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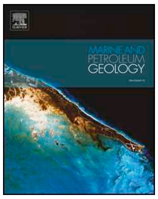

Research paper

Polyphase rifting and break-up of the central Mozambique margin

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ABSTRACT

The break-up of the Gondwana supercontinent resulted in the formation of the Central Mozambique passive margin as Africa and Antarctica were separated during the mid-Jurassic period. Although plate kinematics during the oceanic spreading phase are well constrained, the initial fit of Africa and Antarctica, their earliest relative movements and margin architectures remain active areas of interest. This study uses high quality multichannel seismic reflection profiles to identify the major crustal domains in the Angoche and Beira regions of the Central Mozambique margin. Our results show that the Central Mozambique passive margin is characterised by intense but localised magmatic activity, evidenced by the existence of seaward dipping reflectors (SDRs) in the Angoche region, and magmatic sills and volcanoclastic material marking the Beira High. The Angoche and Beira regions possess faulted upper-continental crusts, with possible exhumation of lower crustal material forming an extended ocean-continent transition (OCT). The Beira High segment reveals an offshore continental fragment, which is overlain by a faulted pre-rift sedimentary unit likely to belong to the Karoo Group. The combination of our seismic interpretation with existing geophysical and geological data has allowed us to propose a break-up model which supports the idea that the Central Mozambique margin was affected by polyphase rifting. The Beira High basement is formed by a strike-slip deformation along a proposed lithospheric weakness - the Lurio-Pebane shear zone. Northwestern-southeastern oriented extension follows and results in continental break-up and oceanic spreading. Our results suggest a segmentation of the Central Mozambique margin with oceanisation first occurring in the Angoche segment. The formation of the first oceanic crust in the Beira segment followed, likely delayed by the formation and failure of the northern Beira High rift.

1. Introduction

The Central Mozambique passive margin was formed during an episode of rifting which resulted in the fragmentation of the Gondwana super-continent and the formation of the African and Antarctic continents (Fig. 1). The subsequent southward drift of Antarctica, relative to Africa, formed the Mozambique Basin off the coast of Africa and Riiser-Larsen Sea, north of the conjugate Antarctica margin between the Davie Fracture zone in the east and the Mozambique fracture zone in the west (Fig. 1). The Cenozoic spreading history of the two continents is becoming increasingly well-constrained thanks to recent, dedicated magnetic anomaly studies, which propose different ages for the onset of the oceanic crust spreading. Leinweber and Jokat (2012) successfully identified chron M33n, indicating that the first oceanic crust formed in the Mozambique Basin at *c.* 159.1 Ma (Fig. 1a). It has also been argued that the first oceanic crust may be older still, with the potential identification of chron M38n (164.1 Ma) (Mueller and Jokat, 2017) in the offshore Angoche area (Fig. 1a). The accumulation of potential field and seismic data has resulted in several reconstructive models (Lawver and Scotese, 1987; Lawver et al., 1991; Eagles and König, 2008; Jokat et al., 2003; König and Jokat, 2010; Leinweber and Jokat, 2012; Gaina et al., 2013; Reeves, 2014; Nguyen et al., 2016; Reeves et al., 2016). Outcropping geological features across the conjugate margins have also been used to reconstruct the initial positions of Africa and Antarctica within Gondwana (Du Toit, 1937; Cox, 1992; Reeves, 2000; Thompson, 2017), and these models are complimented by dating of the onshore volcanic episodes and dyke complexes (Jourdan et al., 2006, 2007; Klausen, 2009), potentially related to the rifting event. The existing reconstructive models place Antarctica relative to Africa in various initial configurations (Fig. 1a) and despite the distinct views on initial continental fit, there appears to be a growing consensus that the north-south separation of Antarctica and Africa was preceded by an initial rotation or translation of the Antarctic plate, relative to the African plate (Cox, 1992; König and Jokat, 2006; Leinweber and Jokat, 2012; Mahanjane, 2012), Madagascar belonging to the Antarctica block at this time (e.g. Gaina et al., 2013; Reeves et al., 2016; Leinweber and

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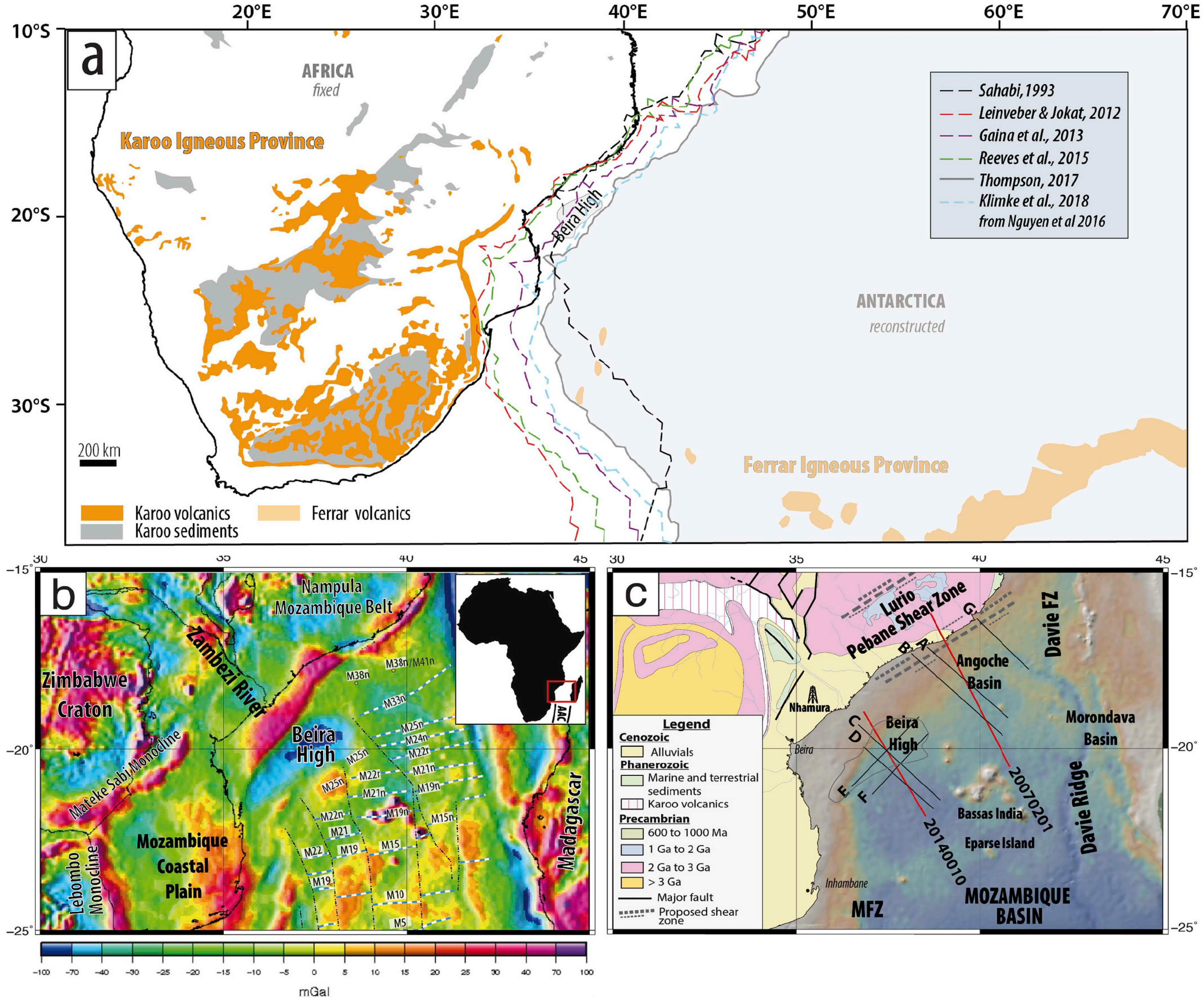


Fig. 1. (a) Map of the extension of the Karoo Igneous province and associated Karoo sediments in the Africa continent. The Ferrar Igneous Province is located in the Antarctica continent which is shown in the position before the opening of the Mozambique basin according to Thompson (2017). The other positions of the Antarctica relative to Africa fixed are drawn in dashed line of different colours. (b) free-air gravity anomaly map (EGM08 - Bureau Gravimetrique International (BGI)) of the study area located at the northernmost reaches of the Africa-Antarctica Corridor (AAC in inset). The interpreted magnetic anomaly data of Leinweber et al. (2012) and Mueller and Jokat (2017) is represented by blue and white dashed lines. (c) Simplified geological map of study area. The location of the seismic reflection profiles interpreted during the course of this study are shown by numbered, solid black lines while the location of the seismic refraction profiles 20070201 of Leinweber et al. (2013) and 20140010 of Mueller et al. (2016) are shown in red. MFZ: Mozambique fracture zone. The grey line corresponds to the location of the Beira High. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Jokat, 2012; Nguyen et al., 2016; Klimke et al., 2018). The timing of this initial movement may be intimately linked with the emplacement of the Karoo and Ferrar continental flood basalts across the conjugate margins at *c.* 180 Ma.

Wide-angle seismic data has provided good insight into the crustal structure of the Central Mozambique margin (Leinweber et al., 2013) as well as provided evidence of the continental origin of the deep offshore Beira High (Fig. 1a; Mueller et al., 2016). Despite this accumulated knowledge, the tectonic structure and rifting style of the Central Mozambique passive margin remains an unanswered question. In order to reconstruct the deformation history of this margin it is essential that the accommodating structures and crustal zones are well defined. This means combining the existing geophysical datasets with seismic reflection surveys where possible. Interpretation of deep crustal structures is an inherently complicated task and in the case of volcanic margins these problems are exasperated by the acoustic screening effect of lava flows which hinder penetration of seismic energy into the underlying crust. The complexity and inaccessibility of passive margins mean that many questions remain unanswered. By what mechanism is lithospheric stretching accommodated? Is there a relationship between previous tectonic episodes and the localisation or geometry of the rift? How does the thermal regime and notably the presence of magmatic material within the crust affect the style of deformation? The search for answers to these questions, as well as the discovery of hyperextended continental margins (Boillot et al., 1980) have helped to refine the original ideas of McKenzie (1978) and Wernicke (1981), with more recent studies showing that crustal extension may be accommodated by the activation of intra-crustal shear zones that are thought to cause basinward exhumation of the lower crust and/or subcontinental mantle (Lavier and Manatschal, 2006; Clerc et al., 2015; Jolivet et al., 2015). These recent advances have somewhat changed the vocabulary of passive margins with terms such as *exhumed domain*, *steady-state*, *proto-*

oceanic, or *embryonic oceanic crust* becoming increasingly common despite the relatively poor understanding of the true nature of these domains (Péron-Pinvidic and Manatschal, 2009). The Ocean Continent Transition (OCT) marks the gradual change from highly stretched and thinned unequivocal continental crust to steady state oceanic crust (e.g. Nonn et al., 2017). The OCT comprises zone of exhumed material (continental mantle or lower continental crust) and the proto-oceanic crust (between the poorly defined basement of the transitional domain and the unambiguous oceanic crust, e.g. Péron-Pinvidic and Osmundsen, 2016).

In the case of “hot” passive margins, Stab et al. (2016) recently showed that in addition to large quantities of extrusive volcanism and the presence of mafic underplating which characterises this style of margin, deformation of the Central Afar volcanic passive margin is distributed in a style they called “magmatic wide rifting”. The authors postulate that crustal extension is accommodated by mid-crustal shear zones, which root in a narrow necking zone. This recent discovery is a rare example of distributed tectonic deformation of a magma-rich passive margin, highlighting the importance of intracrustal shear zones in the accommodation of extension during rifting. Our study presents the results of the interpretation of several, multi-channel seismic (MCS) reflection profiles which are described in detail in order to identify important crustal domains and establish a style of rifting which may help to fill gaps in the reconstructive history of the conjugate margins. The interpretation of two profiles, located in the northern margin, is complimented by observations made across intersecting and parallel profiles in order to obtain a clearer image of the deformation that took place in this region. Our interpretations show that the Central Mozambique continental margin is characterised by localised magmatic activity, intracrustal shearing, as well as zones of highly stretched, magmatically intruded, possibly exhumed continental crust. We also show that the Beira High, a deep-water continental fragment, has recorded several episodes of tectonic deformation and that these phases of deformation can be correlated with the earliest stages of rifting between Africa and Antarctica.

2. Geological setting

The rifting and dispersal of Gondwana is temporally associated with the formation of a vast continental flood basalt province known as the Karoo Igneous Province in Africa and the Ferrar Igneous Province in Antarctica (Fig. 1a). Fitch and Miller (1984) dated the peak volcanism during the formation of the Karoo Igneous Province to 200–190 Ma while Duncan et al. (1997) dated the formation of the Ferrar Igneous Province to 183 ± 1 Ma and concluded that the dates of both formations are indistinguishable from each other. More recent work shows that the majority of the Karoo volcanics were emplaced between 184 and 177 Ma (Jourdan et al., 2007), placing this event in the Toarcian (Uppermost Lias) age. Evidence of the Karoo Igneous Province emplacement can be found over much of southern Africa including the basaltic Lebombo monocline (Fig. 1b) which was formed during this event. Despite the varying age estimates, it is generally agreed that pre-rift Gondwana was characterised by widespread extrusive volcanism during the early Jurassic.

Post-break-up, the southward drift of Antarctica, relative to Africa has resulted in a long, narrow oceanic basin which separates the conjugate margins - the Africa-Antarctica Corridor (AAC) (Fig. 1b, inset). Magnetic anomaly data reveals that the first oceanic crust was formed in the AAC sometime between 166 Ma and 154 Ma (Fig. 1a; Leinweber and Jokat, 2012; Leinweber et al., 2013; Mueller and Jokat, 2017). The Mozambique Basin is located in the northern part of the AAC and is delimited by the African continent to the west and by Madagascar to the east (Fig. 1c). The deep-water area of the Mozambique Basin is punctuated by volcanic seamounts and atolls such as the Bassas da India and Ile Europa (Fig. 1c). Another feature of this domain is the Beira High, a morphological basement high that lies approximately 70 km off the coast of the Zambezi Delta (Fig. 1b). This complex structure is approximately 300 km long, 120 km wide and is oriented (using its largest dimension) sub-parallel to the central Mozambican margin. Seismic reflection and wide-angle seismic data (Mahanjane, 2012; Mueller et al., 2016), as well as a pronounced negative free air anomaly (Fig. 1b) indicate that the Beira high is a continental fragment, individualised during the breakup of Gondwana, during the rifting episode that saw the separation of the African and Antarctic plates.

The onshore geology of the Central Mozambique margin varies along strike between the Angoche and Beira regions. In the region of Angoche, a thin tract of unconsolidated Quaternary sediments separates the Mozambique Basin from the outcropping Proterozoic basement (Fig. 1c). This basement consists of a Precambrian orogenic zone (Daly et al., 1989) and forms part of the greater Mozambique Belt. The area covered by the Quaternary sediments becomes larger to the southwest eventually forming the Mozambique Coastal Plains, a vast low-lying area of Cretaceous and Quaternary alluvial and clastic sediments which abuts in unconformity against the aforementioned, seaward-dipping Lebombo monocline (Fig. 1b). The nature of the crust which underlies the MCP is the subject of debate and is likely to consist of either the transitional crust of a volcanic rifted margin (Klausen, 2009) or thickened oceanic crust (Leinweber and Jokat, 2012).

3. Data acquisition and method

The MCS reflection profiles used in this study are commercial profiles acquired by INP - WesternGeco multiclient in 2013. Both time-migrated and depth converted images were used with depth conversion achieved using the sonic velocities of the onshore Nhamura well (Fig. 1c).

Six profiles were interpreted at Total CSTJF, Pau using *Sismage*®, the proprietary seismic interpretation platform of Total (Fig. 1c). The profiles are located in two areas corresponding to the Angoche and Beira High segments of the continental margin of Central Mozambique (Fig. 2). Detailed interpretations were generally carried out using the time-migrated image due to the superior image quality. The detailed observations of time-migrated data therefore ensure the integrity of the interpretations which could then be transcribed manually to depth converted profiles where available to give real geometries. Interpretations were heavily reliant on observation and description of seismic facies types and geometries which are further developed in the following chapter.

4. Results and key observations

4.1. Angoche area

The distinction between the basement and overlying sedimentary units in profile 48 is made possible by the existence of a near-continuous, high amplitude reflector (Fig. 3a). This reflector separates the low-to-medium amplitude, parallel reflectors typical of sediments from the deeper, high amplitude chaotic basement reflectors.

4.1.1. Sedimentary cover – Profile A

A detailed study of the sedimentary column is beyond the scope of this paper, however a brief description of the observed geometries and ages, where available, is necessary and provides insight into the tectonic evolution of this margin. Key horizons visible in Fig. 3a come from literature (e.g. Castelino et al., 2015; Mahanjane, 2012, 2014; Franke et al., 2015; Ponte et al., 2018; Klimke et al., 2018). From oldest to youngest these are Top Neocomian (129.4 Ma), Base Cenomanian (100.5 Ma), Top Oligocene (23 Ma), and Top Miocene (5.3 Ma). The oldest identified sediments overlying the basement are found in the proximal half of the profile, from 40 to 110 km (Figs. 3a and 4). Characterised by transparent to low-amplitude, parallel reflectors, the geometry of this thin (approximately 800 m thick at the depocentre)

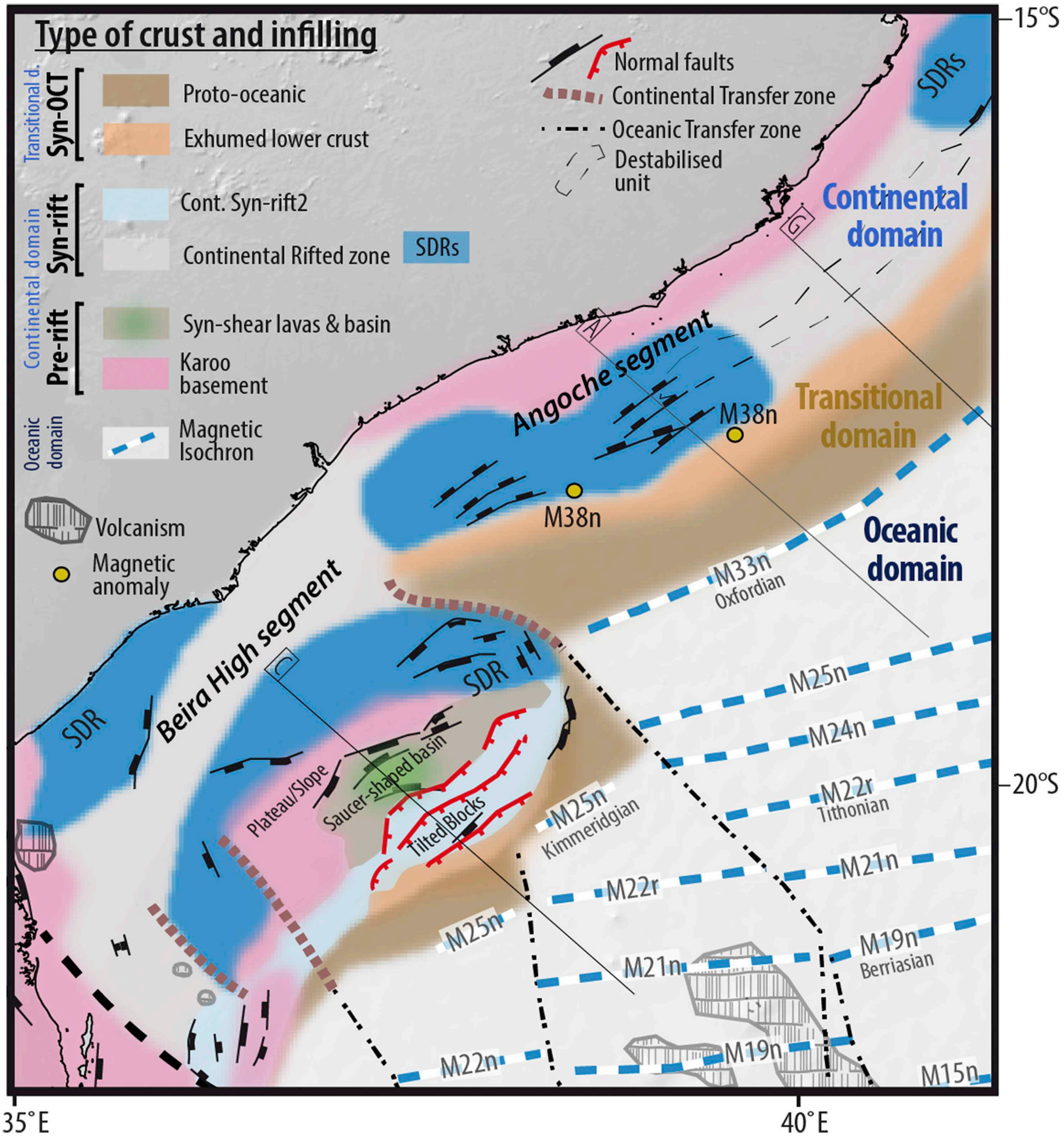


Fig. 2. Structural map proposed for the Central Mozambique margin constructed using our observations and modified after Castilla et al. (2015). The map shows a segmentation of the margin with both the Beira High and Angoche segments characterised by well-developed continental and transitional domains. The oceanic domain is defined by seismic profile interpretation. Magnetic anomaly identifications (MXX blue and white dashed lines) are after Leinweber et al. (2012) and Mueller and Jokat (2017) for the M38n. OCT: Ocean Continent Transition. SDRs: Seaward dipping reflectors. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

unit is that of a basin which has been tilted seaward. In the south-east this sedimentary prism onlaps onto a basement high (Fig. 4). A second sedimentary prism immediately overlies the aforementioned prism with the northwest extremity onlapping onto the older unit between 45 and 50 km (Figs. 3a and 4). The overall geometry of the younger prism is once again a shallow basin with a maximum thickness of around 200 m. Reflector geometries show that this prism onlap onto the southeast with progressively younger sediments onlapping further and further southeast (Fig. 4). The younger sedimentary unit terminates at around 150 km, onlapping onto a small topographical rise of the top basement.

Both sedimentary units described here were deposited pre-Top Neocomian. They represent a geographically restricted sedimentary deposit with younger sediments draping the basement to the southeast and onlapping onto it progressively further northwest as subsidence became generalised.

4.1.2. Basement – profile A

The depth of the top acoustic basement increases from < 1 km to approximately 9.5 km bsl over the first 95 km of profile A (Fig. 3a). Beyond 95 km, the depth of the top acoustic basement remains relatively constant with the exception of small rises at 150 km, 170 km and some buried seamounts at around 280 and 300 km. The seismic characteristics of the basement vary along its length with the most proximal 100 km being characterised by zones of coherent reflectors in the uppermost 4 km of the basement (Fig. 3a; 4).

Between 10 and 20 km along-profile we observe a series of sub-parallel, medium amplitude reflectors that are truncated at the top basement indicating the existence of a sedimentary unit and erosional surface in this region (Fig. 3a, inset). The continuity of this sedimentary unit at greater depths is unclear, however the existence of sub-parallel reflectors with similar geometry and amplitude exists between 25 and

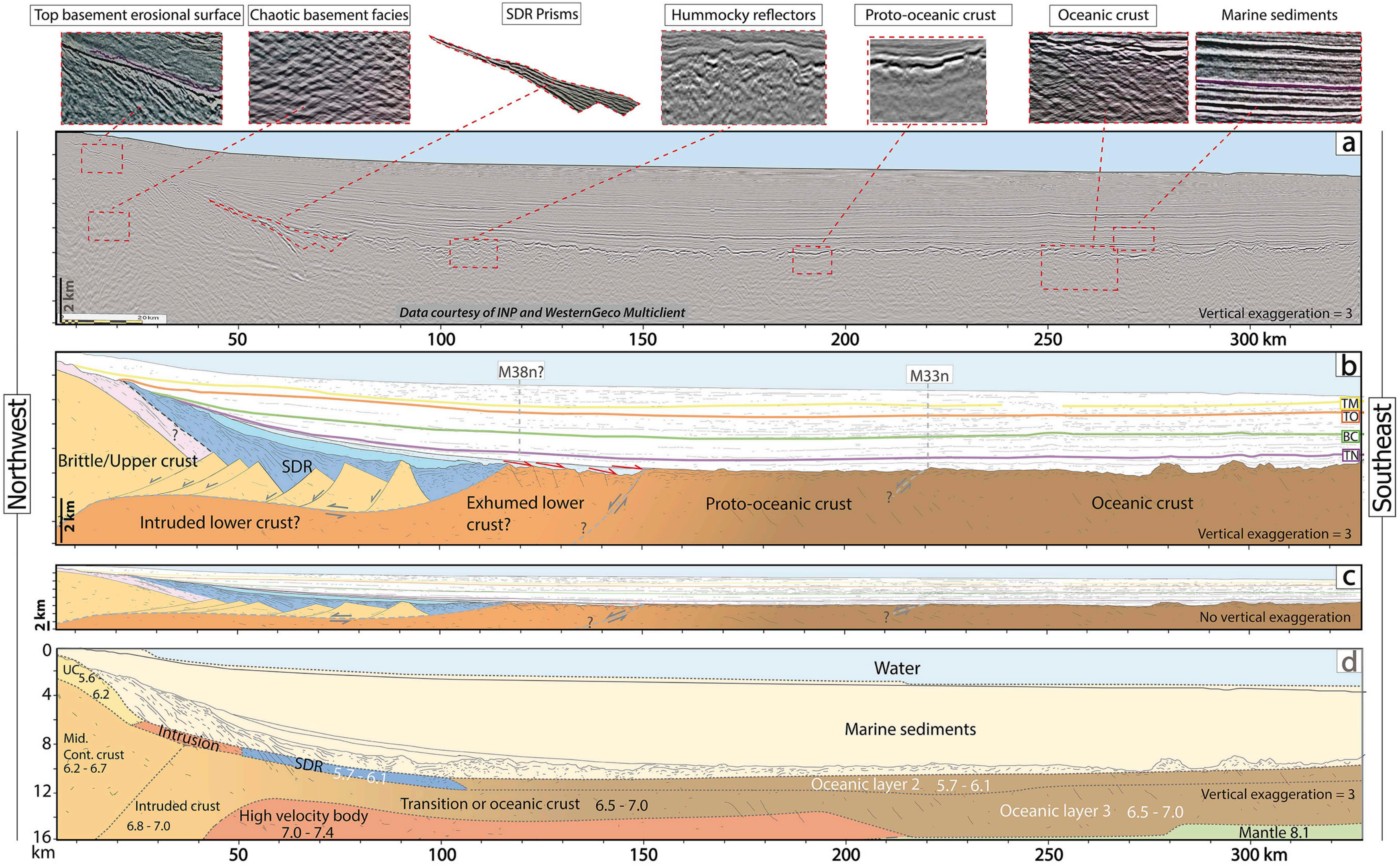


Fig. 3. (a) Line drawing and characteristic seismic facies of profile A. Isochrons – TN: Top Neocomian, BC: Base Cenomanian, TO: Top Oligocene, TM: Top Oligocene. (b) Interpretation of profile A. Chrons M38n and M33n (Mueller and Jokat, 2017) have been projected onto our profile. (c) Interpretation of profile A shown without vertical exaggeration. (d) A projection of the interpreted seismic refraction model 20070201 of Mueller and Jokat (2017) onto profile A (see Fig. 1c for profile locations). The numbers are P-wave propagation velocities in km/s.

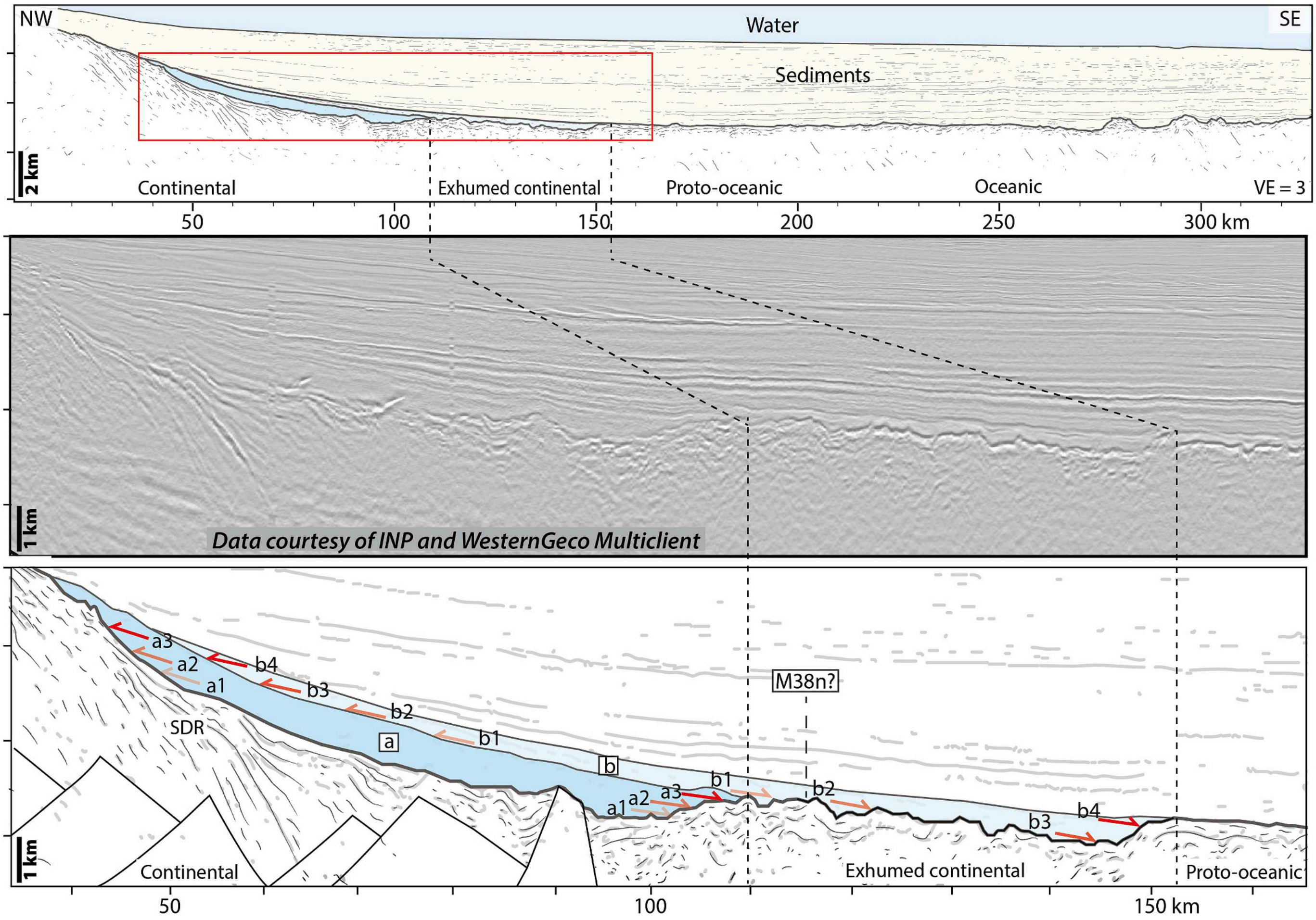


Fig. 4. A zoom of the earliest sedimentary basins along profile A. The oldest sedimentary prisms are identified by differing shades of blue and a letter. Profile A shows that the depocentre of the sedimentary prisms shifts abruptly southeast between the deposition of prism 'a' and prism 'b'. The uppermost prism 'b', younger sediments (denoted by increasing number) onlap further and further southeast. The projected location of chron M38n of Mueller and Jokat (2017) is also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

35 km and likely shows that the truncated unit exists at least until this point. Below the parallel series of reflectors we observe chaotic seismic facies, interpreted as crystalline basement (Fig. 3a, inset). Between 40 and 75 km we observe a zone of continuous, high amplitude, low frequency reflectors which clearly show a divergent geometry, typical of volcanic or volcanoclastic SDR (Fig. 3a, inset). The geometry of the SDR is controlled by a series of continentward-dipping normal faults and we estimate the maximum thickness of the SDR to be around 3–4 km, however due to increased noise in the seismic image at increasing depths it is difficult to be certain. From 90 to 120 km we observe a small rise of the top basement, of which uppermost 1–2 km is characterised by a wedge of high amplitude, low frequency reflectors which are hummocky in appearance and appear to mark the seaward limit of the large-offset normal faulting which characterises the region of SDR (Fig. 3a, inset; Fig. 4). The seismic facies of this wedge indicates that this basement rise likely also consists of volcanic material, deposited in a different tectonic regime to the SDR. The top basement maintains a certain rugosity between 120 and 150 km and we observe a number of seaward-dipping, small offset normal faults which affect the top basement (Fig. 4). The uppermost 1 km of the basement appears to consist of a layer of volcanic material with the seismic image below this layer providing few clues as to its nature. Beyond 150 km we observe little obvious further evolution in the characteristics of the basement. A small (approximately 1 km) rise in the top basement is visible at 170 km and marks the point beyond which we are able to observe a series of seaward-tilted intracrustal reflectors at depths of 12–13 km (Fig. 3a). These reflectors, interpreted as probable ancient, oceanic detachments, have previously been described in oceanic crust (Bécel et al., 2015).

4.1.3. *Proximal margin – Profile G*

Profile G is oriented parallel to profile A, further northwest along the Angoche margin (Figs. 1c and 5). Along the basement slope of profile G we observe an uppermost acoustic basement consisting of a layer of volcanic material which shows evidence of extension as evidenced by normal faulting (Fig. 5). The equivalent, pre-top Neocomian sedimentary units observed and described in profile A are once again present. The deeper sedimentary unit (a) has been affected by gravity sliding, in the region of the faulted acoustic basement, likely due to the presence of an underlying layer of evaporites or undercompacted shales (Morley et al., 2011). The presence of an erosional truncation of the lower sedimentary prism, the absence of lateral ramp activity in the upper unit (b), and the southeast shift in the depocentre leads us to believe that the gravity sliding event occurred coeval with the first stages of formation of the upper prism.

4.1.4. *Proximal margin – Profile B*

Profile B is oriented parallel to profile A, at a distance of approximately 45 km southwest (Fig. 1c). The overall geometry of the sedimentary cover in profile B strongly resembles that of profile A described above. Similar to profile A, the top acoustic basement is defined by a continuous, high amplitude reflector (Fig. 6). Though geographically close, the proximal basement of profile B has a different appearance to

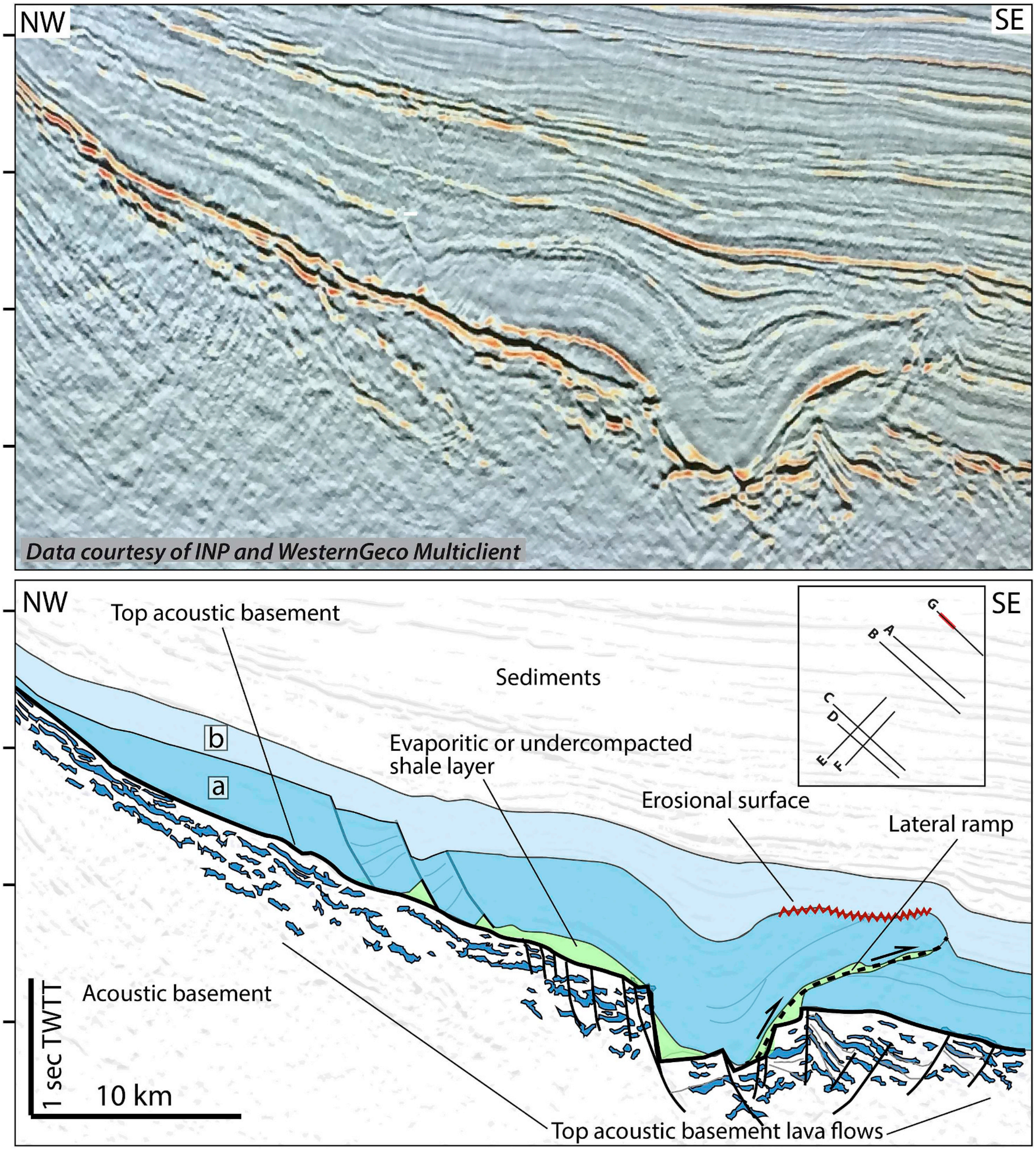


Fig. 5. Profile G – Structural interpretation of the Angoche margin slope (location indicated by red bar in inset). Like profile A (Fig. 3a) the margin slope consists of an uppermost acoustic basement consisting of lava flows overlain by early sedimentary prisms which are ubiquitous (prisms 'a' and 'b') in the Angoche region (Figs. 3a and 4). Layer of evaporites or uncompacted clay (green) allows sliding of the sedimentary cover (a). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

that of profile A, notably an upper basement slope featuring chaotic, high frequency seismic facies (Fig. 6a, inset). Immediately below the top basement reflector in the northernmost part of the profile B, we observe a series of low amplitude, high frequency, parallel reflectors, at a depth of approximately 2 s TWTT from the top of the figure (Fig. 6a, inset). These reflectors, typical of sediments, are able to be traced until the rupture of the basement slope at which point they appear to be cut by a seaward-dipping normal fault. This normal fault can be traced to a depth of around 6 s TWTT in the basement (Fig. 6a). From around 2 to 4.5 s TWTT the hanging wall of this fault is characterised by a high frequency, chaotic facies which locally forms the top acoustic basement (Fig. 6a, inset). This high frequency, chaotic facies is observed on other profiles in this study (see following section on Beira High) and along with the previously mentioned sediments is thought to represent a sedimentary pre-rift unit (PRU). The PRU is emplaced above a zone characterised by lower frequency chaotic facies interspersed with discontinuous, high amplitude reflectors interpreted as intruded crystalline basement (Fig. 6). This arrangement of PRU overlying intruded basement can be traced seaward with these formations being affected by normal faults with an apparent seaward dip. Magmatic intrusion of the basement becomes increasingly pronounced toward the southeast with the appearance of high amplitude, hummocky reflectors (Fig. 6). The normal faults, which control the basement geometry, root into an upward-convex zone of high amplitude, low frequency, semicontinuous reflectors (Fig. 6a, and top inset). This geometry is characteristic of an intracrustal shear zone (Reston et al., 2007; Clerc et al., 2015), and it can be traced seaward, intersecting the top acoustic basement at around 6.5 s TWTT from the top of the profile (Fig. 6). The volcanic material is affected by normal faults that show in the proximal part, an apparent dip toward the continent, forming SDR geometries, however these

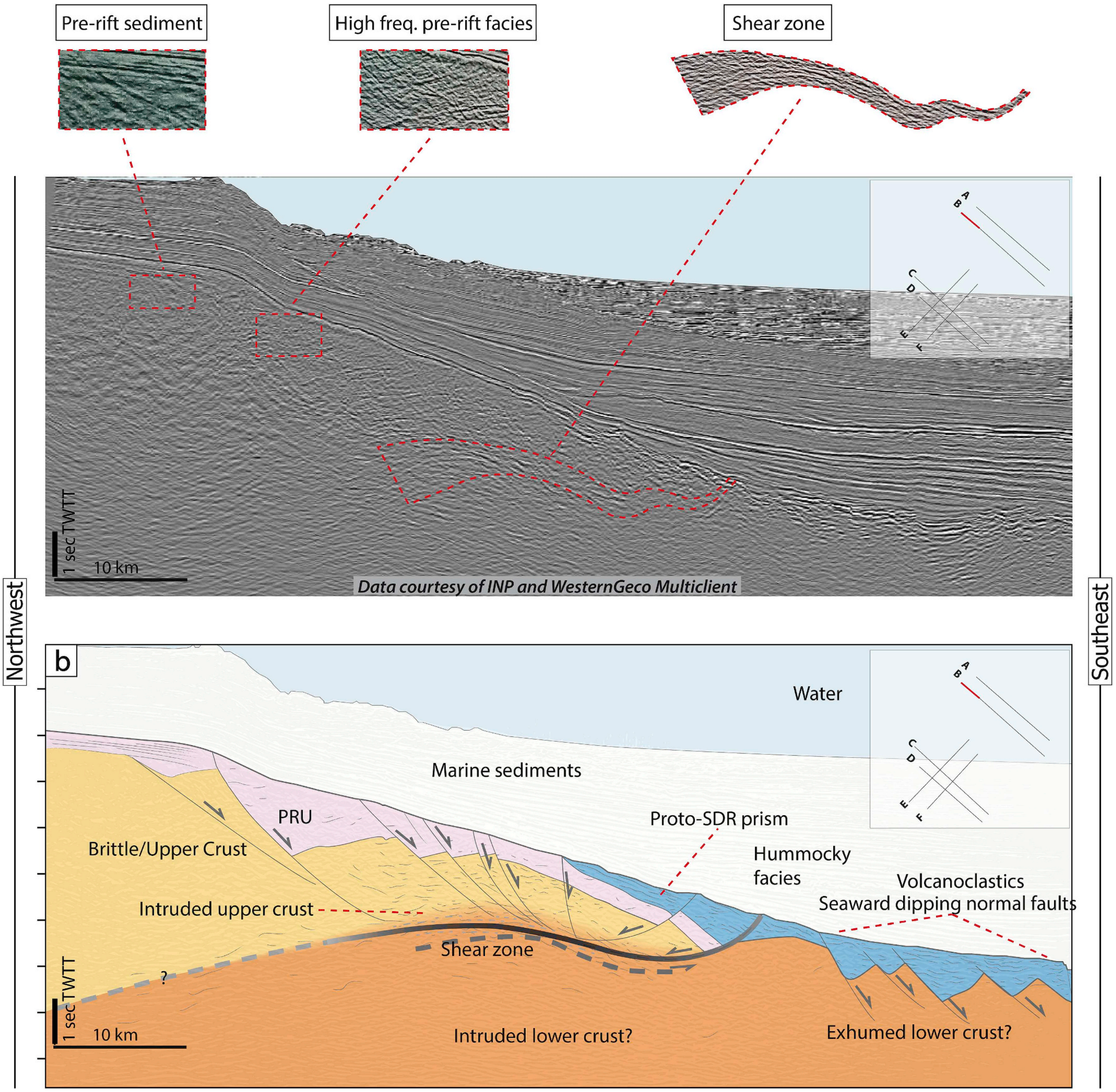


Fig. 6. (a) Line drawing and structural interpretation of the proximal zone of profile B (location shown by red coloured area in inset profile map). The uppermost acoustic basement in the most proximal zone is characterised by parallel, high frequency reflectors likely to be pre-rift sediments (top inset). These reflectors are less coherent basinward (top inset) and are affected by a network of normal faults which appear to root into what looks to be an intracrustal shear zone (top inset). (b) Interpretation of the proximal zone of profile B. PRU: Pre-rift sedimentary unit. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

remain under-developed when compared with the SDR observed on profile A (Fig. 3a, inset). Southeast of the emergence of the shear zone we observe a basement geometry which is reminiscent of that seen in profile A where volcanic material, characterised by semi-continuous reflectors, overlies a faulted basement in a zone where the tendency for continentward dipping faults is inversed (Fig. 6a).

4.2. The Beira High

Located offshore in the region of the Zambezi Delta, profile C is oriented northwest-southeast, perpendicular to the Mozambican coastline (Figs. 1c and 2). The location and orientation of profile C is such that it intersects the Beira High across its width (Fig. 1b). The Beira High is identified as the bulge in the top acoustic basement between approximately 45 and 195 km along profile C (Fig. 7a).

4.2.1. Sedimentary cover – Profile C

The thickness of the sedimentary cover in profile C is greatest in the most proximal area - between the Beira High and the coast (Fig. 7a). This appears to be due to the presence of the Zambezi Delta as well as significant subsidence in the area of the Offshore Zambezi Depression (Mahanjane, 2012). We estimate the thickness of the sedimentary pile

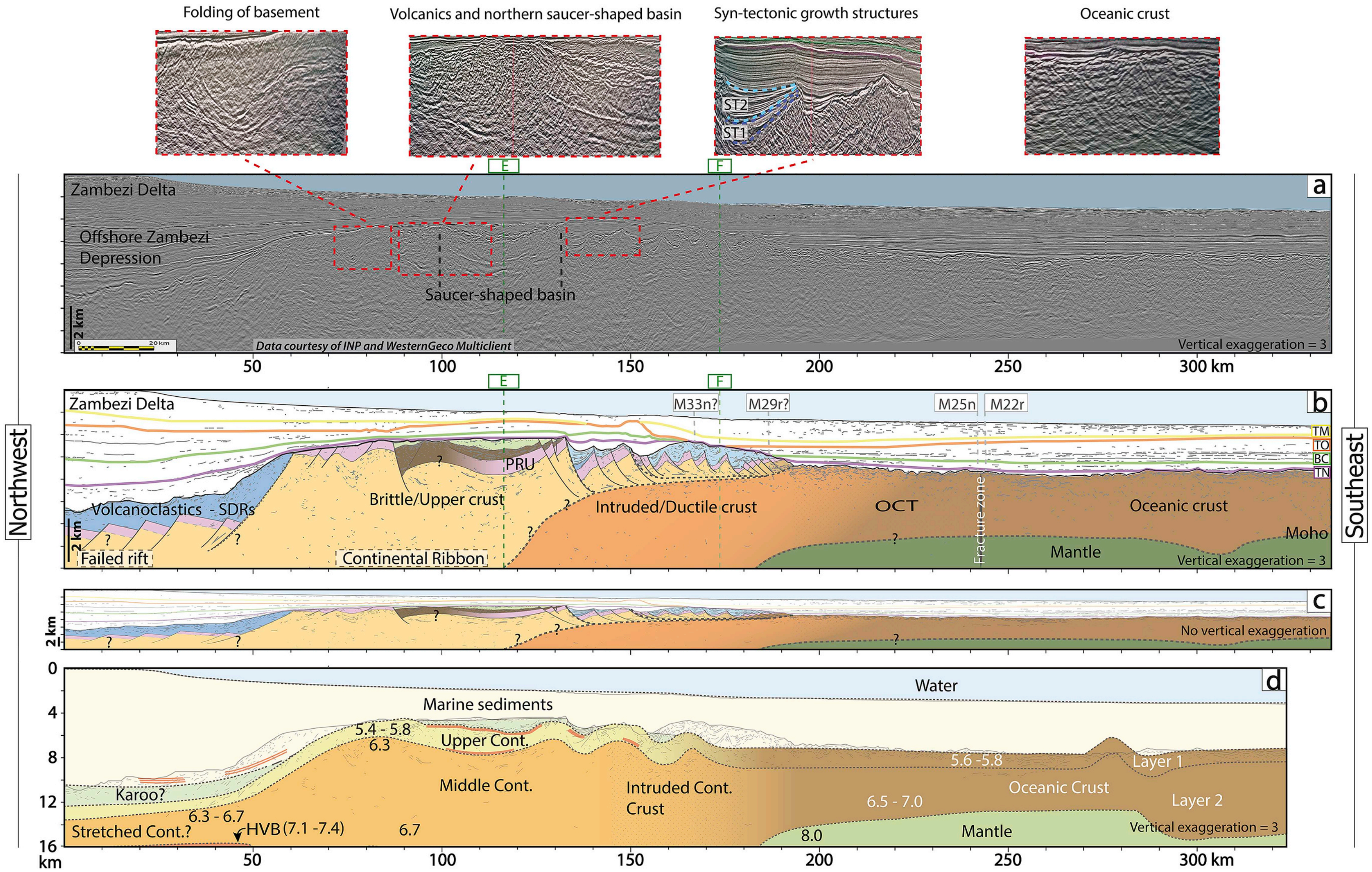


Fig. 7. (a) Line drawing and characteristic seismic facies of profile C. The Beira High is the bulge in the top acoustic basement from around 45 to 195 km. Intersecting points with other profiles used in this study are shown by green dashed lines and picked isochrons are as in Fig. 3a. (b) Interpretation of profile C showing the Beira High bounded to the northwest by a failed rift as suggested by Mahanjane (2012). Dark blue is the SDR (ST1 unit), the light blue the ST2 unit, in pink the pre-rift unit (PRU), in light green the Evaporitic layer in the saucer shape basin. The magnetic anomalies of Leinweber and Jokat (2012) and Mueller and Jokat (2017) are shown by chrons M33n, M29r, M25n. (c) Interpretation of profile C shown without vertical exaggeration. (d) A projection of the interpreted seismic refraction model of Mueller et al. (2016) onto profile C (see Fig. 1c for profile locations). The numbers are P-wave propagation velocities in km/s. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in the depression to be approximately 9–10 km. From 0 km to 50 km, we observe a series of high amplitude, hummocky reflectors which are semi-continuous. These high amplitude facies decrease in depth and are overlain by high amplitude, parallel, continuous reflectors which terminate in onlap onto the northwest flank of the Beira High between 6 and 9 km in depth (Fig. 7a). This organisation of parallel, continuous reflectors overlying a high amplitude, hummocky facies is interpreted to be the base of the sedimentary column, deposited over volcanic material. This is coherent with the findings of Mahanjane (2012) who identified the presence of lava flows in the Offshore Zambezi Depression. Between 130 and 190 km the deepest sediments exist in the form of syn-tectonic growth structures (Fig. 7a, top inset) which fill a series of half-grabens. The infill in the most north-western half-graben is up to 2 km thick and able to be subdivided into two units with an upper wedge-shaped unit of medium to high amplitude reflectors (ST2) overlying a lower, more transparent unit (ST1) (Fig. 7a, and top inset). From 160 to 190 km, growth structures at the base of the sedimentary column become less well-defined and the top-basement limit is defined by a near-continuous, high amplitude reflector which outlines the upper limit of a series of tilted blocks. The rift fill in this region is of higher amplitude and more chaotic-to-hummocky facies than the more north-western half grabens and likely consists of built-up volcanoclastic material, up to 2 km thick. From 195 km to the southeast termination of profile C, the sedimentary cover is easily distinguished from the underlying basement by the medium to low amplitude, continuous reflectors. The sedimentary cover in this most distal zone of profile C drapes the underlying basement and maintains a thickness of around 4 km (Fig. 7 b).

4.2.2. Basement – The Beira High area

Due to the thickness of the sedimentary cover and the probable existence of underlying volcanoclastic material in the most proximal 50 km, the seismic image provides little information as to the nature and structure of the basement below the hummocky set of reflectors which are found at depths (Fig. 7).

We have defined the northwest flank of the Beira High using a continuous reflector that rises from about 6 to 3 km in depth (from the top of the profile) between 45 and 60 km along the profile (Fig. 7a). It is onto this structure that the oldest sediments onlap and this reflector merges with the summit of the Beira High at around 60 km. Interior reflections of the north-western flank are characterised by medium amplitude, discontinuous reflectors which are oriented parallel to the reflector which outlines the northwest flank. This group of reflectors form a prism which reaches its maximum thickness between 40 and 50 km along the profile and continues below the sedimentary pile merging with the underlying volcanoclastic material in the Offshore Zambezi Depression. We have therefore interpreted this structure as a volcanoclastic prism which overlies the crust of the Beira High. From 60 to around 85 km along profile C the summit of the Beira High rises from 4 km to 2.5 km in depth and the top basement surface is remarkably smooth, suggesting a significant erosional episode (Fig. 7a). The uppermost 1–2 km of acoustic basement in this zone consists of a high frequency, chaotic facies similar to that seen in the proximal zones of profile B (Fig. 6a, inset). This zone shows evidence of continentward-dipping faulting with fault displacement difficult to observe due to the chaotic nature of the facies and the fact that the faults are cut by the top basement erosional surface. The lower limit of the high frequency chaotic facies is marked by a sharp transition to facies characterised by high amplitude, banded reflectors at depths. Between 60 and 70 km the banded facies is affected by the aforementioned faults while between 75 and 80 km, these reflectors define a folded structure (Fig. 7a, inset). Below this banded facies, the basement is characterised by medium to high amplitude, chaotic facies, typical of crystalline crust.

Profile D is oriented parallel to profile C and crosses the Beira High at a distance of around 40 km to the southwest (Fig. 1c). Once again, we observe a top basement erosional surface (Fig. 8). This profile exhibits a marked vertical discontinuity in seismic facies with the deeper, chaotic facies of the crystalline basement overlain by a high frequency, chaotic, low amplitude, parallel facies (Fig. 8). The high frequency facies which forms the upper 0.5 s TWTT of the basement are separated from the crystalline basement by a continuous, high amplitude reflector at 2–2.5 s TWTT from the top of the profile, suggesting a sharp vertical change in acoustic properties and probably lithology. Our observations of low amplitude, parallel reflectors suggest that the upper, higher frequency facies is sedimentary in nature. These sediments show strong evidence of normal faulting which appears to be controlled by crustal-scale antithetic faulting of the underlying crust (Fig. 8), while the absence of growth structures in the sedimentary unit confirms that its deposition occurred pre-deformation and therefore constitutes a pre-rift sedimentary unit (PRU).

In profile C, the top basement of the Beira High continues to show little evolution in relief between 85 and 135 km (Figs. 7a and 10). This portion of the Beira High is delimited by two large normal faults which have an apparent dip to the southeast. To the southeast of 85 km, the seismic characteristics of the upper 4 km of the basement change. We observe a significant increase in the abundance of high amplitude, intra-basement reflectors interpreted as magmatic intrusions. From 85 to 100 km, the upper 2 km of the basement is dominated by a highly reflective and chaotic area which we interpret as a local volcanic centre (Fig. 7a, inset). Other signs of magmatic activity in this zone of the Beira High are found between 100 and 130 km where we observe near-continuous, very high amplitude reflectors between 1.5 s from the top of the Fig. 9 which we interpret as probable lava flows. From 100 to 130 km along profile C, these lava flows (LF in Figs. 9 and 10) appear to be emplaced above the PRU and overlain by a transparent sedimentary prism which may consist of evaporitic material or undercompacted shales (EV? in Fig. 10). These facies all have an apparent upwardly concave appearance giving the impression of the existence of a saucer-shaped basin (Figs. 7a and 9).

Profile E was used to further study the structure of the upper Beira High basement and in particular, the saucer-shaped basin (Fig. 9). Profile E is oriented perpendicular to profile C (Figs. 1c and 7a). A striking feature of profile E is the similarity in appearance to profile C between 100 and 130 km (Figs. 7a and 9). By correlating profiles C and E we are able to show that the pre-rift unit, lava flows, and upper transparent unit lie in a saucer-shaped depression which was caused in part by the existence of a crustal-scale fault, apparent in profile E (Fig. 9). The drag fault exists in a zone showing heavy magmatic intrusion, and is one of a network of faults visible in profile E. A peculiarity observed in profile E is a zone where the pre-rift unit appears to be folded over the crust (Fig. 9).

From 125 to 135 km along profile C, deep normal faults affect and cause noticeable offsets of the PRU, the LF and the EV? units (Fig. 10). From 135 to 195 km along profile C the morphology of the Beira High basement changes significantly from that which is observed to the northwest as the plateau gives way to a faulted upper basement (Figs. 7a, 10 and 11). These faults are characterised by vertical offsets of up to 3 km and have resulted in the formation of tilted blocks and asymmetrical half-grabens. The distance between major faults (and therefore size of tilted blocks) decreases toward the southeast of this zone. This basinward decrease in block-size is accompanied by increased magmatism as indicated by an evolution toward volcanoclastic-type rift-fill and intra-basement intrusion between 160 and 190 km (Fig. 11). In the more north-western tilted blocks we are able to identify the characteristic facies of the PRU which forms the summits of the blocks of this zone (Figs. 10 and 11), however this identification becomes more difficult toward the southeast, possibly due to the acoustic screening effect of the overlying volcanoclastic rift-fill. A structural interpretation of this highly intruded zone has been made which shows the pre-rift unit overlying a highly-faulted crust (Fig. 11). Growth structures in the rift-fill help to define fault planes which root in a highly reflective, banded zone in the basement at a depth of around

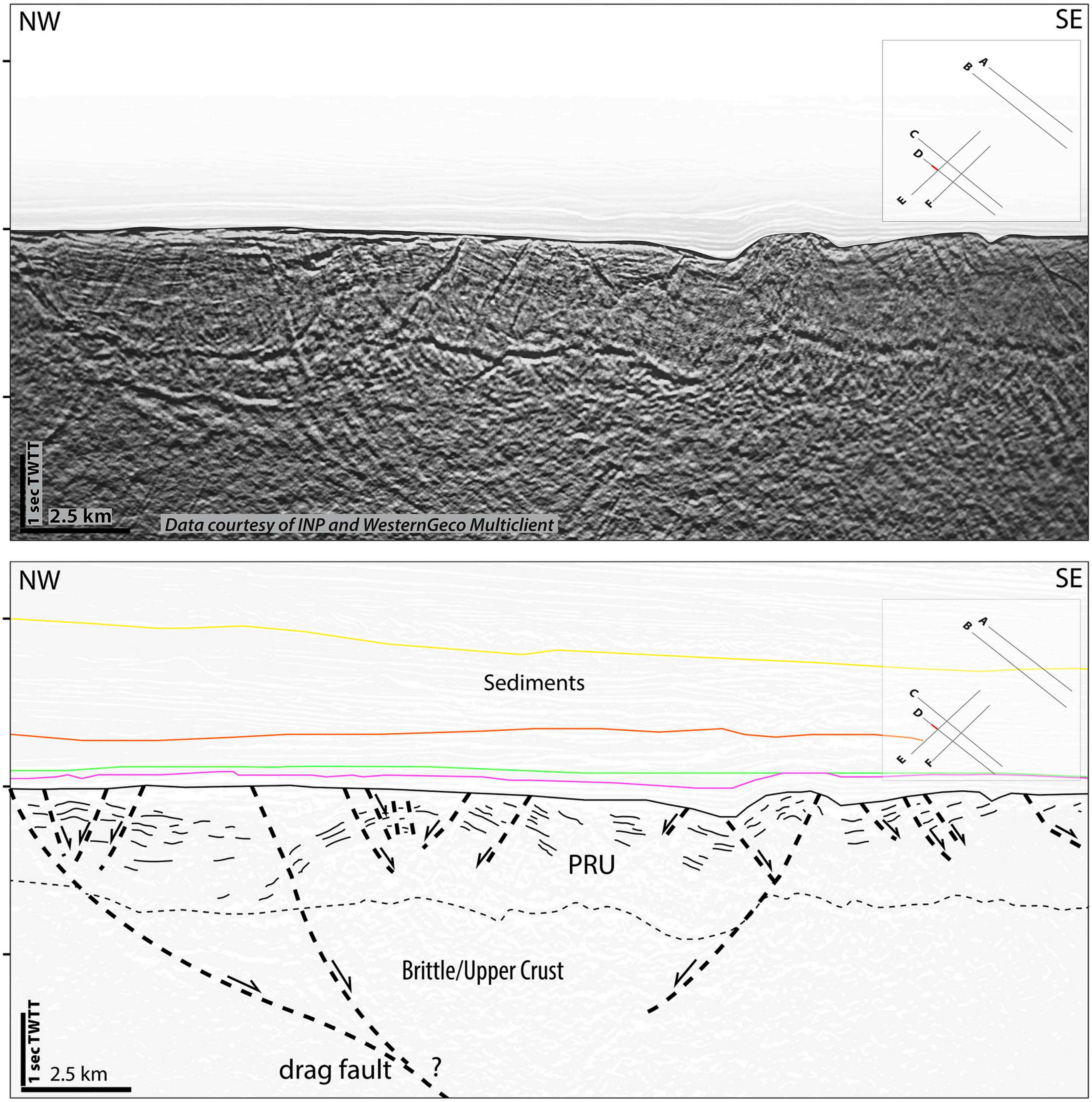


Fig. 8. Profile D – Structural interpretation of the Beira High whose uppermost basement is characterised by high frequency, parallel facies interpreted to be a pre-rift sedimentary unit (PRU). Key horizons as in Fig. 7a. Thick dashed lines are faults, thin dashed line is the base of the PRU.

1.5 s TWTT from the top of the Fig. 11. Below this banded area we no longer are able to observe brittle faulting of the crust in this zone.

Profile F was used to enhance our understanding of the structure of the southeast margin of the Beira High (Fig. 12). Profile F is oriented perpendicular to profile C, intersecting profile C at a distance of approximately 175 km along profile (Figs. 1c and 7a). By correlating profiles C and E we observe what appears to be a fragment of basement material and its PRU which overlies a highly reflective, banded facies at a depth of 2 s TWTT from the top of the figure (Fig. 12).

Southeast of 190 km along profile C we observe little further evolution in the morphology of the basement (Fig. 7a). The top acoustic basement is characterised by an highly reflective seismic facies which are locally hummocky immediately southeast of the Beira High, and probably represents accumulated volcanic material. Beyond 240 km the top acoustic basement is characterised by a highly reflective uppermost layer of around 0.5–1 km characteristic of an oceanic-type crust. The deeper basement is characterised by medium amplitude, chaotic reflections and shows no obvious structuration. In the most distal part of profile C we observe a discontinuous, low amplitude reflector which may indicate the location of the Moho discontinuity (Fig. 7a).

The structure of the north-eastern edge of the Beira High was interpreted using profile E (Fig. 13). This margin is characterised by a chaotic basement facies overlain by continuous, medium amplitude reflectors that dip down onto the footwall of normal faults interpreted as probable SDR. The basement to the north of these SDR is characterised by a layer of smooth volcanic material overlying low

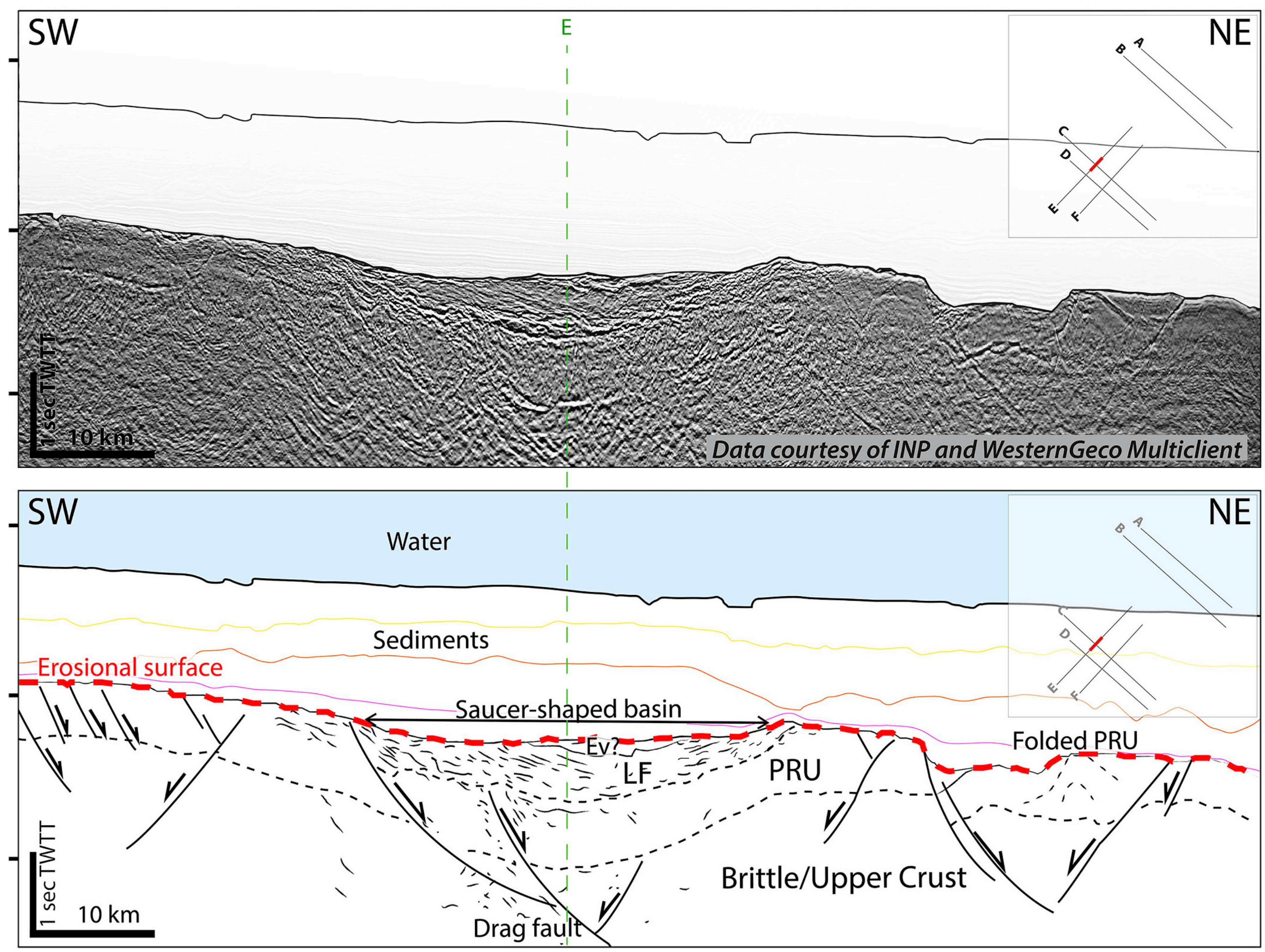


Fig. 9. Profile E – Structural interpretation of the saucer-shaped basin of the Beira High in an along-strike profile. The saucer-shaped basin appears to have a similar geometry in both along-dip and along-strike profiles. The PRU is affected by a crustal scale drag fault. This deformation is associated with abundant magmatism as evidenced by the basin fill consisting principally of lava flows (LF) and the presence magmatic intrusions within the crust. A preserved, ancient fold is seen above a basement block which is affected by normal faulting in the NE of this figure. The green dashed line indicates the point of intersection with profile C. key horizons as in Fig. 7b. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

frequency chaotic facies (Fig. 13). The nature of this crust is not speculated upon here as we have insufficient observations.

5. Discussion

5.1. Structure and nature of the basement

5.1.1. Angoche area

The presence of a PRU is observed in profile B (Fig. 6a), and in profile A (Fig. 3a), and may be ubiquitous along this margin. This PRU appears to be deposited in conformity upon the underlying basement and may belong to the Karoo supergroup observed across much of southern Africa (Johnson et al., 1996). The structural characteristics of the most proximal zones of the Angoche area profiles gives clues as to the nature of this basement. The presence of large-offset normal faults and SDR is a good indicator that the underlying basement consists of extended, upper continental crust (Geoffroy et al., 2015). In profile A, these SDR have been used to interpret the structure of the underlying continental crust in which extension is accommodated by continentward-dipping listric faults (Fig. 3b and c). Profile B shows a similar south-easterly evolution of basement structures with the appearance of basinward-tilted normal faulting at approximately 50 km from the beginning of the profile (Fig. 6a). Profile B also shows that this zone is separated from the zone of listric faulting by an apparent intracrustal shear zone (Fig. 6a and b) similar to those observed in volcanic margins, such as the Uruguayan margin (Clerc et al., 2015), and non-volcanic margins such as the Gulf of Lion (Jolivet et al., 2015) under a high thermal regime. The existence of these intracrustal shear zones is also supported by numerical modelling (e.g. Huismans and Beaumont, 2014). In profile B, the tendency of the listric faults which affect the upper basement and PRU to root into this shear zone suggests that it represents a rheological boundary between brittle upper and ductile lower continental crust (Fig. 6b). The direction of shear, as imposed by fault throws along this shear zone, appears to have resulted in the basinward exhumation of the lower continental crust, forming the basement southeast of the faulted upper continental crust. The thin prism of sediment which onlaps onto the hummocky basement southeast of the SDRs on profile C may be testament to this exhumation as the younger sediments onlap progressively further southeast in a geometry consistent with exhumation of new crust which we propose consists of lower crustal material (Figs. 3b and 4). Uplift of the Angoche margin is likely to have coincided with the exhumation phase as evidenced by the fact that the sediments which onlap onto the proposed exhumed domain were likely deposited coeval with the gravity sliding event which

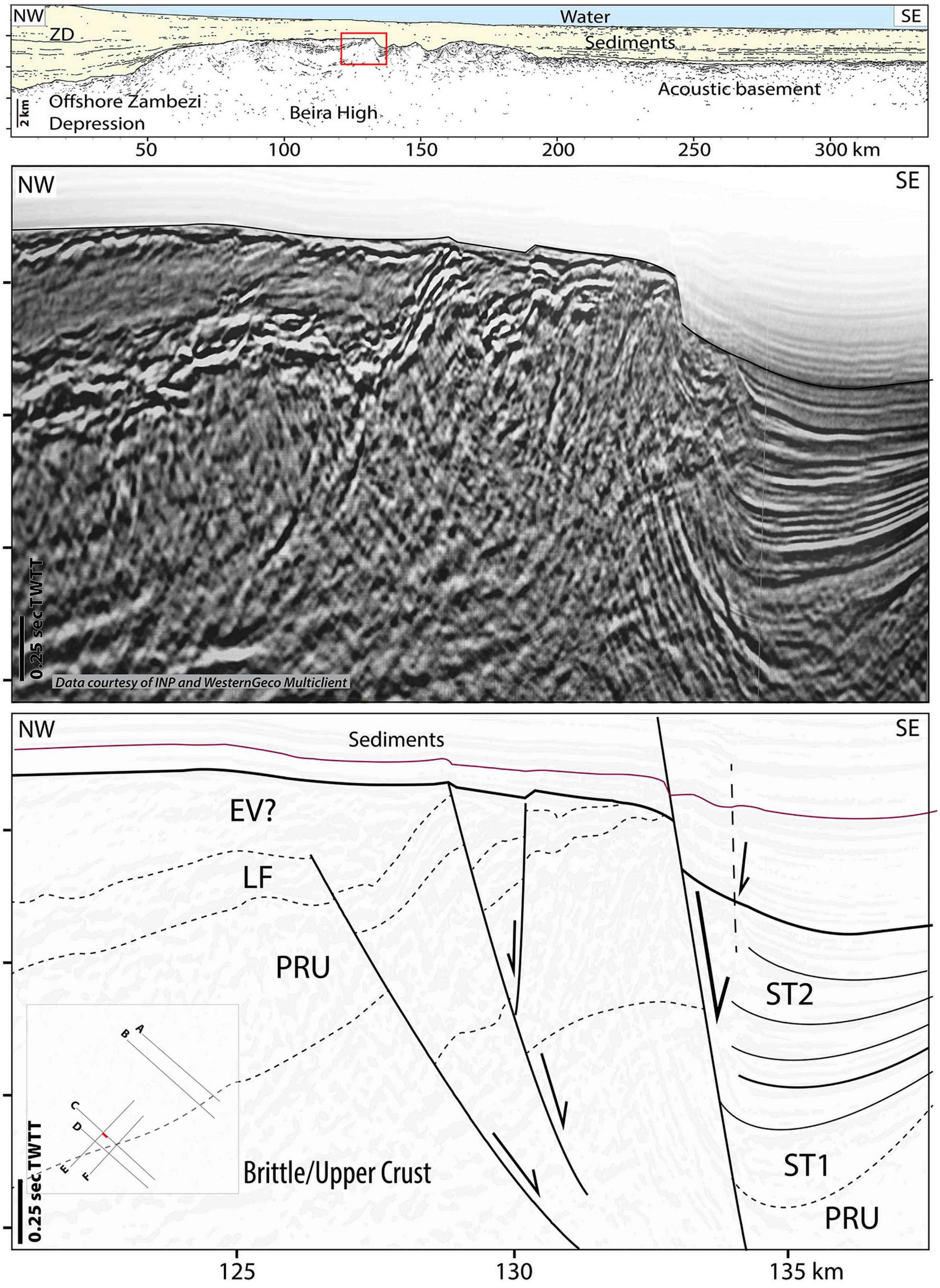


Fig. 10. Profile C – Structural interpretation of the normal faulting which affect the southern extremity of the Beira High plateau. The Top panel show the entire profile. The middle panel, the seismic profile with the sedimentary cover masks by a transparency colour. This figure shows that the major normal fault which controls the geometry of the syn-rift units (**ST1 & ST2**) is associated with satellite faults which affect the **PRU** as well as the saucer-shaped basin fill consisting of lava flows (**LF**) and an evaporitic or clayey unit (**EV**?). Key horizons as in Fig. 7b. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

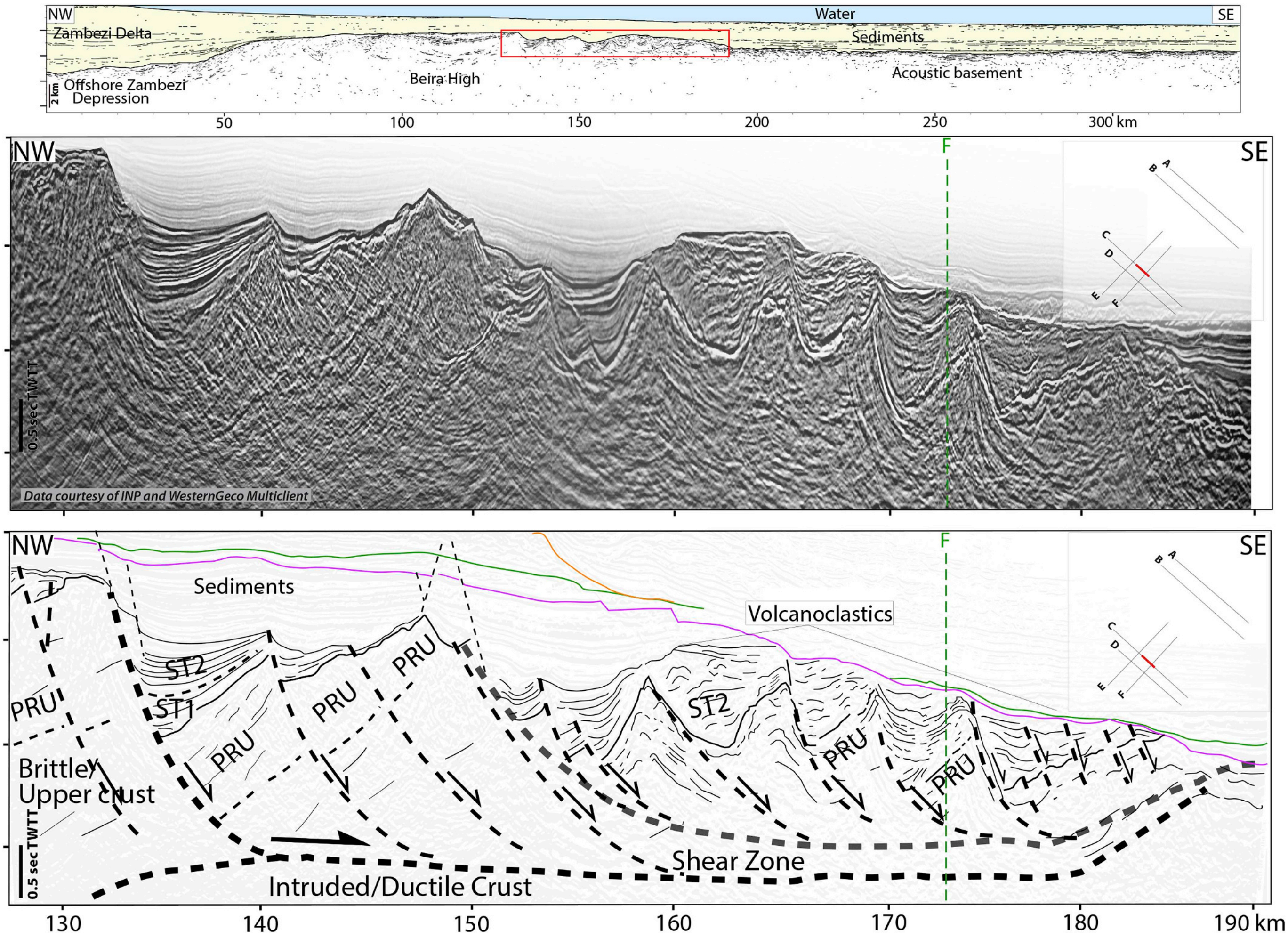


Fig. 11. Profile C – Structural interpretation of the southern Beira High Margin. This zoom shows a series of tilted blocks whose geometries are controlled by listric faulting of the pre-rift unit (**PRU**) and the upper, brittle parts of the crust. These half-grabens are filled by two generations of syn-tectonic sediments (**ST1 & ST2**). key horizons as in Fig. 7.

affected this margin (Figs. 4, 5 and 14).

The small step-like rise in the top basement at 150 km along profile A is proposed to mark a final change in crustal nature, as beyond this point we observe no further faulting of the top basement and near-constant thickness of the volcanic material which forms the top basement in this region (Fig. 3a). The eventual appearance of intracrustal detachments at around 170 km along the profile suggests that this zone represents a transition between the continental and oceanic domains. Due to the difficulty in clearly defining continental and oceanic domains, we propose that the ocean-continent transition (OCT) consists of a proto-oceanic domain formed partly by exhumation and partly by ultra-slow oceanic spreading (Cannat et al., 2009) (Fig. 2b). This style of deformation has already been documented in the magma-poor Australian-Antarctic (Gillard et al., 2015), and Gulf of Lion (Jolivet et al., 2015) rifted margins however, it appears to be a relatively new proposition in magma-rich settings. Despite the well-imaged continental crust shear zones present in the magma-rich Uruguayan margin (Clerc et al., 2015), it remains unclear if the activation of this shear zone has resulted in the exhumation of the lower continental crust or mantle. The location of identified magnetic anomalies (Mueller and Jokat, 2017) have been projected onto our interpretation of profile A (Fig. 3b). We observe that the location of chron M38n is in the area interpreted as exhumed continental crust and probably is related to a volcanism origin, while chron M33n is located at around 220 km from the beginning of the profile, in an area where the seismic facies appears typical of oceanic crust (Figs. 1b, 2 and 3b).

In the absence of dedicated wide angle seismic data, we have compared profile A to the refraction model 20070201 of Mueller and Jokat (2017) (Fig. 3d). Using both land-based and ocean bottom seismometer (OBS) data, the authors constructed velocity and density models of the Angoche margin along a profile that intersects profile A (Figs. 1c and 2). The strong agreement between the two profiles in bathymetry as well as the location and depth of SDR suggest that the profiles are broadly comparable. We observe a large difference in the depth of the top basement and quantity of marine sediments in the northwest of the profile. This may be explained by along-strike variations of the structure of this margin or the presence of a significant quantity of pre-rift sediment as suggested by our interpretation (Fig. 3c). Our profile does not reach depths sufficient enough to allow us to evaluate the morphology of the necking zone, however our interpretation of the basinward exhumation of intruded continental crust appears consistent with the velocity model which suggests similar P-waves velocities in the lower crust and the upper basement from 90 to 150 km along the profile (Fig. 3d).

5.1.2. *Beira High area*

The presence of the Zambezi Delta and a thick layer of volcanoclastic material in the northwest Beira High margin mean that only few coherent reflections are observed in the underlying crust (Fig. 7a). Possible offsets in the upper volcanoclastic material may indicate the

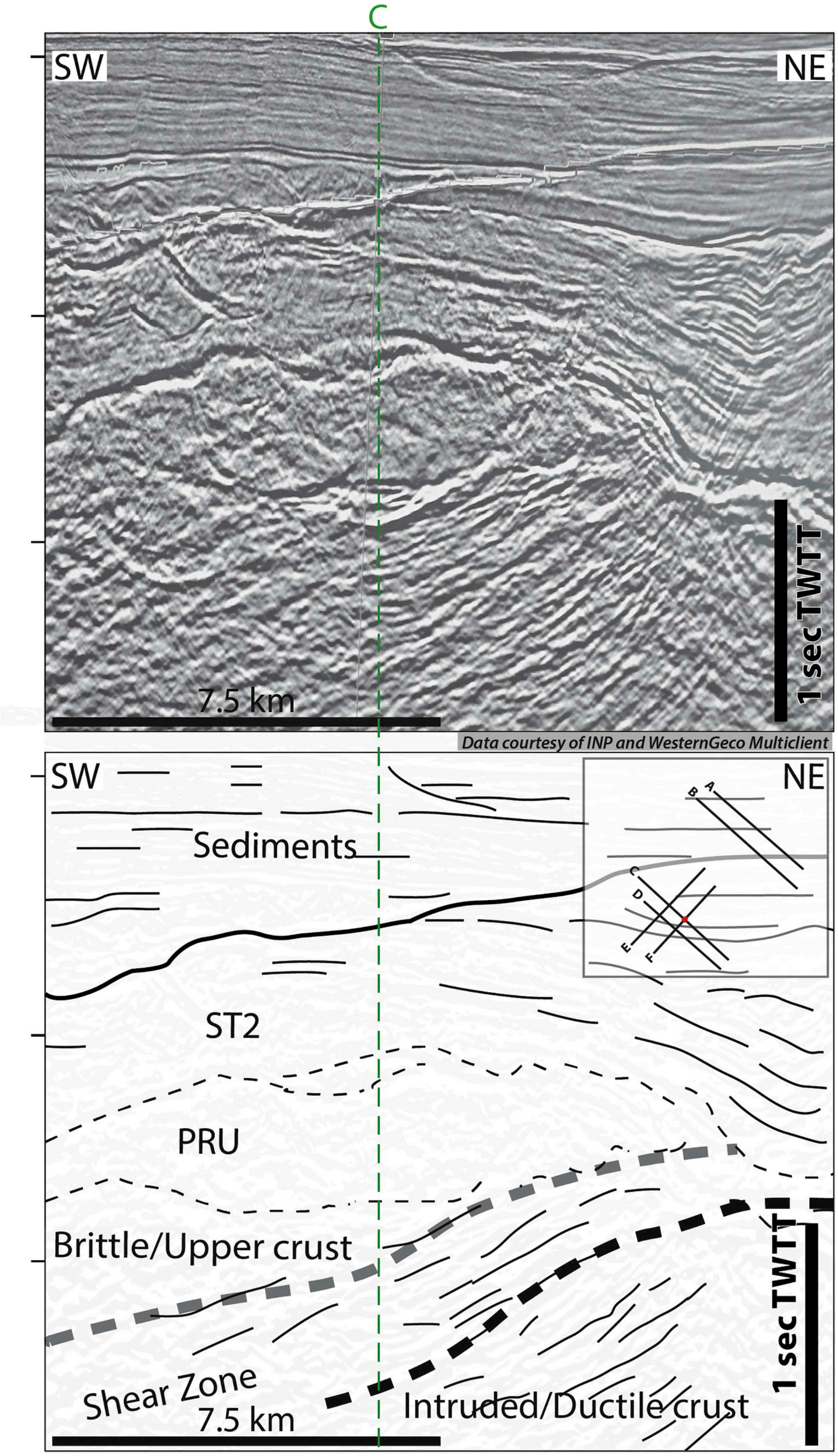
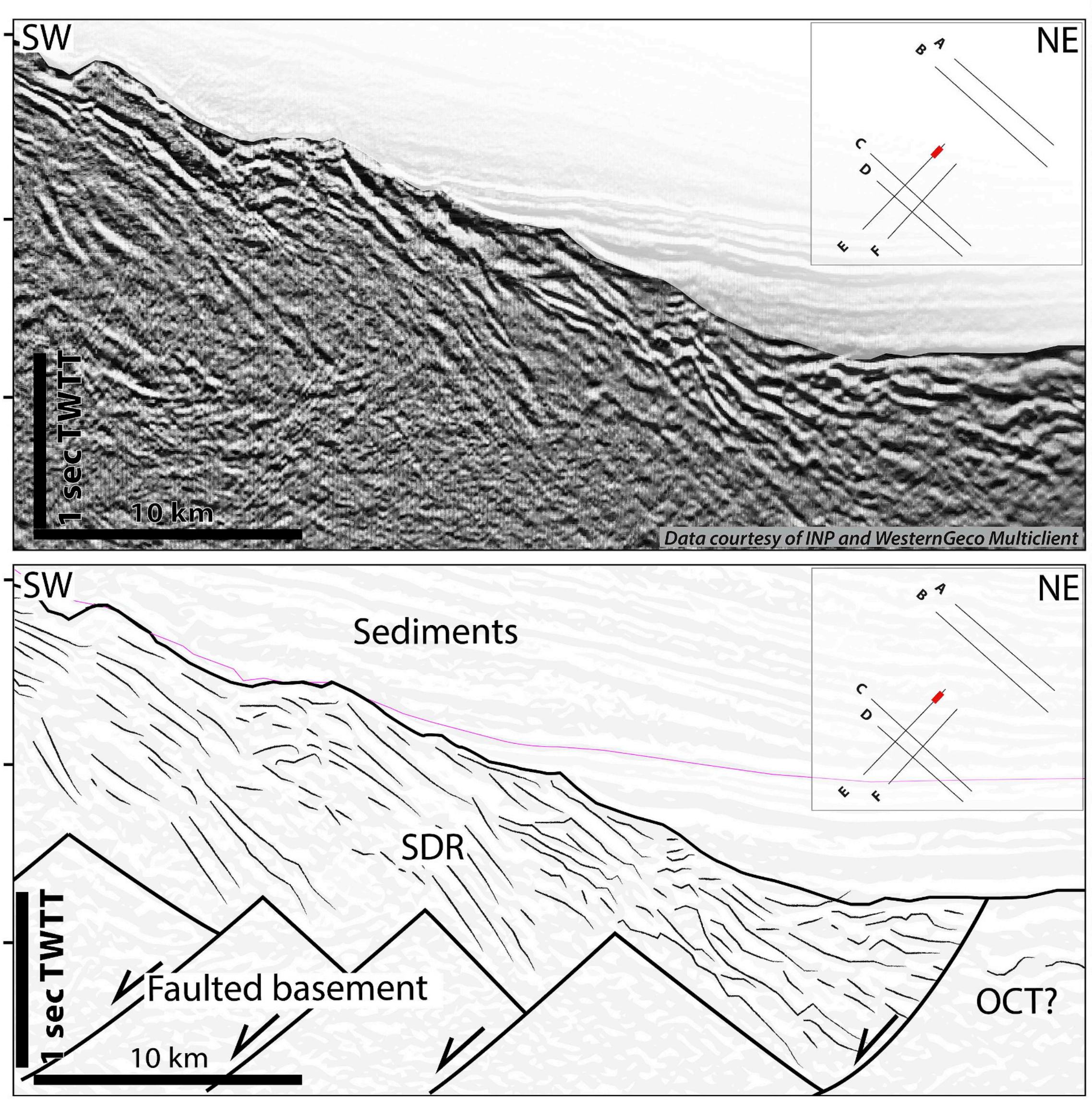


Fig. 12. Profile F – Structural interpretation of along-strike view of a tilted block identified in profile C (Fig. 11). We observe possible boudinage of the PRU and brittle crust over a well-defined and highly intruded shear zone and ductile crustal level.

presence of continentward tilted normal faults in the underlying crust and a very tentative structural interpretation has been made here (Fig. 7b). The Offshore Zambezi Depression has previously been interpreted as a narrow, failed V-shaped rift by Mahanjane (2012), which for the moment appears to be the highest quality interpretation of seismic reflection data in this area. We are unable to confirm or repudiate the presence of stretched continental or oceanic crust in the area of the Offshore Zambezi Depression using profile C alone. Due to the stratigraphic position and abundance of the volcanoclastic material observed in the depression, we believe that the deposition of this unit is related to



Data courtesy of INP and WesternGeco Multiclient

Fig. 13. Profile E – Structural interpretation of the northeast of the Beira High showing SDR formed by volcanic or volcanoclastic material deposited over a faulted crystalline basement. This indicates that this region of the Beira High experienced an extension, likely associated with the rifting episode. The SDR are reasonably well expressed, however extension appears to be attenuated when compared to the structures observed along the southern Beira High margin. OCT: Ocean Continent Transition.

the late-Karoo magmatic episode as in the Angoche segment (Fig. 2) as Klimke et al. (2018) also propose.

The profiles used in this study indicate that the vast majority of the igneous basement of the Beira High is covered by a sedimentary unit which was deposited prior to the break-up of Gondwana - the PRU (Figs. 7b, 8 and 9 & 10). This PRU forms the summit of the Beira High with a highly reflective erosional surface (Figs. 8 and 9) confirming the findings of Mahanjane (2012) who identified this erosional surface as the break-up unconformity (BU) related to the continental rupture of Africa and Antarctica. The existence of the BU across the Beira High infers that the tectonic deformation observed below, across the Beira High, is a record of the tectonic events which occurred prior to the break-up of Gondwana. The characteristic seismic facies of the PRU and the reflective limit which separates it from the underlying crust means that it is a particularly useful tool for analysing the tectonic history of the Beira High. In profile E, the PRU appears to have recorded a compressive phase of deformation, having been folded over the underlying crystalline basement (Fig. 9). In profile C the folded crystalline basement appears to have recorded an episode of compressive deformation which may be associated with inverse faulting of the overlying PRU (Fig. 7a, inset). The relatively sparse number of compressive structures observed, the absence of these structures in adjacent profiles (folding in profile C vs no folding in D), as well as the varying apparent directions of compression, suggests that these structures represent local and not regional tectonic stresses during a complex episode of deformation.

Due to the amplitude of faulting responsible for the creation of the saucer-shaped basin observed in profiles C and E (Figs. 7a and 9, respectively), this tectonic feature appears to be a better representation of regional tectonic stresses during its formation. Profile E shows that this basin likely formed by tectonic subsidence cause by the activation of a crustal-scale drag fault (Fig. 9). The activation of this fault was accompanied by abundant magmatism as indicated by the highly intruded crystalline crust and lava flows which in part fill the basin. To the southwest and northeast of the saucer-shaped basin in profile E, the PRU and upper basement has recorded this extensional phase, showing evidence of normal faulting with smaller offsets (Fig. 9). The presence of large and small offset normal faults in profile E shows that the Beira High has recorded an episode of extension, possibly under a complex

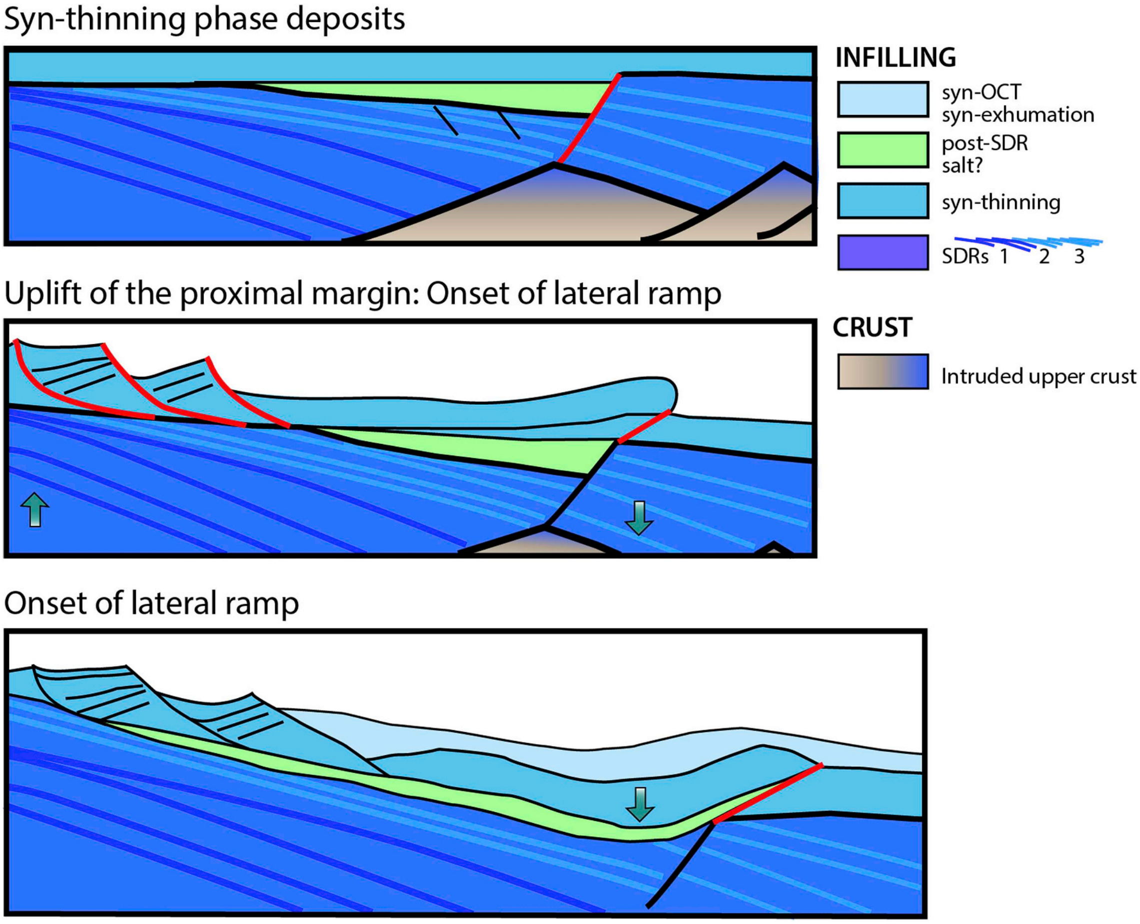


Fig. 14. Sketch of the evolution of the Angoche segment after the SDR emplacement and the syn-thinning phase. The red feature is supposed to be active. The corresponding seismic profile G is shown Fig. 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

stress regime, which occurred prior to continental break-up. The coast-parallel orientation of profile E, as well as the visibility of these faults strongly suggests that they are not directly related to the episode of extension which formed the northern and southern Beira high margins.

When viewed in profile C, the structure of the northwest part of the saucer-shaped basin is unclear due to the presence of a probable volcanic centre (Fig. 7, inset). At its southeast extremity, the saucer-shaped basin is affected by a family of normal faults which have caused a noticeable offset in the PRU and lava flows (Figs. 6b and 10). These faults are of apparent basinward tilt and are the most proximal of the normal faults of the southern Beira High margin (Fig. 10). Their geometry suggests a direction of extension which is approximately in line with profile C, northwest – southeast, while the fact that these faults cause offsets in the PRU, LF and EV? units shows that they were active post-saucer-shaped basin formation. Our observations therefore suggest a diachronism in the major tectonic phases recorded by the Beira High, as well as different regional stress regimes.

The extended southeast margin of the Beira High is complex. The presence of sedimentary growth structures formed by the activation of listric faults is a strong indication that this zone is continental in nature (Fig. 7a (inset) & Fig. 11). It follows that the PRU, present in this area, is observed across the majority of the Beira High, confirming its continental origin. The rift-fill in the most northwest half-grabens shows the clearest growth structures where we observe two units defined by different seismic facies (Fig. 7a, inset). It is within these structures that Mahanjane (2012) also identified two distinct syn-rift phases with a thinner, chaotic phase being overlain by a thicker coherent phase. These two units have previously been identified and linked with successive phases of tectonic deformation using their respective geometries (Mahanjane, 2012). Profile C does not show any evidence of angular unconformity between these two syn-rift units, however the earliest phase was only observed by us in the most north-western half-graben. We propose that this earliest syn-rift phase (ST1) belongs to an initial extension whose orientation does not significantly differ from the direction of extension which affected the rest of this area of the margin. The basinward evolution to smaller tilted blocks is accompanied by a shallowing of the shear zone into which the listric faults are rooted (Figs. 6b and 11). Due to the fault geometries observed along this margin, the highly reflective zone at the termination of the faults as well as the apparent absence of brittle behaviour deeper than this zone, we propose that this shear zone represents a ductile-brittle rheological boundary of the continental crust. Magmatism played a greater role as extension of the continental crust was localised in the southeast of this margin, as indicated by basement intrusion and volcanoclastic-type rift-fill (Figs. 6b and 11). We have interpreted this part of the margin as highly extended continental crust with extension being accommodated by brittle faulting in its uppermost region and by ductile flow and magmatic injection below the brittle-ductile boundary. A similar deformation style is thought to have occurred in the Pyrenean, hot paleomargin (Clerc and Lagabrielle, 2014). This particular style of deformation involves a high geothermal gradient, allowing for crustal thinning via rheological weakening and *ductilisation* of much of the continental crust.

At around 190 km along profile C the nature of the crust changes as this marks the southeast limit of faulted blocks (Figs. 7b and 11). This point also corresponds to the area where the shear zone intersects the top basement. The location of the onset of oceanic spreading is difficult to interpret along profile C and the magnetic anomaly data of Leinweber and Jokat (2012) is invaluable. The magnetic anomalies mapped by these authors have been plotted on profile C and shows that both chrons M33n and M29r fall in a domain that this study interprets, based on seismic data, as continental in nature (Fig. 7b). The anomalies observed at this location maybe due to the significant quantities of magmatic material we observe here. Chron M25n (156Ma) appears to be the best candidate for the oldest magnetic anomaly of oceanic origin to the south of the Beira High and is located in immediate proximity to a fracture zone which juxtaposes oceanic crusts of different ages along profile C (Fig. 7b). This means that the area of the crust which lies between 190 and 240 km in profile C is an OCT of indeterminate nature. The throw of the faults and the presence of an intracrustal shear zone in the southeast Beira High margin suggest the underlying material has flowed in a ductile manner toward the basin and is likely to be highly intruded. 1D velocity profiles in the vicinity of the southern Beira High margin (Mueller et al., 2016) rule out the presence of serpentinised mantle and we therefore propose that the OCT is composed of extended, ductile continental crust, injected with magmatic material. Lateral extraction of the continental crust in a hot passive margin setting is supported by the work of Clerc and Lagabrielle (2014), while the OCT of the southeast Beira High margin may resemble the East Greenland volcanic rifted margin where continental rupture occurs when continental crust dilation due to magmatic injection reaches 100% (Klausen and Larsen, 2002).

To gain further insight into the structure and nature of the Beira High as well as the Offshore Zambezi Depression and Mozambique Basin we have compared profile C with the interpreted wide-angle seismic data of Mueller et al. (2016) (Fig. 7d). Using OBS data, the authors constructed velocity and density models along a profile which intersects profile C at a distance of about 110 km along profile – in the area of the saucer-shaped basin (Figs. 1c and 2). The profile of Mueller et al. (2016) is of slightly different azimuth to profile C and so has been projected onto our profile. The area of the Offshore Zambezi Depression shows strong similarities between the two profiles with the wide-angle data also identifying a deep sedimentary layer and lava flows (Fig. 7d). The question of the exact nature of the underlying crust however, remains unanswered. In the central regions of the Beira High, the location of the top basement, the transparent sedimentary unit, and lava flows/magmatic intrusions are all in strong agreement. The interpretations vary however when it comes to the nature of the unit which forms the summit of the Beira High, interpreted by the authors as upper continental crust. Our data show that this unit shows evidence of bedding planes and we believe probably consists of highly compacted, Karoo-group sediments. The refraction data suggests the continuity of this unit in the southeast margin of the Beira High, with a morphology that loosely conforms to our observations. The absence of volcanoclastic rift-fill in the distal part of the margin could suggest that this magmatic event is localised, however both interpretations agree that this part of the margin has experienced a significant amount of magmatic intrusion. Mueller et al. (2016) have interpreted a sharp continent-ocean boundary at the southeast limit of the intruded crust, where the top basement shows little further evolution in relief. The point on profile C where the top basement shows little further evolution in relief occurs at around 190 km (Fig. 7). We believe that the intracrustal shear zone observed in this area is more compatible with an extended OCT. This hypothesis is also supported by the magnetic anomaly framework of Leinweber and Jokat (2012) who interpreted Chron M25n to be the oldest magnetic anomaly of oceanic origin on the conjugate Antarctic margin. Our interpretation of profiles A and C have allowed us to propose an updated structural map of the crustal domains of the Central Mozambique margin (Fig. 2).

5.2. Correlation between the Beira High and Angoche profiles

The absence of a syn-deformation chronostratigraphic framework along the margin makes correlating the tectonic events in the Angoche and Beira High zones difficult. The identification of the Beira High as a continental fragment means that the tectonic histories of the Beira High and the Angoche area margin are inextricably linked. A feature common to both zones is the presence of an eroded PRU which overlies the crystalline basement, and shows evidence of stratification. We propose that the PRU observed in both areas of the margin are equivalent features, likely to be ancient, Karoo sediments.

5.3. Reconstruction of early African and Antarctic relative plate motions and tectonic evolution

Combining our observations with existing published data has allowed us to propose a continental break-up scenario (Figs. 15 and 16) which resulted in the emplacement of the Beira High continental fragment as well as the formation of the Central Mozambique margin. For the reconstruction, we choose to take the Gondwana fit proposed by Thompson (2017), which is not too far from the Nguyen et al., 2016 fit used by Klimke et al., (2018). They propose that Antarctica initially moved away from Africa in a WNW-ESE direction between 184 Ma and 171 Ma before this direction changed to SSE post-171 Ma. Despite uncertainties in precise extensional directions and timings, our observations across the Central Mozambique margin appear coherent with these models in that two separate phases of deformation are observed (Figs. 8–10).

5.3.1. Stage 1: initial deformation of the Beira High (late-to-post Karoo) - pre-rift stage

Stage 1 represents the earliest relative movements of Africa and Antarctica and is proposed to begin during the Late Karoo volcanic episode (Lebombo and Mateke Sabi monoclines, Jourdan et al., 2007) (Fig. 15). One of the way to observe the complex extension and compression of the Beira High fragment which deforms the pre-rift units and results in the formation of the saucer-shaped basin (Figs. 9 and 16e) is in a strike-slip zone. As Cox (1992), Reeves et al. (2016) Nguyen et al. (2016) who proposed a two-stage plate motions model in which Antarctica initially moved in a northeast direction relative to Africa, we propose a strike-slip movement along the proposed inherited Lurio-Pebane shear zone in the Mozambique belt around 182 Ma (Klausen, 2009) (Fig. 1c, b, 15, 16a & 16b). It has been argued that a spreading centre could be associated with this movement, oriented NS to form the Lebombo monocline (Fig. 1c) Mozambique Coastal Plains and Limpopo Basin (Cox, 1992; Klausen, 2009). We propose that the strike-slip movement is responsible for the formation of deep basins in Limpopo plain and that similar tectonic features to the east of the Mozambique Belt may have resulted in the synchronous opening of the Rovuma and Mandaya Basins (Fig. 15). The Mozambique belt is supposed to have an initial thickness of at least 30 km in accordance with gravity studies in the area (Gwavava et al., 1992).

5.3.2. Stage 2: rifting along the Beira and Angoche segments (Dogger?)

The Angoche area margin was formed during the final phase of separation of Africa and Antarctica as shown by the magnetic anomaly data of Leinweber and Jokat (2012) and Leinweber et al. (2013) which shows the existence of margin-parallel magnetic anomalies in the offshore domain (Fig. 1b). We propose that a local stress field rotation caused the principal axis of extension to be oriented NNW-SSE and resulted in the initial separation of Antarctica and Africa along a segmented margin which forms, more or less, the modern day African coastline with a transfer zone separating the Angoche and Beira High

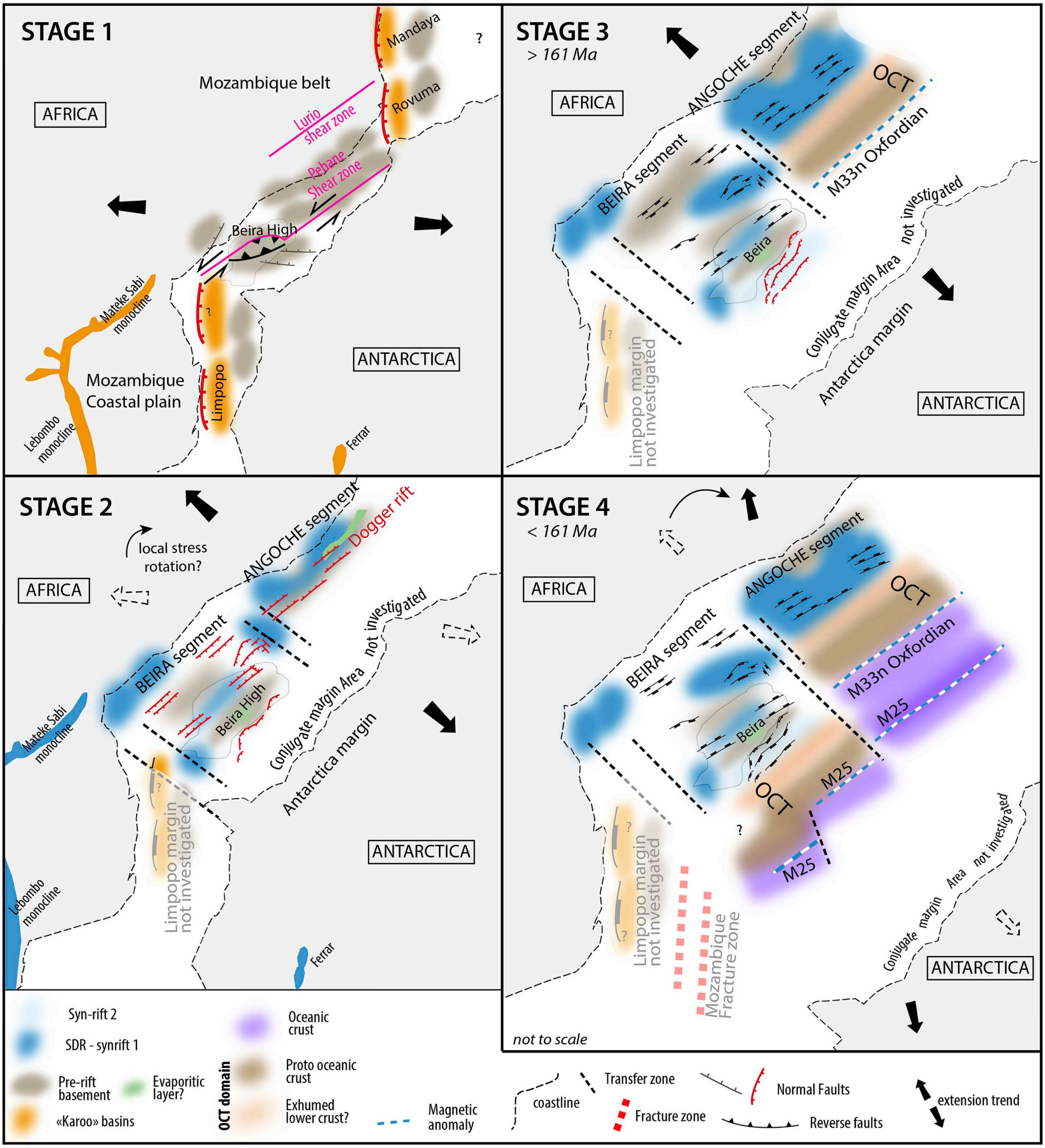


Fig. 15. A conceptual reconstruction of the Africa and Antarctica relative plate motions (Africa fixed). Our reconstruction based on the Gondwana fit from Thompson (2017) proposed a first strike-slip movement along the Lurio-Pebane shear zone responsible for the deformation (fold-faults) obvious in the Beira High and Angoche basin seismic basement. This movement allows the formation of the Limpopo, Rovuma and Mandaya basins. During this time, the Lebombo monocline and the Ferrar has onset their emplacement. The first stage is compatible with the model of Cox (1992), then we consider the extension trend parallel to the transfer zone, as in oblique rifting context (Leroy et al., 2012; Bellahsen et al., 2013). For the stage 2–4 we focus on the Beira and Angoche segments. See text for explanations and discussion. Note that the Antartica margin is not investigated in the study, as well as the Limpopo and Rovuma margins.

segments (Fig. 15). The transfer zone or accommodation zone is often observed in oblique rifting context that allows the juxtaposition of distinct type of crust (as in the Gulf of Aden, Leroy et al., 2012; Bellahsen et al., 2013). Extension along the Angoche segment causes downward flexing of the upper continental crust as well as activation of the intracrustal shear zone allowing for the extraction of the lower continental crust (Fig. 16b). Shallowing of the hot subcontinental mantle causes the production of large quantities of magma, resulting in

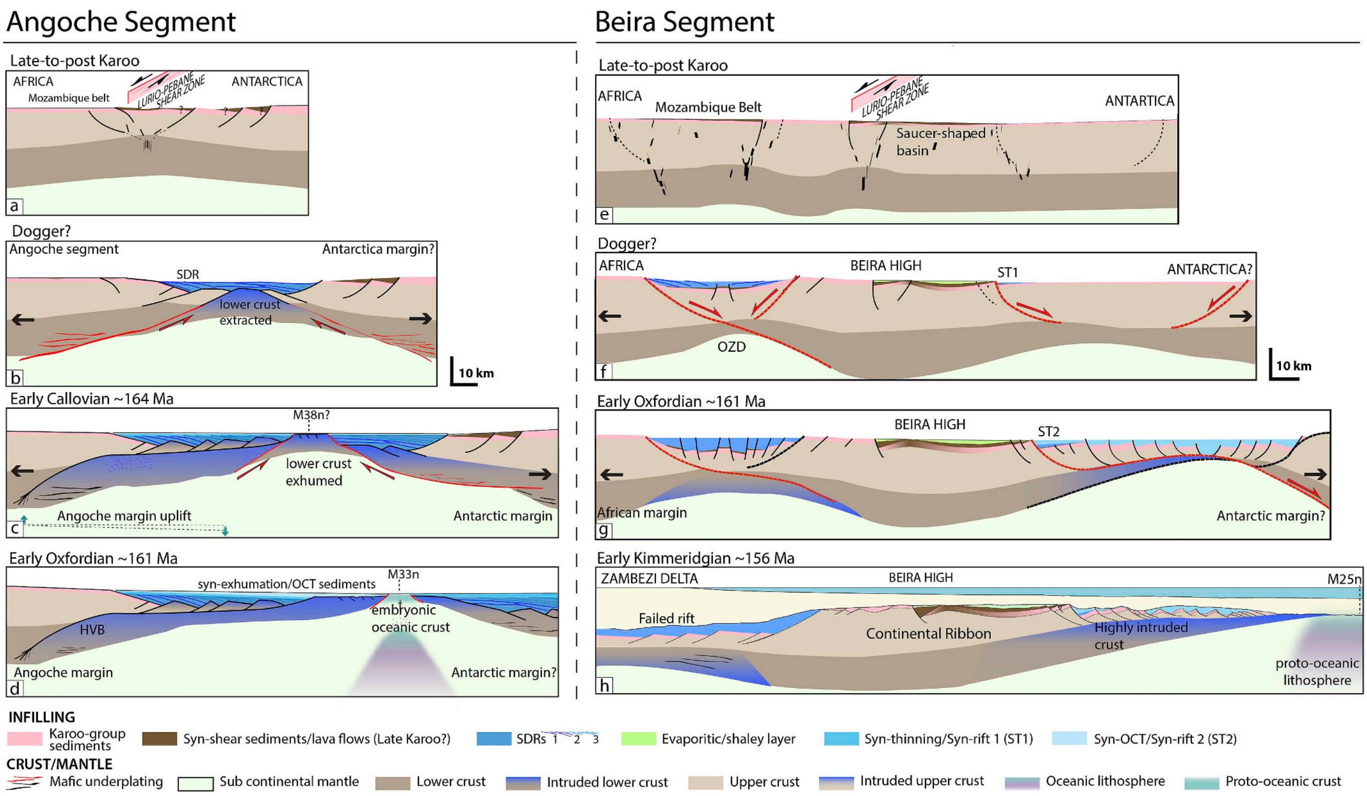


Fig. 16. (a–d) Conceptual model of the tectonic evolution of the Angoche segment from strike-slip deformation during pre-rift time, the magma-rich continental rifting to oceanic spreading. The Angoche segment is characterised by the hyperextension of the upper continental crust and exhumation and intrusion lower crust to form the OCT. The high velocity body (HVB) is after Leinweber et al. (2013) and Mueller and Jokat (2017) and likely consists of mafic underplating. Green arrows represent relative vertical movements of the continental and marginal domains during the early Callovian. See text for discussion of evolution. **(e–h)** Conceptual model of the tectonic evolution of the Beira segment from the initial strike-slip relative movements of the African and Antarctic plates to continental rupture. See text for discussion of evolution. OZD: Offshore Zambezi depression. Note: For both segments, the Antarctic margin is shown for illustration purposes only. Its structure is not constrained by this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

intrusion of the lower continental crust, successive generations of SDRs (as per Geoffroy et al. (2015)) as well as mafic underplating. We interpret the anomaly M38n (Mueller and Jokat, 2017) which is located in the transitional domain in our interpretation of the Angoche segment (Fig. 2; 3b) and suggest that the volcanism observed in this area (Fig. 3a) may be responsible for the magnetic signal. This suggests that the deposition of the oldest sediments in the Angoche area as well as the formation of the SDR occurred prior to 164 Ma, placing this event within the Dogger epoch.

Rifting also begins in Beira segment in a narrow, V-shaped rift (Mahanjane, 2012) accompanied by the effusive volcanism observed in this area (Figs. 6b and 16f). This stage is also characterised by a distributed extension encompassing all the Beira High area. We propose that extension in the Offshore Zambezi Depression preceded the formation of the southeast Beira High margin and was coeval with the initial phases of extension in the Angoche area. This model is supported by the Mueller and Jokat (2017) who argue that the normal polarity of the lava flows observed in the Offshore Zambezi Depression coincides with the inferred SDRs of the conjugate Antarctic margin which may have been emplaced between 166.8 and 164.1 Ma (M39 – M38). Mahanjane (2012) proposed that the Offshore Zambezi Depression was the site of a failed oceanic spreading centre that existed before the localisation of extension along the southeast Beira High margin while Mueller et al. (2016), using wide angle seismic models, were unable to confirm the presence of oceanic crust. Both of these works propose a rift-jump to the southeast Beira High margin upon the failure of the northwest margin rift, in agreement with our observations (Fig. 7b). The beginning of extension is also obvious in the southeast Beira High with the deposition of the first syn-tectonic units (ST1) on the northernmost tilted blocks of the rifted zone (Fig. 3a, inset & 16f). It is likely that the Beira High fragment begins to separate from Antarctica during this stage with extensional features formed along the northeast of the Beira High (Fig. 13).

5.3.3. *Stage 3: margin development*

Stage three is characterised by a continual rotation of the local stress field with the principal extension axis becoming NW-SE in orientation (Fig. 15). The Angoche segment continues to undergo extension with Antarctica moving in a SSE direction with respect to Africa. It is likely that the Angoche OCT begins forming via the basinward exhumation of the lower crust along the intracrustal shear zone early in this stage (Figs. 3b, 15 and 16c). Angoche OCT formation was synchronous with the uplift of the Angoche rift shoulder as observed by the gravity sliding event related to the salt deposit observed in this segment during the deposition of the syn-OCT sedimentary prism (Figs. 1, 4, 5, 13 and 146c). Klimke et al. (2018) with seismic image of lower resolution interpret the area as a deformation zone in both margins.

Failure of the northern Beira High margin rift occurs, extension jumps and becomes localised along the southeast margin with the deposition of the late syn-tectonic phases (ST2) across progressively smaller tilted blocks (Fig. 7a, inset, Fig. 10, 15 & 16g). The continental crust of the southern Beira High margin is hyper-thinned resulting in the shallowing of the sub-continental mantle and the development of intense basal shear heating, mantle adiabatic decompression and magmatic intrusion in the upper crust. The location of the nascent spreading ridge axis in the adjoining Angoche segment margin may have triggered the localisation of continental break-up in the neighbouring, Beira segment (Fig. 16). Structurally, the Beira High now resembles a continental ribbon as described by Péron-Pinvidic and Manatschal (2010).

5.3.4. Stage 4: continental rupture and oceanic spreading (< 161 Ma)

Stage 4 sees the principal axis of extension become N-S in orientation with the southward movement of Antarctica relative to Africa along a major transform fault which is preserved as the Mozambique Fracture Zone and also second-order transform faults (Figs. 1c and 15). Proto-oceanic crust formation (Fig. 16d) gives way to true oceanic spreading with formation of the first oceanic crust of the Central Mozambique margin occurring in the Angoche segment at approximately 161 Ma as recorded by chron M33n (Figs. 1b, 3b and 15). While oceanic spreading has begun in the Angoche segment, it's likely that intracrustal crustal shear as well as magmatic intrusion continue in the southeast Beira High margin until at least 159 Ma (chron M29r). This means that the southern Beira High OCT is likely to have formed by exhumation of the intruded lower crust between 159 and 156 Ma, before the onset of oceanic spreading recorded by the oceanic magnetic anomaly (chron M25n) (Figs. 1b, 7b and 4). The rift jump and localisation of deformation along the southern Beira High margin may be the result of an increase in the local thermal regime caused by the presence of the nascent spreading ridge in the adjacent Angoche segment.

The models presented here may be able to satisfactorily explain the observations made in the course of this study and appears to be in agreement with previous works, we must however note that these results may be also explained by an initial anticlockwise rotation of the Antarctic plate as suggested by Leinweber and Jokat (2012). Depending on the position of the pole of rotation, this could result in a predominantly strike-slip motion in the region of the Beira High, and to a lesser extent the Angoche area. Answers to this question would require a more thorough mapping of the tectonic structures along this margin, accompanied by robust temporal constraints to give a chronological order, and if possible, age of formation.

6. Conclusion

This study has shown that the Central Mozambique margin is characterised by localised magmatism and possesses architectures which are consistent with depth-dependant pure shear extension as well as intracrustal shear zones and may therefore represent something of a structurally hybrid margin. Continental break-up of eastern Gondwana follows a period of intense volcanic activity which marked the termination of the Karoo episode, however, a causal link remains unclear. The multi-channel seismic reflection data has allowed us to build a clearer picture of the structural characteristics and evolution of the Central Mozambican margin and the Beira High. Despite the relatively short distance that separates the Angoche area from the Beira High area, we have shown that the tectonic evolution of these segments differs with the Beira High continental fragment having apparently recorded successive episodes of deformation. We have also shown that the complex tectonic history of the Beira High domain has likely resulted in it being located in the deep-offshore domain, as well as caused a delay in the onset of oceanic spreading in the Beira High segment.

The interpretation of two along-strike profiles located in the Angoche area reveal a hyperextended continental domain. Thinning of the upper crust is accommodated by listric faults of variable geometries, with the activation of continentward dipping faults often providing the necessary tectonic framework for the formation of volcanoclastic SDR, a strong indicator of a magma-rich margin. The normal faults which accommodate crustal thinning appear to be rooted in localised, ductile shear zones, evidenced in the profiles by areas of highly reflective, banded seismic facies. Oceanic domains formed by steady-state accretion have been identified by combining seismic observations and magnetic anomaly data which reveals that enigmatic zones of crust exist between the continental and oceanic domains. These zones are characterised by increased subsidence, an older overlying sedimentary cover and variations in upper basement volcanic facies. These crustal zones are also observed to be in approximate continuity with the aforementioned intracrustal ductile shear zones, and we therefore conclude that they likely consist of areas of exhumed, ductile lower crust as well as proto-oceanic domains.

The southern Beira High margin shares many similarities with the structural characteristics of the more northern, Angoche margins with the presence of a continental crust which has been thinned by listric normal faults which are rooted in a lower ductile shear zone. A high geothermal gradient may be responsible for the creation of an extensive OCT, which we argue consists of laterally exhumed and intruded lower continental crust, as well as a possible proto-oceanic domain. Observations across the length and width of the Beira High reveal that this continental fragment has recorded a series of tectonic episodes that we have related to the earliest relative movements between the African and Antarctic continents. These structures appear to suggest that the north-south relative movement which resulted in the creation of the Mozambique basin was preceded by a complex tectonic phase that has been recorded by deformed basement and pre-rift units. We have shown in this study that this initial deformation is compatible with a left-lateral strike-slip motion along an inherited, crustal scale heterogeneity, such as an ancient shear zone in the Neo-Proterozoic Mozambique Belt however, in the absence of further observations, the kinematics and timing of this initial movement remain an open topic of discussion.

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