- the transform motion over a wide area ranging from few km to <100 km;
- the vertical movements often associated with transpressional and transtensional deformation happened mainly during the transform activity, and after in some places.

(2) The formation and evolution of transform systems along the SEAM are not the same. At the first order, it mainly depends on plate kinematics reorganizations, and thus related to far-field forces induced by large-scale mantle flow. However, in the Limpopo case, we find that the pre-existing crustal and thermal features related to the mantle plume activity also influence the formation and evolution of the transform fault zone. In all cases, transform faults zones are excellent markers to follow the long-term evolution of plates tectonics.

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Figure Captions

Figure 1: Paleogeographic reconstruction of Pangea modified from Torsvik et al. (2012). (a) Snapshot of the paleo-Pacific active margin (red line) during the Triassic-Jurassic showing schematic distribution of the acidic Chon Aike (white) and the Karoo and Ferrar LIPs (black) based on previous studies (e.g., Bastias et al. 2021). Note that the Chon Aike province started at 189 Ma and ended at 145 Ma (e.g., Pankhurst et al. 2000; Bastias et al. 2021) whereas the Karoo and Ferrar LIPs show a fast emplacement (i.e., only few Ma, e.g., Svensen et al. 2012; Burgess et al. 2015). C-A=Chon Aike province; F-LIP=Ferrar Large igneous Province; K-LIP=Karoo Large igneous Province; (b) Snapshot at 150 Ma showing the oceanic spreading in the Western Somali Basin (WSB) and the Mozambique Basin (MB). Note the presence of the two active transform segments (red line). The Agulhas transform fault is not yet active. The direction of the interpreted movement is indicated by white arrows. FLK=Falkland; FZ=Fracture Zone. (c) Snapshot at 100 Ma showing the oceanic spreading in the South Atlantic and Indian Ocean whereas it ceased in the whole Somali Basin. The Agulhas system is still active (red line) compared to the Davie and Limpopo systems becoming fracture zones (black lines). The direction of the interpreted movement is indicated by white arrows. (d) At 50 Ma, oceanic spreading is ongoing all transform systems are inactive.

Figure 2: Correlation of wells used in this study based on the seismic stratigraphy interpretation. The seismic marker calibrations come from TotalEnergies and published data (see references therein). Note that the two wells located in the Outeniqua Basin are not present for confidentiality reasons.

Figure 3: Simplified map of the study area showing the crustal domains and the main segment of the transform systems. A detailed interpretation and discussion of the newly defined crustal domains is beyond the scope of the paper. For more information, please refer to the recent works of Roche and Ringenbach (2021) in the Western Somali Basin, Roche *et al.* (2021) in the Natal Valley and Chauvet *et al.* (2021) in the austral segment of the South Atlantic Ocean. See text for the discussion of the debated crustal genetic domain. Location of Figures 4, 7, 10 and 11 are also indicated. Thick black lines represent the transform segments based on our seismic observations. Wells: B= Brulpadda; C= Cachalote-1; F= Funhalouro; KIB= Kiboko-1; L= Luiperd; N= Nhachengue; SAV= Savane-1; SAN= Sangussi-Marine-1; Za= Zambesi-3; Z= Zululand. SDR = Seaward dipping reflector.

Figure 4: Simplified maps of the Agulhas FZ showing the (a) onshore geology and (b) the main structural elements. Magnetic anomalies and the location of regional cross-section and seismic lines are also indicated. SDR= Seaward Dipping Reflector. (c) Regional section based on seismic observations. A. B.= Agulhas Basin; Bre. B.= Bredasdorp Basin; DMR= Diaz Marginal Ridge; K. B.= Karoo Basin.

Figure 5: Detail of the Agulhas margin with the different sedimentary sequences identified on the (a) East and (b) Central seismic profiles. Vol.= Volcano. (b) Inserts show the presence of reverse faults forming locally an accretionary wedge. The main structural features are labelled. The crustal genetic distinct domains identified are below the seismic profile. See text for explanations. The data are courtesy of PGS.

Figure 6: (a) Detail of the western seismic profile showing the main structures along the Agulhas margin. (b) Zoom showing the main inversion occurring before 120 Ma. See text for explanations. The data are courtesy of PGS.

Figure 7: Simplified maps of the Davie FZ showing the (a) onshore geology and (b) the main structural elements. Magnetic anomalies and the location of regional section and seismic lines are also indicated. DMF= Davie Main Fault; DWF= Davie Walu Fault; SDR= Seaward Dipping Reflector; SGF= Sea Gap Fault.

Figure 8: Detail of the (a) Northern and (b) Central Mozambique margins with the different sedimentary sequences identified on the seismic profile. See text for explanations. The data are courtesy of ION. DM= Davie Main; DW= Davie-Walu; FZ= Fracture Zone.

Figure 9: (a) Detail of the Southern Mozambique margin with the different sedimentary sequences identified on the seismic profile. (b) Zoom showing the syn-thrusting and -transtensional sequences. Note that the vertical scale was deliberately removed. See text for explanations. The data are courtesy of WesternGeco and INP. DM= Davie Main; FZ= Fracture Zone; SDR= Seaward Dipping Reflector.

Figure 10: Detail of the (a) Northern and (b) Central South Mozambique Coastal Plain (SMCP) margin with the different sedimentary sequences identified on the seismic profile modified from Roche *et al.* (2021). (c) Insert shows the syn-transtensional magmatic sequences within the transform fault zone. The data are courtesy of WesternGeco and INP. FZ= Fracture Zone.

Figure 11: (a) Detail of the Natal margin with the different sedimentary sequences identified on the seismic profile. Moz. B. = Mozambique Basin; Volc. = Volcano. (b) Insert shows the presence of syn-rift interpreted as volcano-sedimentary sequences (VSS). (c) Insert shows the syn-transtensional magmatic sequences close to the transform fault zone. See text for explanations. The data are courtesy of Pamela and more information can be found in Leprêtre *et al.* (2018). FZ= Fracture Zone.

Figure 12: Simplified geodynamic chart covering the main tectonic and magmatic features associated with the fracture zones along the main segments. Note that the Intra Continental Transform Fault (ICTF) stage is only documented in the Limpopo case whereas it is not observed/preserved in the others transform zones according to our seismic interpretations. The Active Transform Margin (ATM) stage started at the same time in the Davie and Limpopo systems at ~156 Ma, and at ~137 Ma along the Outeniqua margin. Note the diachrony concerning the age of compressional structures along the Agulhas FZ. The Oceanic Transform Fault (OTF) stage corresponds to the passage of the mid-ocean oceanic spreading centre along the previous older oceanic crust. More information about the Mesozoic and Cenozoic inversions and reactivations of the older segments of the Davie transform system may be found in Roche and Ringenbach (2021). FZ= Fracture Zone; INV= Inversion; S-SLIP= Strike-slip; TRANST= Transtension; TRANSP= Transpression

Figure 13: Schematic evolution of a transform margin and adjacent divergent margins based on the model of Basile (2015). Note that transform fault zones evolution results from major changes in the far-field forces induced by large-scale mantle flow. In the Limpopo case, the transform fault zone first forms in the continental lithosphere and is contemporaneous with plume activity whose

intensity decreases over time. Note the obliquity of the intra-continental faults compared to the opening direction that may result from thermal evolution and tectonic inheritance. Here, "volcanic" basins have a depocenter located parallel to the strike-slip fault traces. In the Davie and Agulhas cases, transform faults form after the initiation of seafloor spreading connecting propagating oceanic spreading axes. The basin trending is also parallel to the strike-slip fault traces during the transform activity. See text for further explanations. AM= Angoche Margin; BHM= Beira High Margin; FM= Falkland Margin; FZ= Fracture Zone; NM= Natal Margin; OCT= Ocean Continental Transition; OM= Outeniqua Margin.

SDRs = Seaward dipping reflectors; SM= Somali Margin.

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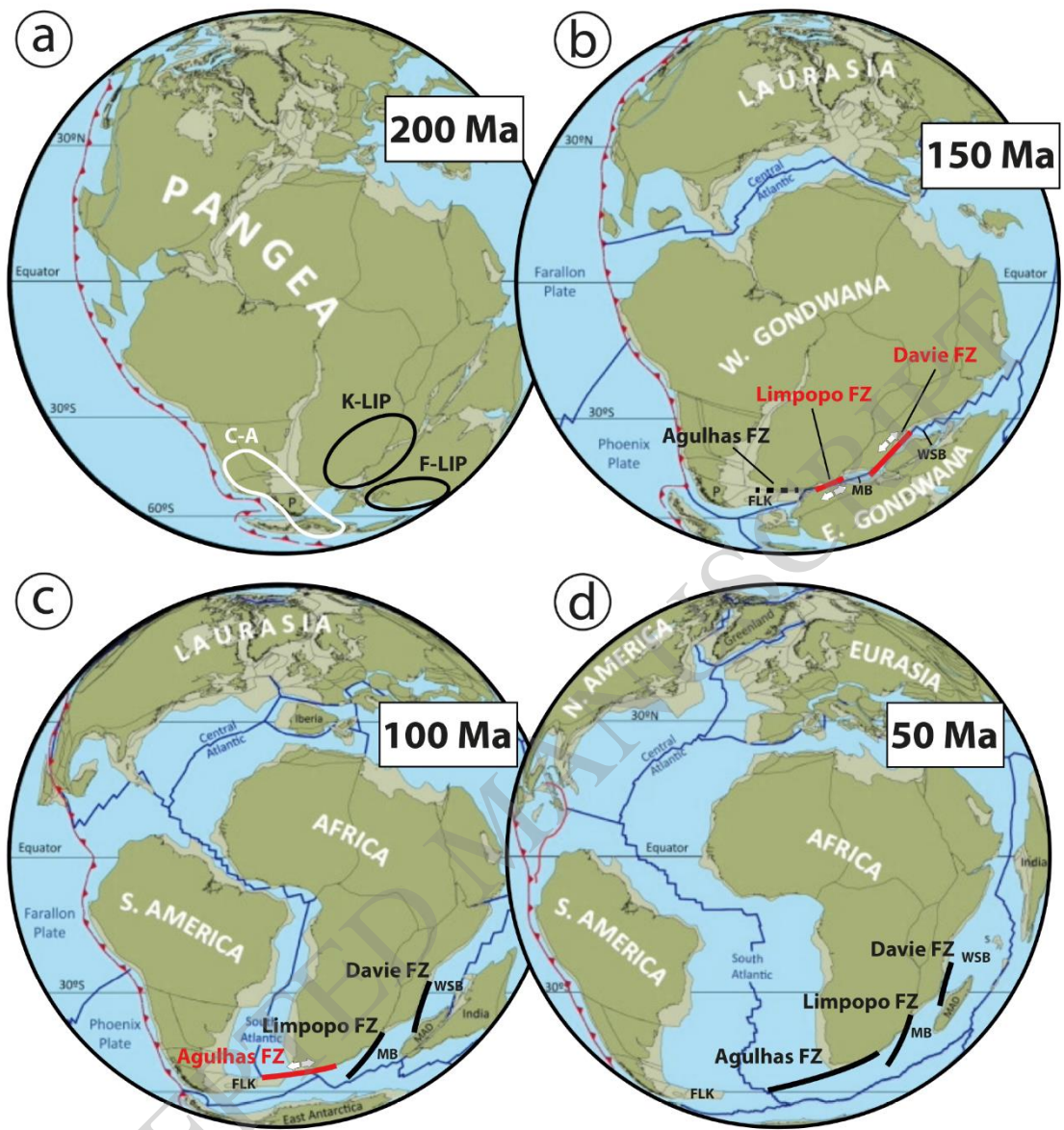


Figure 1

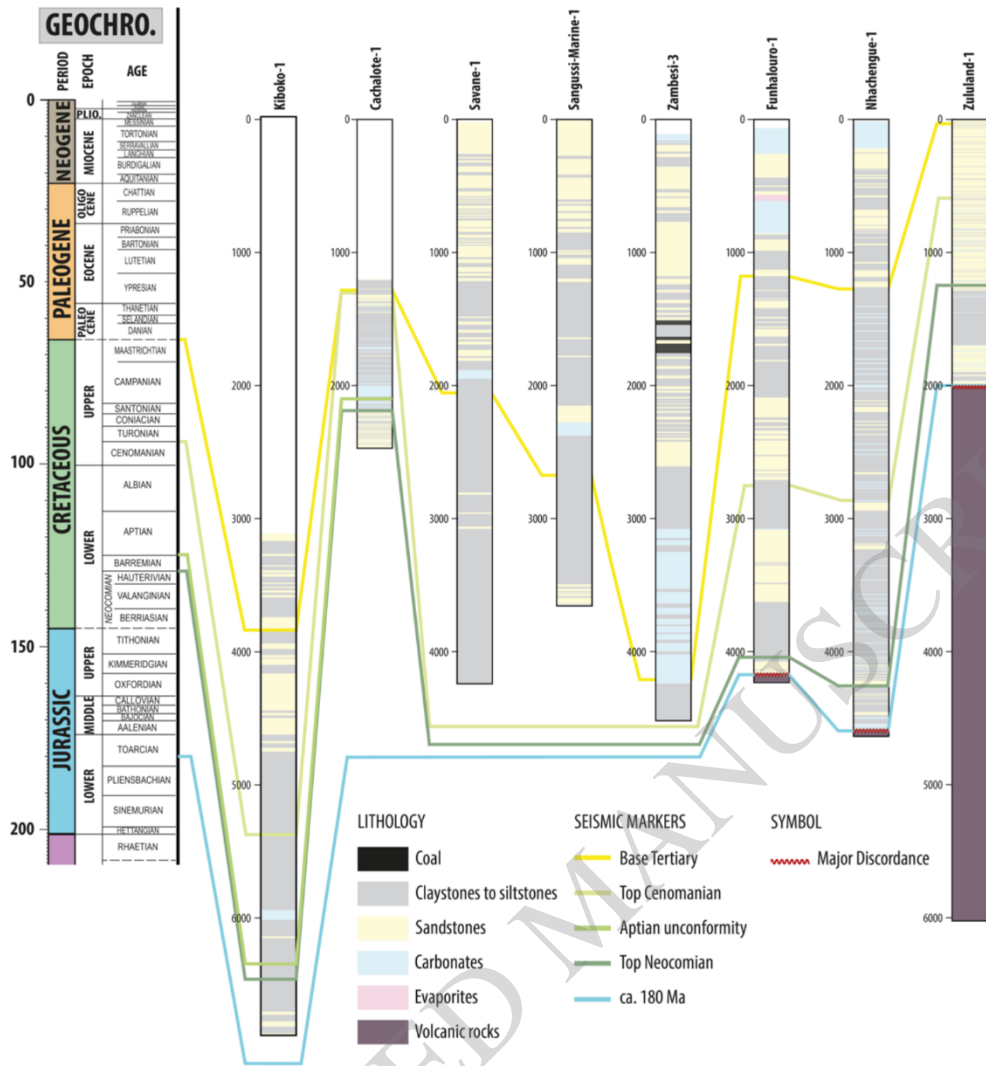


Figure 2

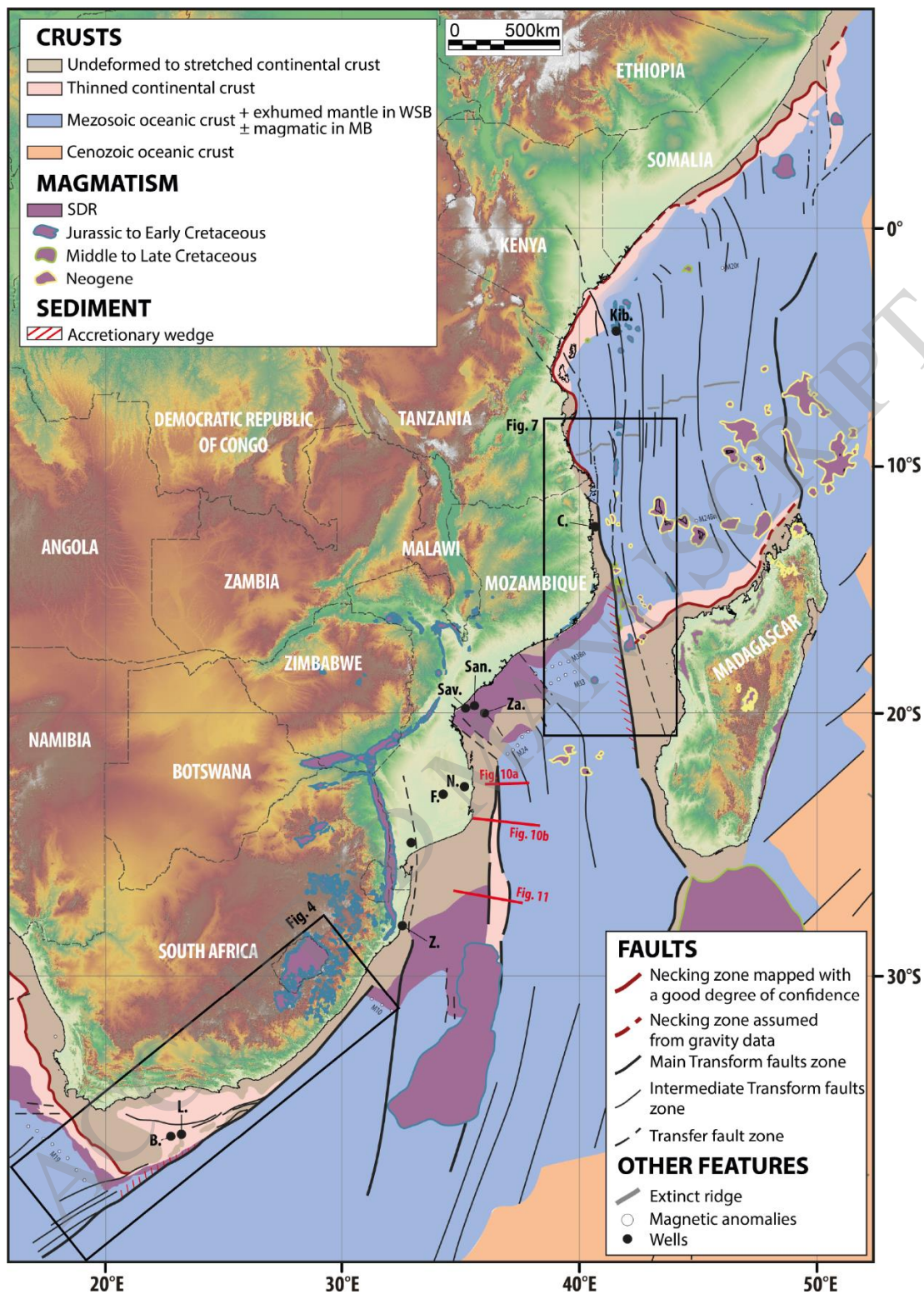


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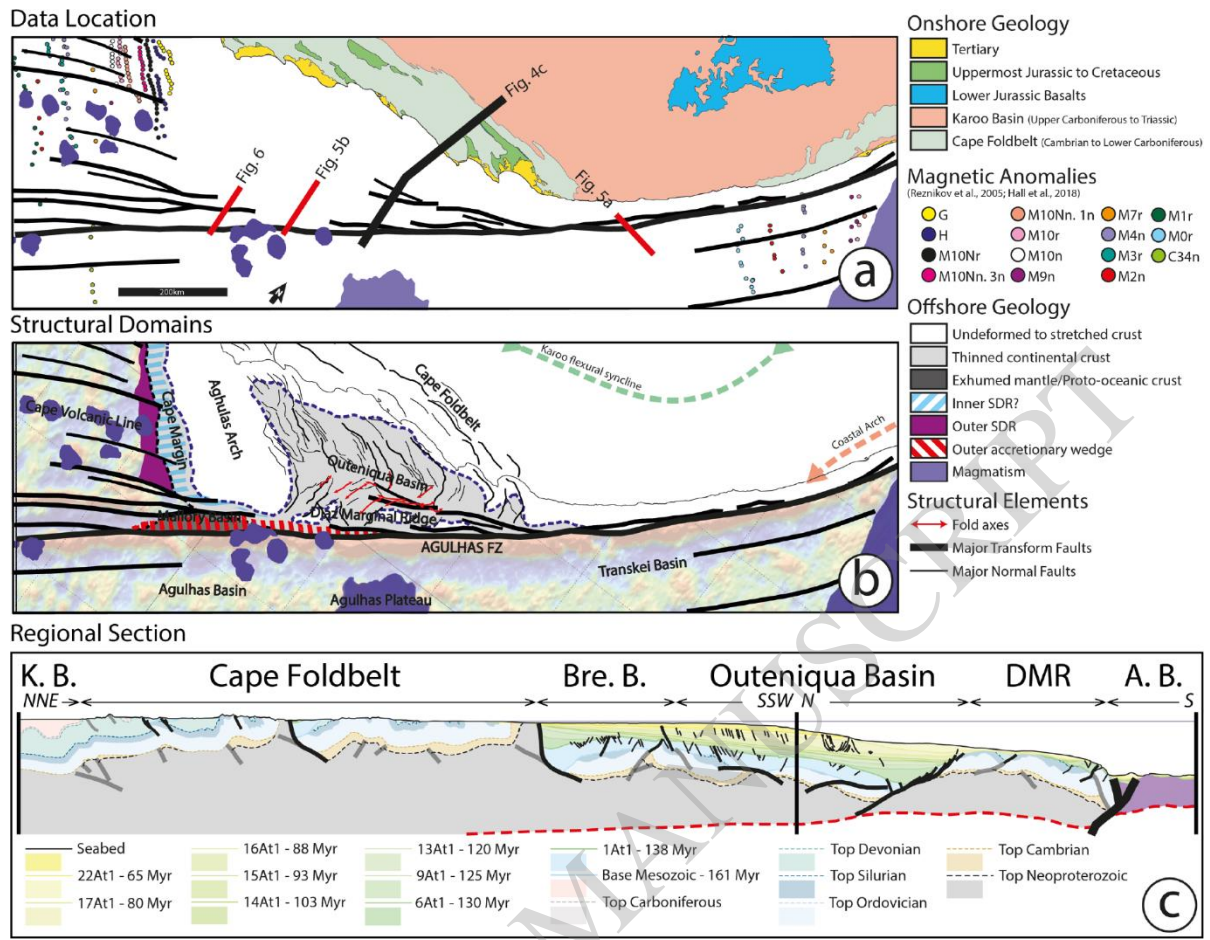


Figure 4

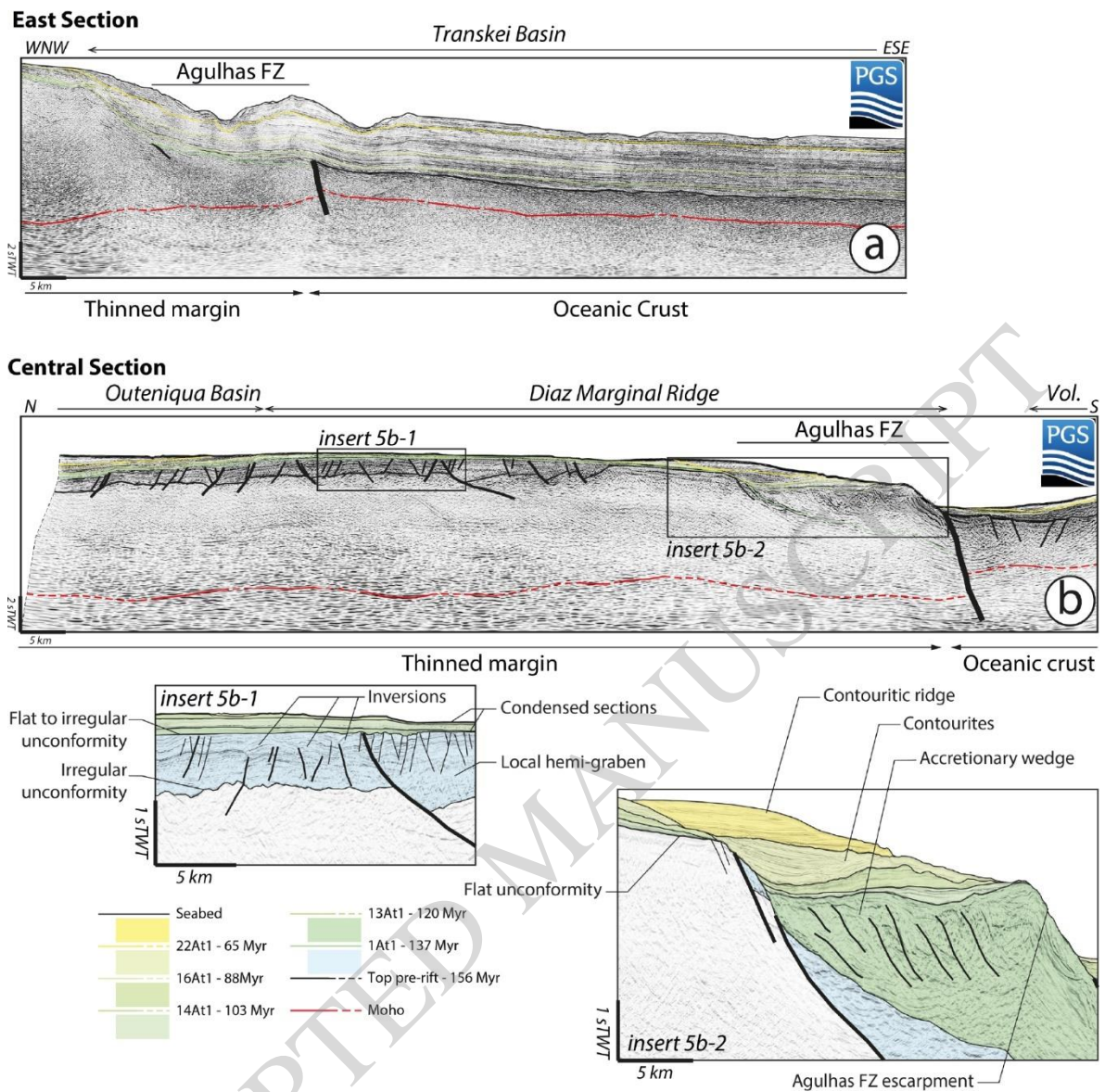


Figure 5

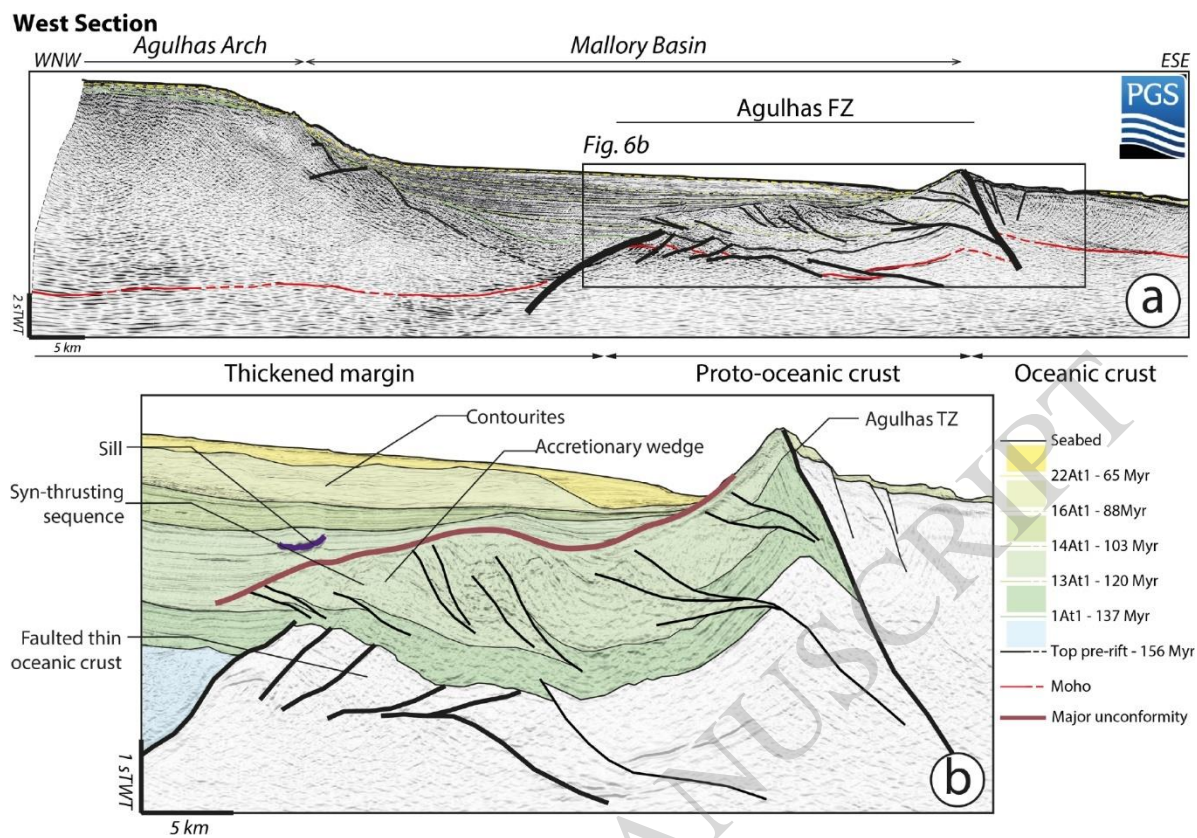


Figure 6

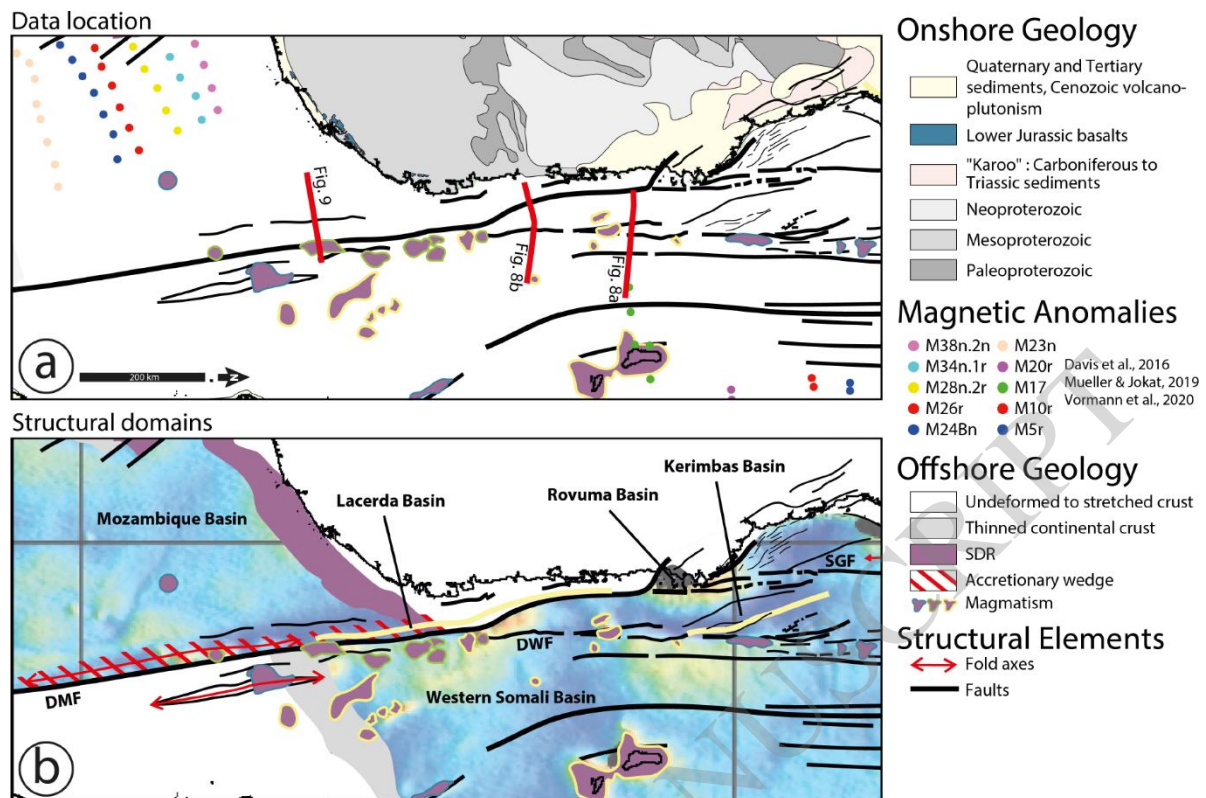


Figure 7

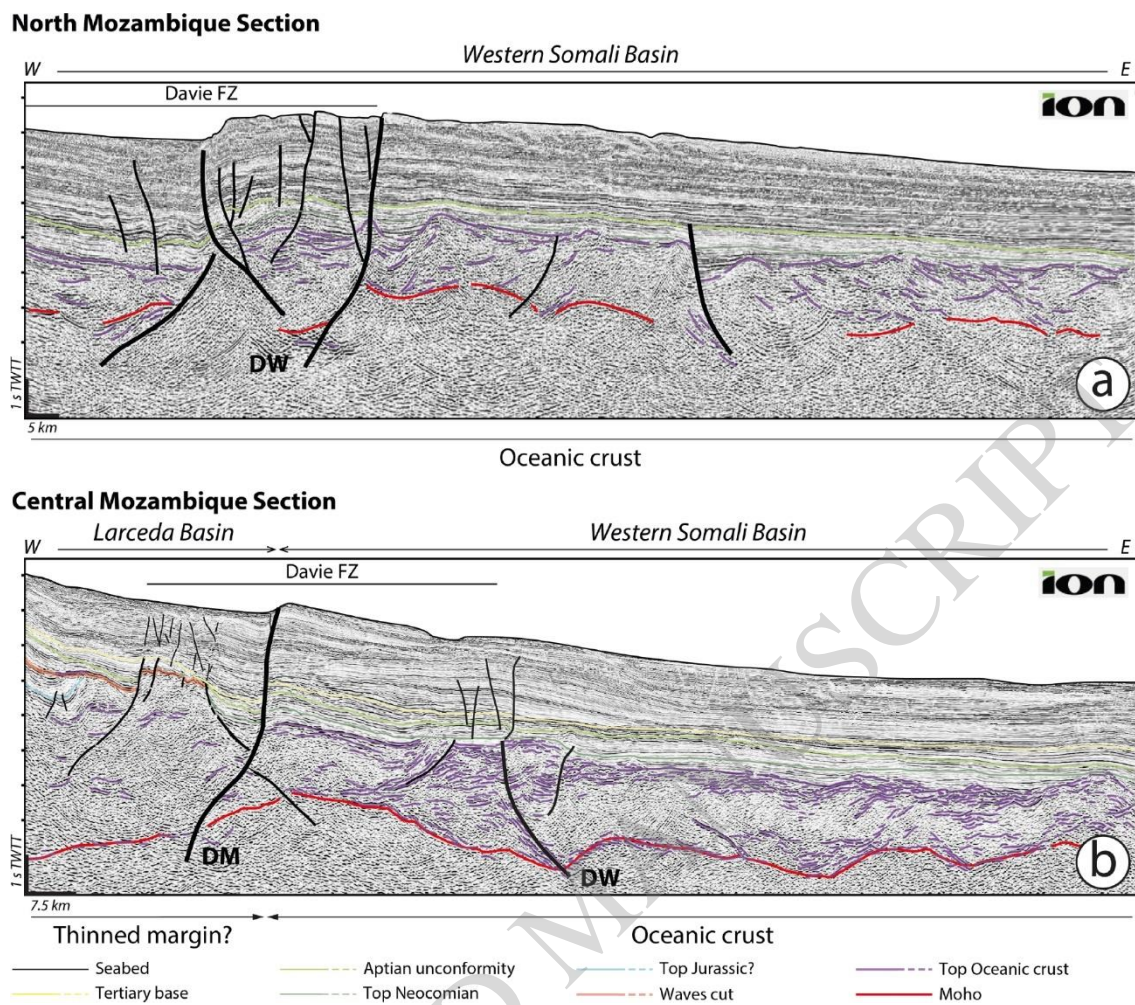


Figure 8

Southern Mozambique Section

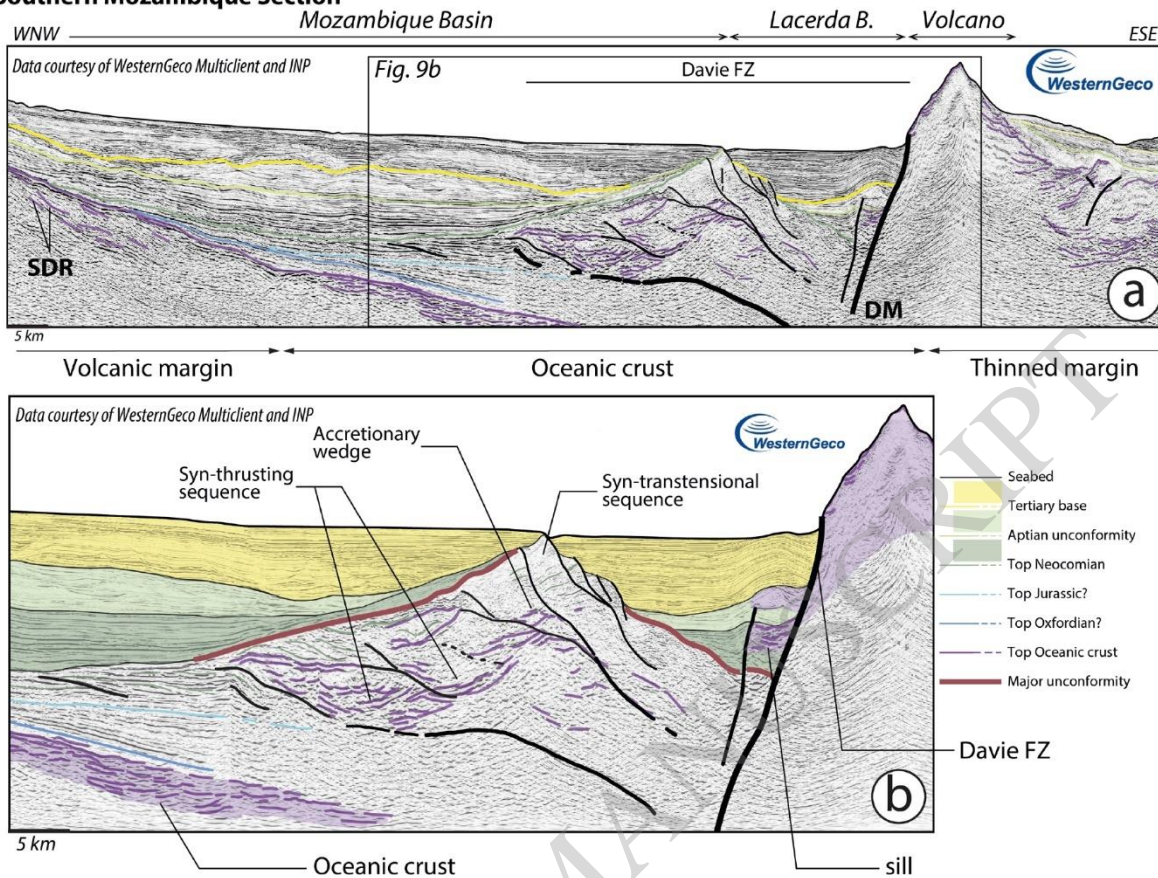


Figure 9

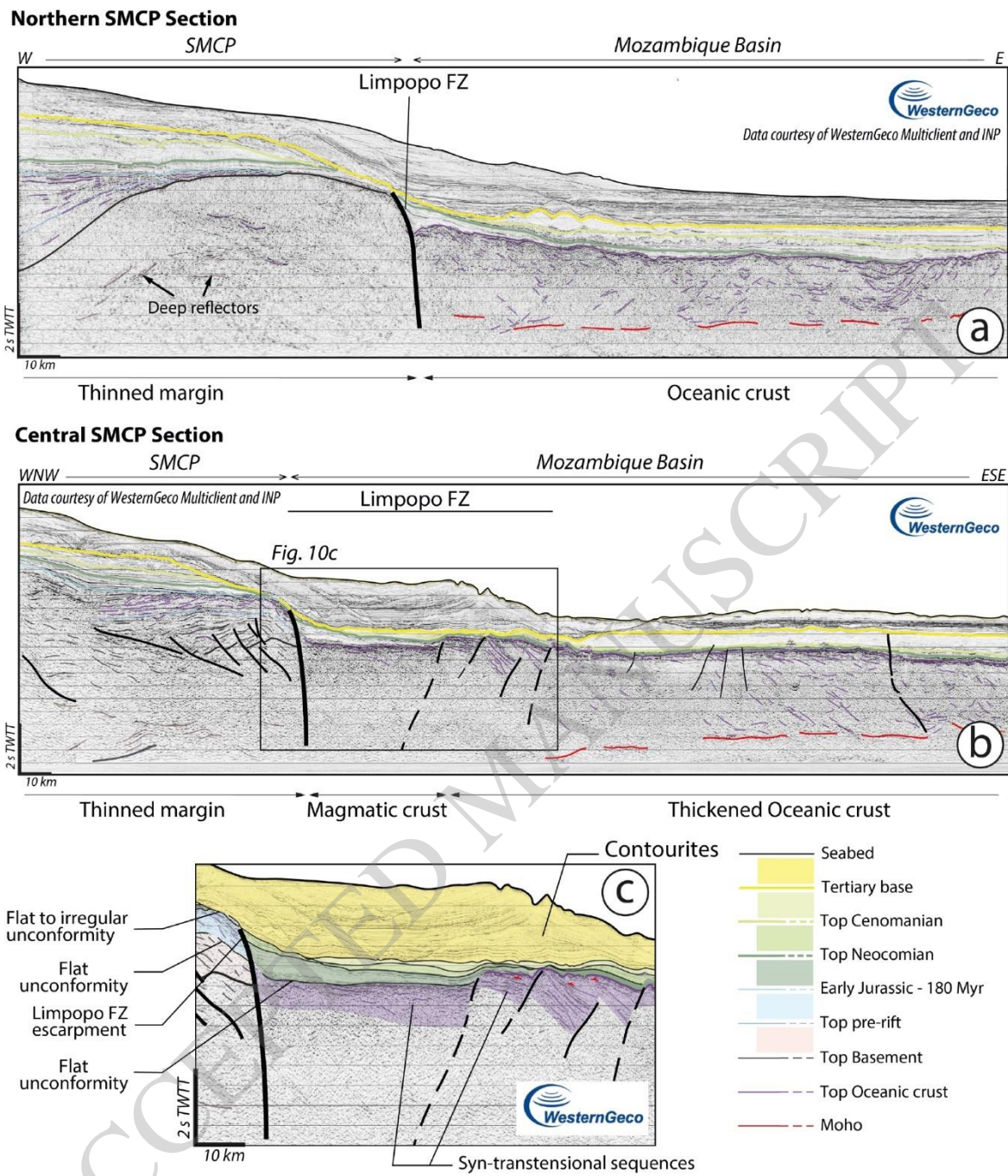


Figure 10

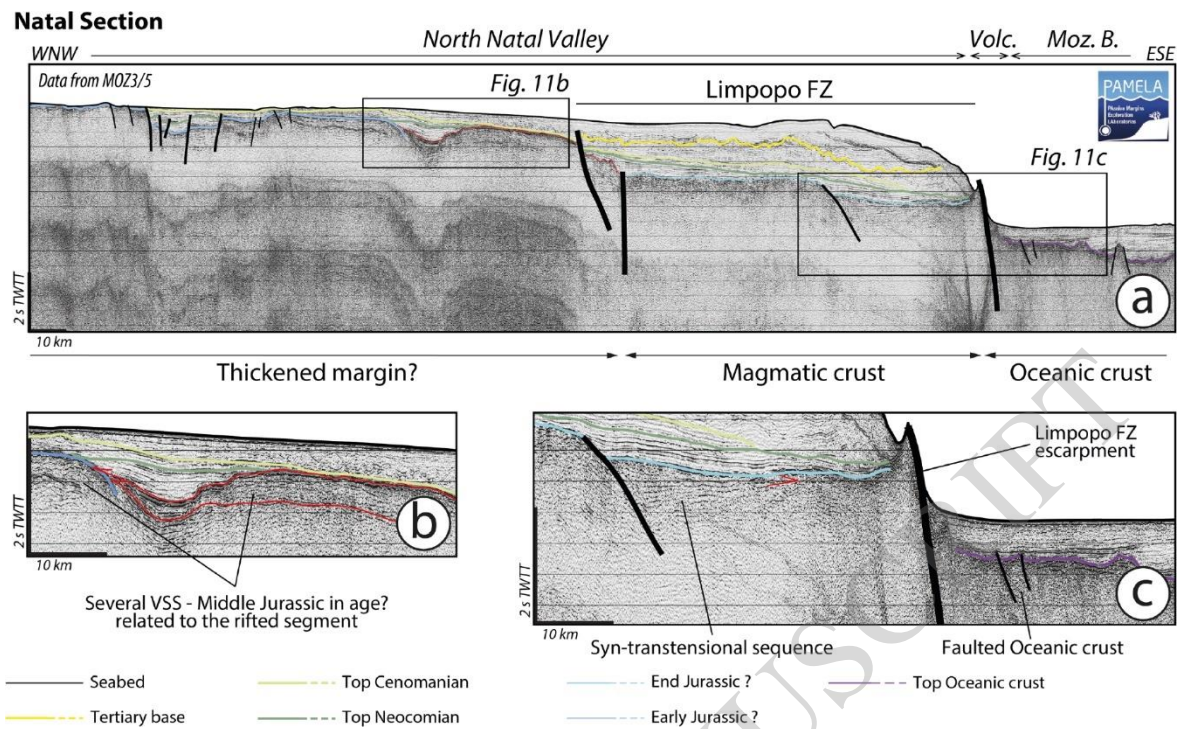


Figure 11

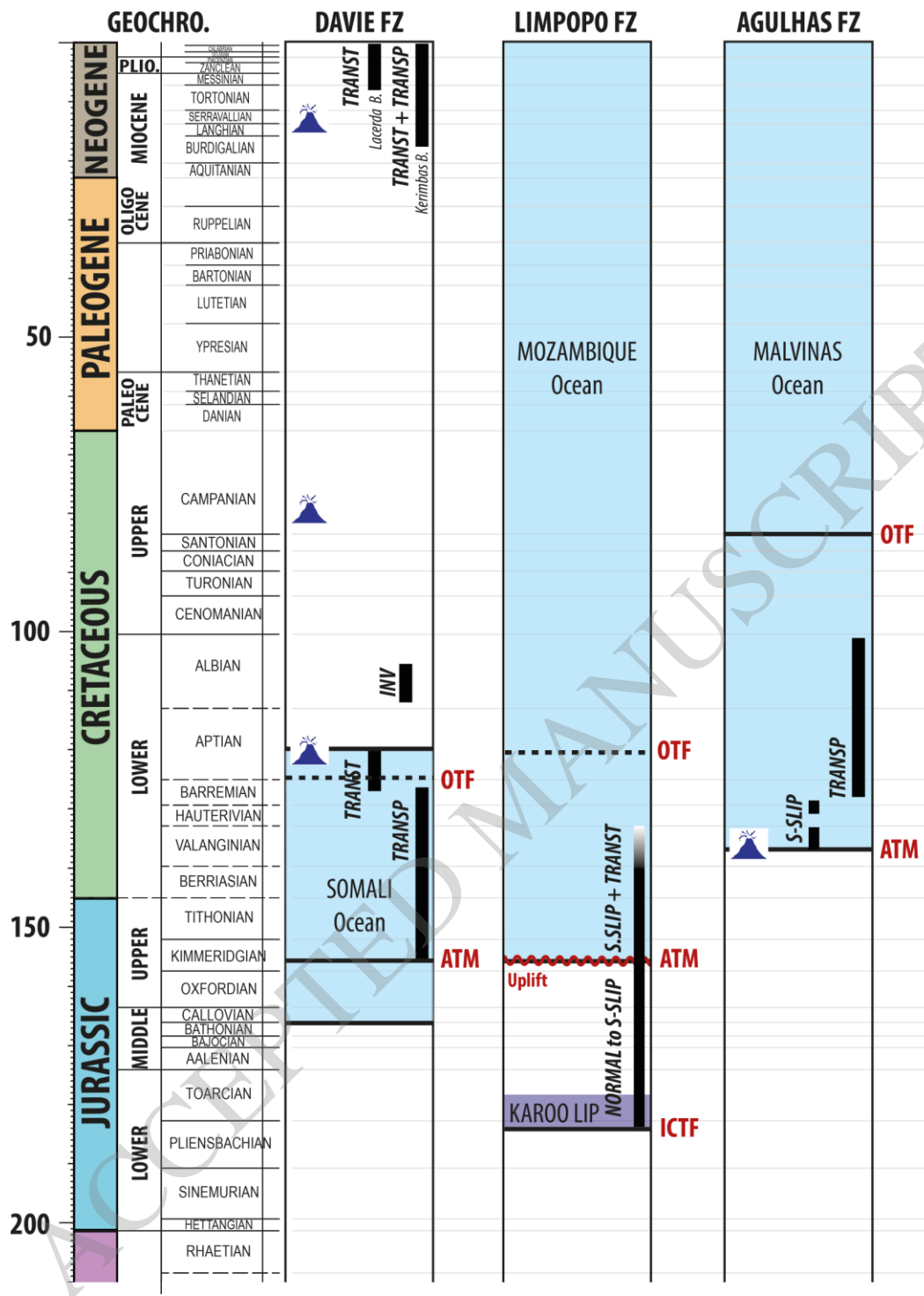


Figure 12

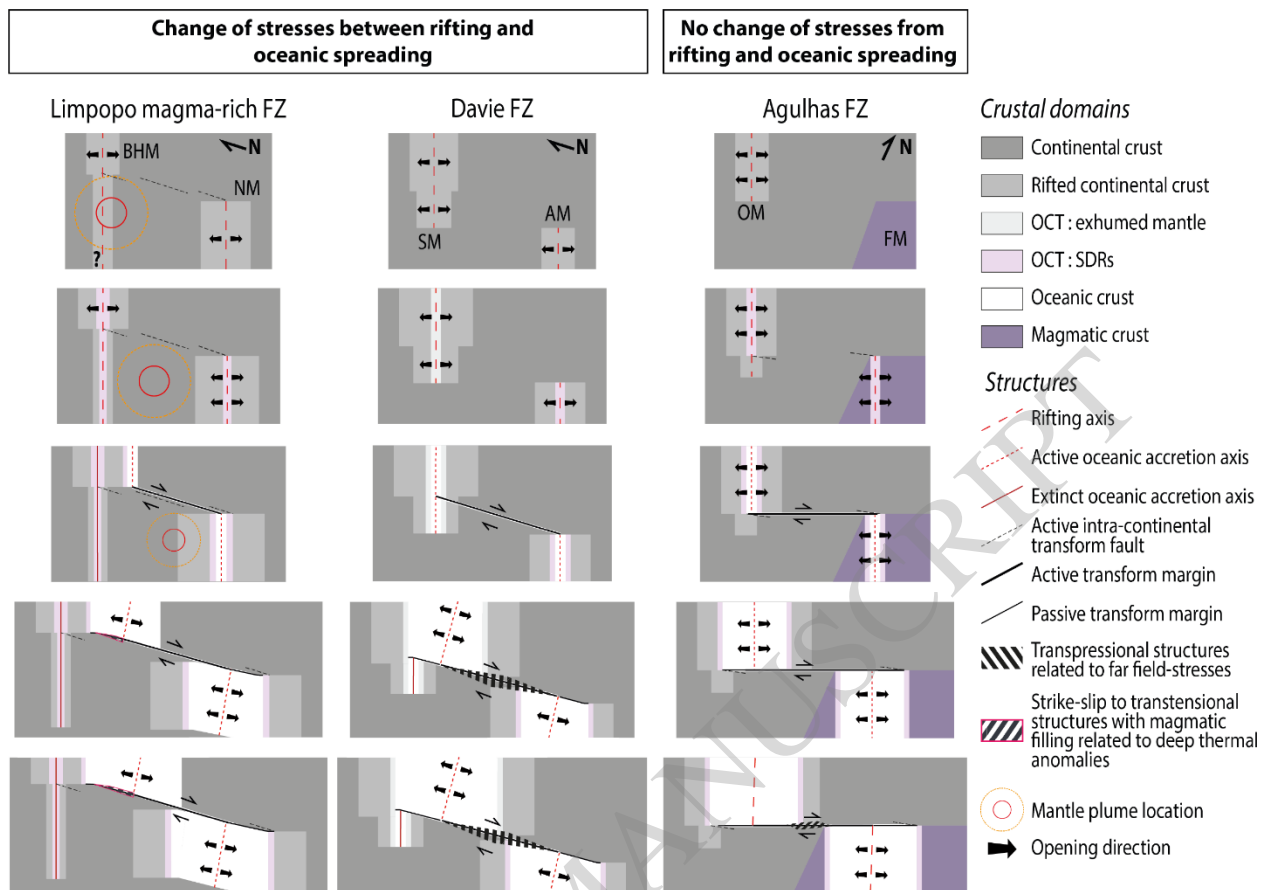


Figure 13