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Seismic evidence for crustal architecture and stratigraphy of the Limpopo Corridor: New insights into the evolution of the sheared margin offshore southern Mozambique

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Abstract :

The Gondwana breakup along the Mozambique continental margin caused the formation of extensional and/or sheared margins. One of these sheared margins offshore southern Mozambique, the Limpopo Corridor (LC), is a key area for understanding the evolution of the southward movement of Eastern Gondwana with respect to Western Gondwana. However, crustal architecture and stratigraphy in this area have been inadequately studied, mainly due to the lack of deep seismic data.

In this study, we present interpretations of new multichannel seismic reflection profiles oriented west to east across the LC and Mozambique Fracture Zone (MFZ). Our results show that the basement of the LC is characterized by dipping and alternating strong and weak reflectors, revealing a thick Volcano-Sedimentary Sequence (VSS). To the west of the LC, a marginal basement high zone extends from north to south, consisting of an eroded and fractured VSS. Besides, the acoustic basement is characterized by an eastward dipping or flat VSS in the LC. Sediments overlying the top of the VSS reveal an onlap geometry against the basement high. Five major stratigraphic units (U1-U5) with well-layered sedimentary sequences are mainly constrained from the western boundary of the basement high to the eastern MFZ, and dated to Neocomian, Middle Cretaceous, Late Cretaceous, Paleogene, and Neogene times respectively.

We propose that the VSS in the acoustic basement likely formed in pre-Neocomian time. An uplift event occurred continuously from the Oxfordian-Kimmeridgian to Middle Cretaceous, resulting in a basement high that represents the western limit of the LC. Between this limit and the MFZ, the LC experienced the intracontinental rifting, wrench faulting, and discrepant subsidence associated with the southward strike-slip movement of East Gondwana along the MFZ. The earliest sediments overlying the fractured and deformed VSS consist of a wedge-shaped unit (U1) that deposited along the entire LC during the active transform stage. When the spreading centre passed the adjacent segment of the LC in the Mozambique Basin, the depocentre rapidly shifted to the basin, and the LC entered a passive transform margin stage. We propose that the LC results from three successive stages: (1) intracontinental rifting stage with substantial uplift and erosion, (2) active transform margin stage with strike-slip movement along the MFZ, and (3) passive transform margin with a different sedimentary setting.

Highlights

► New multichannel seismic reflection data crossing the southern Mozambique margin delineate the crustal architecture and stratigraphy. ► The Limpopo Corridor (LC), offshore southern Mozambique margin, evolved in a large shear zone associated with a transform fault during and after the breakup of Gondwana. ► The basement of the LC is characterized by Volcano-Sedimentary Sequence (VSS), not the crystalline basement or oceanic crust.

Keywords : Limpopo Corridor (LC), Sheared/transform margin, Seismic stratigraphy, Basement architecture, Southern Mozambique margin

1. Introduction

Sheared/transform margins, which are mainly controlled by a transform fault during the strike-slip extension, have been distinguished from divergent passive margins (Mascle and Blarez, 1987; Basile et al., 1998; Bird, 2001; Basile, 2015; Mercier de Lépinay et al., 2016; Nemcok et al., 2016). Generally, these so-called transform margins, located at the boundary between two rifted plates, are characterized by sharp necking zones, steep continental slopes, and marginal ridges (Sage et al., 2000; Basile, 2015). In association with continental rifting and oceanic accretion, three stages have been proposed in the evolution of transform margins, including the intracontinental transform stage, active transform stage, and passive transform stage (Mascle and Blarez, 1987; Basile, 2015).

The separation between Eastern Gondwana (Madagascar, Antarctica, India, and Australia) and Western Gondwana (South America and Africa) resulted in the formation of several normal fault-controlled extensional margins (e.g., the northern Mozambique Basin and Somali Basin) and strike-slip fault-controlled transform margins in the East African continental margin (König and Jokat, 2006; Mahanjane, 2012; Klimke and Franke, 2016). These transform margins, linked with three transform fracture zones (Davie Fracture Zone (DFZ), Mozambique Fracture Zone (MFZ), and Agulhas-Falkland Fracture Zone (AFFZ)) offshore the

Mozambique margins record the sedimentary and tectonic events during the development of the Gondwana breakup (Bird, 2001; Mercier de Lépinay et al., 2016; Klimke et al., 2016; Baby et al., 2018; Sinha et al., 2019; Vormann et al., 2020). The N-S oriented DFZ was described as proto-transform faults in the Mozambique Channel, resulting from the southward movement of the East Gondwana plate (Sinha et al., 2019; Vormann et al., 2020). The crustal nature and transform evolution of the adjacent transform margin along the DFZ have been well studied (Seton et al., 2012; Gaina et al., 2013; Reeves et al., 2016; Sinha et al., 2019; Vormann et al., 2020). However, another remnant of the N-S strike-slip movement between the Eastern and Western Gondwana along the MFZ was poorly constrained. Little is known about the crustal architecture and stratigraphy of the adjacent Limpopo Corridor (LC) that fringed by the N–S trending MFZ. Knowledge about the architecture of the LC is crucial as it represents a junction between two regions with different geodynamics: the Northern Natal Valley (NNV) to the west, and the Mozambique Channel to the east (Figure 1).

Understanding the crustal nature of passive margins and continental deformations is also essential to avoid gaps and overlaps in paleo-geographic reconstructions (Thompson et al., 2019; Moulin et al., 2020). Nevertheless, the crustal nature and origin of the LC remain largely enigmatic and controversial because of poor geophysical and seismic data. Combined with observation of an N–S trending positive gravity anomaly similar to the southern Mozambique Ridge (MozR), the LC was proposed to be the northward segment of the MozR with a thickened oceanic crust formed by oceanic spreading (Leinweber and Jokat, 2011). Based on the tectonic reconstruction of the Gondwana breakup, the NNV and the LC were proposed to have been floored by oceanic crust, with emplacement during the opening of the Mozambique Basin (Leinweber and Jokat., 2012; Mueller and Jokat, 2019). However, in the debate about the origin of LC, recent geological and geophysical data seem to favour a continental origin albeit with strong magmatic intrusions underlain the NNV and LC (Hanyu et al., 2017; Thompson et al., 2019; Moulin et al., 2020). Using dense vector geomagnetic anomaly data and satellite gravity data, Hanyu et al. (2017) recently invalidated the existence of the magnetic lineaments in the NNV and interpreted the stretched continental crust with basaltic magma intrusions underlying the LC. A recent seismic refraction study in the NNV was performed as part of the PAMELA (PAssive Margins Exploration Laboratories) project, revealing the continental origin of the NNV and LC (Moulin et al., 2020; Leprêtre et al., 2021; Evain et al., 2021).

In 2016, the PAMELA project acquired 7 multichannel seismic (MCS) and wide-angle seismic profiles in the NNV. The project revealed the continental crustal nature of the NNV and Mozambique Coast Plain

(MCP), and provided crucial information for understanding the development of the transform margin along the LC during and after the Gondwana breakup (Moulin et al., 2020). As a part of this project, we focus on the seismic stratigraphy and basement structure of the LC between 25° S and 29° S in the vicinity of the MFZ. We first present a structural interpretation of unpublished multichannel seismic data crossing the LC and MFZ to determine basement architecture and development of the LC. We reveal the basement deformation and the Neocomian-to-recent sedimentary units along the LC. In addition, investigations of the submerged LC adjacent to a transform plate boundary might indicate early uplift and subsidence deformation during the southward movement of East Gondwana.

2. Background and regional setting

2.1 Geodynamic and tectonic setting of the study area

The breakup of Gondwana resulted in the formation of the East African continental margins (Sahabi, 1993; Konig and Jokat, 2006; Eagles and Konig, 2008; Leinweber and Jokat, 2012; Gaina et al., 2013; Davis et al., 2016; Nguyen et al., 2016; Reeves et al., 2016; Mueller and Jokat, 2019; Thompson et al., 2019). Combined with the different initial configuration of Gondwana, series of kinematic models with the detailed information of early rifting and oceanic spreading phases were proposed (König and Jokat, 2010; Leinweber and Jokat, 2012;Gaina et al., 2013;

Nguyen et al., 2016; Reeves et al., 2016; Mueller and Jokat, 2019, Thompson et al., 2019). Based on these models, the time and direction of early rifting and oceanic spreading phases in the Mozambique Basin are well constrained. Most plate kinematic models rely on the initial breakup of Gondwana along the East African margin took place in the Early Jurassic at approximately 183–177 Ma (Leinweber and Jokat, 2012; Gaina et al., 2013; Nguyen et al., 2016; Reeves et al., 2016). The volcanic Lebombo and Matake-Sabi monoclines, associated with the emplacement of the Karoo flood basalts from 184 Ma to 172 Ma, were concomitant to the onset of Gondwana breakup (Jourdan et al., 2007). Interpretation of the oldest seafloor magnetic anomalies from M38.2n to M25 (164-154 Ma) also suggest that the oldest oceanic crust was diachronously formed in different segments (e.g., Angoche Basin, Beira High, Zambezi Depression) of the Mozambique Basin (König and Jokat, 2010; Leinweber et al., 2013; Mueller and Jokat, 2017, 2019; Thompson et al., 2019) (Figure 1b).

The directions of the earliest rifting and spreading phase are critical to understand the evolution of the Gondwana breakup. The onset of first oceanic crust is dated to 164 Ma (M38.2). Mueller and Jokat (2017) identified the oldest magnetic anomaly and suggested a significant seafloor spreading direction change from NW-SE to N-S in the Mozambique Basin (Mueller and Jokat, 2019; Vormann et al., 2020).

Klimke et al. (2018) proposed the NW–SE directed seafloor spreading was subsequently overprinted by the Late Middle Jurassic N–S-directed strike-slip deformation. Nguyen et al. (2016) suggested a simple NNW-SSE-directed opening of the Mozambique Basin. The NW–SE-directed rifting and seafloor spreading in the Mozambique Basin may have resulted in the initial movement between Africa and Antarctica (e.g., Eagles and König, 2008; Gaina et al., 2013; Reeves et al., 2016), followed by a spreading direction change and N–S-directed strike-slip movement at M26r (~157 Ma) (Mueller and Jokat, 2019). However, On the basis of the continental origin of the NNV, Thompson et al. (2019) suggested a new reconstruction model with a simultaneous N–S direction oceanic spreading in the Mozambique and Somali basins at M25 (~154 Ma). The aborted rift that developed in the Zambezi Depression and the jump of spreading centre to the south of the Beira High may be associated with the spreading direction change (Mueller and Jokat, 2019; Senkans et al., 2019; Vormann et al., 2020).

2.2 The crustal nature of the NNV and MozR

The crustal nature and origin of the NNV and MozR, which origin is either oceanic or continental, considerably impacted the evolution of the LC. The LC, which is located at the easternmost part of the NNV and bounded to the east by the MFZ, is a large N–S trending structure roughly parallel to the MFZ, as shown on the free-air-gravity anomaly (FAA) map

(Figure 1b). To the south, the LC is bounded by AG which divides the LC and MozR into two segments.

The MozR, adjacent to the MFZ, is an aseismic ridge subdivided into several plateaus based on the gravity and magnetic anomaly characters in the southwestern Indian Ocean (Figure 1). With the interpretation of seismic, gravity, and magnetic data from the recent geophysical investigations, König and Jokat (2010) proposed that the MozR was produced as a result of excess volcanism within a short period. Gohl et al. (2011) found evidence of the oceanic origin of the southwestern MozR in seismic reflection and refraction data. Leinweber and Jokat (2012) suggested the MozR formed at different spreading centres during the breakup between Africa and Antarctica with the total magnetic anomalies interpretation. Fischer et al. (2017) proposed a Large Igneous Province origin of the MozR with multiple excessive volcanic eruptions and magmatic accretion phases on the basis of multichannel seismic reflection data. Geological and geochemical evidences indicate the MozR was formed by a mantle plume originating from the African Large Low Shear Velocity Province (LLSVP) (Jacques et al., 2019).

Due to the absence of seismic observations in the NNV, the crustal nature of the NNV is mainly based on weak magnetic anomalies and plate reconstruction models. Green (1972) interpreted the MozR as an N-S spreading centre and proposed the existence of oceanic crust underlying the NNV. Marks and Tikku (2001) suggested an extinct E-W spreading centre in the middle of the NNV based on the recognition of weak magnetic anomalies, implying an oceanic origin of the NNV (Leinweber and Jokat, 2011; Mueller and Jokat, 2019). However, Hanyu et al. (2017) proposed that the NNV is characterized by stretched continental crust with basaltic magma intrusions rather than an extinct spreading centre with clear magnetic series. A 30 km-thick continental crust in NNV and a thinned continental crust in the LC from the first seismic refraction study conducted in the area (Moulin et al., 2020; Léprêtre et al. ,2021; Evain et al., 2021).

3. Data and methods

3.1 Seismic reflection data

In this study, several marine multichannel seismic datasets across the LC were acquired by different institutes. Seismic data along the S01 profile were acquired by the Second Institute of Oceanography (SIO) during a joint scientific cruise in 2016 by using the seismic vessel XiangYangHong No. 10 with a 108-channel streamer (12.5 m group spacing). Four Sercel GII-Guns totalling 1340 cu inches were towed at a depth of 10 m to generate seismic signal. An equidistant shot interval of 50 m and a sampling rate of 2 ms were used to collect the seismic reflection data with a 14 s two-way travel time (TWT) recording length. We also present the interpretation of two multichannel seismic profiles

MZ01 and MZ05, acquired by PAMELA project (Moulin and Aslanian, 2016; Moulin and Evain, 2016), which extend from the Mozambique Coast Plain to the Mozambique Basin, cross-cutting the NNV and LC. The seismic source was composed of an array of 15 airguns, providing a total volume of 6500 cu inches, with a shot interval of 60 s.

Multichannel seismic data acquired by SIO were processed with the commercial software CGG by the China National Offshore Oil Corporation. All major processing steps were applied in the pre-stack domain, and they included amplitude compensation, static correction, bandpass frequency filtering, gain and mute analysis, predictive deconvolution, multiple suppression using Surface-Related Multiple Elimination (SRME) and a filter in the Radon domain, velocity analysis, and residual static corrections. Pre-stack Kirchhoff depth migration was performed on common-offset gathers. Specifically, a migration velocity field based on a residual move-out analysis was generated. After several migration iterations and subsequent CDP stacking, the data were converted back to the time domain and exported to the interpretation system (GeoFrame/IESX TM by Schlumberger). The detailed processing steps of the seismic data from PAMELA project were performed using CGG software. This sequence included external mute of direct and water wave arrivals, large band filtering, predictive deconvolution, resampling, seafloor multiple attenuation using SRME and a High-Resolution Radon

Demultiple process, time-variant bandpass filtering, and pre-stack Kirchhoff migration. Velocity picking was performed after each major processing step to refine the final velocity model and build a coherent pre-stack Kirchhoff time migrated (PSTM) section.

In this study, we present parts of seismic profiles across the LC. The seismic sections of the S01, MZ01, and MZ05 profiles studied in this paper are located on the eastern edge of the NNV, striking W–E and roughly perpendicular to the LC (Figure 1a). Profile S01 is oriented in NW–SE direction. Seismic profiles (MZ01 and MZ05) trend W–E direction from the NNV to the Mozambique Basin (Figure 1a). We show these seismic sections to reveal the basement structures and key horizons, which can be correlated with specific regional events during the evolution of the LC.

The background image of the gravity anomaly is plotted using the 1-min satellite-derived free-air gravity data from Sandwell and Smith (2009) (Figure 1b). The magnetic anomalies are dated from the latest picks of Mueller and Jokat (2019). Additional information from nearby wells in the Mozambique margin and Deep Sea Drilling Project (DSDP) Site 249 are incorporated in this study (Figure 1a). Since no data from offshore drill holes in the LC have been published, we compiled the published seismo-stratigraphic age models in the northern Mozambique margin to define the age of the seismic horizons and units in this study

(Figure 2).

3.2 Geological age constraints for the stratigraphic model

The sedimentary records from Mozambique continental margin consist of two primary sequences: the pre-breakup formation and post-breakup formation (Nairn et al., 1991; Salman and Abdula, 1995).

The rifting and breakup phases of the supercontinent Gondwana are well constrained from the Early Jurassic to Cretaceous in the central Mozambique margin (Cox, 1992; Eagles and König, 2008; Jokat et al., 2003; Nguyen et al., 2016; Reeves et al., 2016). In this study, key horizons from exploration wells X1, X2, and X3 (Jean-Pierre et al., 2018; Thiéblemont et al., 2020) in the central Mozambique margin and the Jc-C1 borehole (Du Toit and Leith, 1974; Hicks and Green, 2016) in the Durban Basin, South Africa are identified for chronostratigraphic interpretation. Scientific well DSDP Site 249 (Simpson et al., 1974) on the MozR recorded a significant tectonic hiatus during sedimentary deposition and current evolution. These wells, ranging from the land to the shelf and abyssal plain provide regional stratigraphic correlation and age constraints for seismic units and unconformities. Previous stratigraphic results from the northern, central, and southern Mozambique margins (Mahanjane 2012,2014; Franke et al., 2015; Castelino et al., 2015; Klimke et al., 2016; Jean-Pierre et al., 2018; Thiéblemont et al., 2020) are also used to constrain the regional stratigraphic framework

(Figure 2). Recent studies have shown the existence of a Contourite Depositional System (CDS) on the MozR (Fischer and Uenzelmann-Neben, 2018) and in the LC (Thiéblemont et al., 2019; Gao et al., 2020).

In this study, we interpret the basement structures and key horizons by comparing the reflection patterns and unconformities identified in previous studies. As shown in Figure 2, five prominent unconformity horizons are labelled R1, R2, R3, R4, and R5, which correspond to the base Neocomian (~145 Ma), top Neocomian (~129 Ma), top Albian (100.5 Ma), top Cretaceous (66 Ma), and top Oligocene (23 Ma) on the Mozambique continental margin (Mahanjane, 2012, 2014; Franke et al., 2015; Klimke et al., 2018; Jean-Pierre et al., 2018).

4. Results

We use the seismic profile S01, oriented in the NW–SE direction (see Figure 1a for the location) with full coverage of the whole corridor, to interpret the seismic stratigraphy and acoustic basement structures in detail. The LC is correlated to an N-S-oriented highly positive free-air gravity anomaly (FAA) (Figure 1b).

The acoustic basement of the LC is characterized by dipping and alternating strong and weak reflectors that are cross-cut by high-angle faults that we interpreted, according to the results of Moulin et al. (2020) in the NNV, as a volcano-sedimentary sequence (VSS). This VSS is present throughout the Natal Valley and the Mozambique Coastal Plain

(Moulin et al., 2020). Three basement domains (A, B, and C) (Figure 3) in the LC are defined according to the different seismic characteristics and geometries of the internal reflectors in these areas. An erosional unconformity R1 with high-amplitude and near-continuous features separates the highly deformed basement and overlying sedimentary units. Five seismic units (U1-U5) overlying the top erosional basement are divided by unconformities and are involved in providing complementary constraints to delimit the spatial extent of the basement domains along the seismic profiles (Figure 3).

4.1 Prominent basement structures

4.1.1Basement domain A

Basement domain A is characterized by a prominent asymmetrical basement high in the western LC, corresponding to an anticline structure that is sealed by a prominent erosional unconformity. Along with seismic profile S01, the internal VSS in the dome-shaped basement high is fractured by an uplift event (Figure 4; distance: 10-40 km). The depth of the top acoustic basement high increases from 3.2 s to approximately 4.8 s TWT (Figure 4; distance: 10-40 km) with a distinct shallow depth along the S01 profile. Local deep incurved strong reflectors are identified at approximately 6-7 s TWT (Figure 4; distance: 20-30 km), possibly corresponding to the basement of the VSS or deep uplifted crystalline crust.

The basement high represents a large anticline structure consisting of several dipping internal reflectors with low, continuous, and strong amplitudes. The VSS dipping direction and fault patterns are different on the west and east limbs of the anticline. On the west flank of the basement high (Figure 4; distance: 10-25 km), the internal westward dipping reflectors are highly dissected by sub-vertical to vertical faults (Figure 4; distance: 10-25 km). On the east flank (Figure 4; distance: 25-40 km), normal faults with a large offset in the asymmetrical basement high cut the eastward-dipping sequence, resulting in several steps in the basement high. The fractured zone on the eastern flank of the basement high delimits the eastern boundary of the basement high.

In the two limbs and top of the anticline, sedimentary sequences have been highly eroded, resulting in top-lapping reflectors truncated against the top of the basement. The uppermost VSS show clear indications of erosion, implying an intense uplift event as the origin of erosional unconformity R1.

4.1.2 Basement domain B

In basement domain B, eastward-dipping VSSs are dissected by several vertical to sub-vertical normal faults and sealed by a relatively flat unconformity R1. The acoustic basement is characterized by discontinuous, dipping reflectors that are cross-cut by high-angle normal faults. The significant dipping reflectors with high amplitudes, low frequencies and low continuity display a clear divergent geometry typical of the VSS. The dipping VSS is sealed by the relativity flat unconformity R1, which is horizontal and undisturbed or only mildly deformed. The depth of the dipping VSS increases from 4.6 s to 6.0 s (TWT) (Figure 5), but the base of the VSS is difficult to constrain due to the increased noise underlying the sequence. The depth of the top of the VSS remains relatively constant and is observed at approximately 4.8 s TWT in section S01 (Figure 5; distance: 50-90 km).

In the western section of domain B (Figure 5; distance: 50-70 km), the relatively strong amplitude and moderate-highly continuous reflectors represent the VSS with a top-lapping geometry under the unconformity R1. Faulting increases to the SE within the profile (Figure 5; distance: 70-90 km), where VSS are characterized by discontinuous and irregular reflectors. Locally irregular, chaotic, and, in places, opaque seismic facies can be observed in the small topographic high (Figure 3; distance: 85-95 km) between domain B and domain C. The small step in the top of the basement at the east side of the topographic high represents the western boundary of basement domain C.

4.1.3 Basement domain C

Basement domain C, located adjacent to the MFZ, is characterized by dipping VSS and vertical faults. The depth of the top of the acoustic basement is deeper than domains A and B. The most striking observation is the folded VSS at top of the acoustic basement in the domain C.

Along the seismic section S01, the top acoustic basement depth in domain C sharply changes from 5.0 s to approximately 6.0 s TWT (Figure 3; distance: 95-130 km), with a notably greater depth than that of domain B. This domain consists of moderate- to high-amplitude, low-frequency, and low-continuity reflectors. Most of the normal vertical faults that fracture the VSS in the basement are sealed by unconformity R1. Several wrench faults penetrate the top of the basement and earliest sediments overlying R1 but are sealed by unconformity R2 (Figure 6; distance: 100-120 km). The fault-bound VSS adjacent to the transform fault may be controlled by strike-slip movement. The wrench faulting activity phase postdates the VSS formation during the drifting stage since the basement, and earliest sediments are deformed by strike-slip faults adjacent to the prominent MFZ.

4.2 Seismic stratigraphy interpretation of profile S01

Five distinct sedimentary units (U1, U2, U3, U4 and U5) overlying the acoustic basement along the S01 profile are presented from oldest to youngest (Figure 2) as follows: U1: Neocomian unit; U2: Middle Cretaceous unit; U3: Late Cretaceous unit; U4: Palaeocene to Oligocene unit; and U5: Neogene unit. The seismic expressions and internal structures of each seismic unit are identified and given in the following section.

4.2.1 Seismic unit U1 (Neocomian)

Seismic unit U1 is characterized by subparallel, continuous reflectors with low and locally medium amplitude reflectors. Sedimentary layers unconformably overlying the top of the acoustic basement exhibit an aggradational stacking pattern. In seismic unit U1, the sediment thickness decreases over the basement high crest, and most reflectors terminate at the top of the basement high with progressively onlapping features (Figure 8; distance: 25-45 km). On the eastern flank of the basement high, U1 consists of eastward-dipping sedimentary layers with a wedge-shaped geometry, and internal reflection is progressively onlapping unconformity R1 (Figure 8, distance: 25-40 km). Due to the variations of the basement topography and the small sedimentary basin along the profile S01, the total thickness of U1 varies from west to east, ranging from 0.6 s to 0 s TWT. The Decrease in the sediment thickness from the east flank of the basement high to the MFZ (Figure 8; distance: 30-80 km) results in the eastward thinning of the U1.

Strong parallel reflectors with divergent patterns are observed downlapping R1 (Figure 8; distance: 45-55 km) at the base of seismic unit U1. A prominently different reflection pattern with more continuous and parallel reflectors is observed in the upper unit of unit U1. This seismic unit U1 thus can be subdivided into two subunits (U1a and U1b) based on the different internal patterns and downlapping characteristics.

The lower subunit U1a which has a typical wedge-shaped geometry is characterized by divergent, moderately continuous reflectors with generally high frequencies, indicating a high-energy sedimentary environment (Figure 8; distance: 30-80 km). The maximum thickness of the unit at the foot of the basement high can reach approximately 0.5 s TWT and gradually decreases eastward. The lower subunit U1a terminates at approximately 90 km, onlapping onto a small topographic rise at the top of the basement. The upper subunit U1b consists of parallel, high-amplitude, moderate- to low-frequency, mostly continuous and eastward-dipping reflectors. The coverage of subunit U1b is wider than that of U1a，extending from the basement high to the MFZ (Figure 3; distance: 30-135 km). The upper subunit U1b immediately overlies subunit U1a (Figure 8; distance: 30-80 km), and the southeast extremity downlaps onto the top of the basement (Figure 9; distance: 90-130 km).

4.2.2 Seismic unit U2 (Middle Cretaceous)

Seismic unit U2, overlying reflector R2, consists of several subparallel, low-amplitude, low to moderate-frequency and generally continuous reflectors. We identify several prominent reflectors that onlap with the eastward-dipping unconformity R2 (Figure 8; distance: 50-80 km). Downlapping reflectors can be observed at the base of the unit in the southeast section of the profile (Figure 9; distance: 110-125 km). The prograding reflectors in this unit occur as mounded zones onlapping and downlapping onto the underlying unit, and transgressed sedimentary deposition can be observed. Wedge-shaped features with internal reflectors are present in this unit. The thickness of unit U2 increases towards the east from 0 s to 0.8 s TWT (Figure 3; distance: 60-135 km)., with a maximum at the southeast edge of the LC(Figure 9; distance: 100-130 km).

4.2.3 Seismic unit U3 (Late Cretaceous**)**

Seismic unit U3 is defined by generally discontinuous reflectors with moderate to high amplitudes and generally high frequencies. Lower reflectors are successively landward onlapping onto the underlying unit or incision surface (Figure 8; distance: 45-80 km). These features form a succession of high-impedance reflectors that exhibit aggradational stacking above unconformity R2 or unit U2. In contrast to the underlying unit, U3 is deformed by numerous sub-vertical faults with small offsets or slight normal slips (Figure 9; distance: 90-110 km). The thickness and seismic facies of U3 show no significant changes associated with the faults. Fault spacing is on the order of a few kilometres, is regular, and does not vary with the strike of the profile, implying a family of polygonal faults.

The total thickness of the unit varies towards the east and increases from 0.5 s to 1.5 s TWT along the whole profile. The top of unit U3 shows a prominent mounded morphology (Figure 9; distance: 100-130 km). Prominent channel incisions are observed at the top of unit U3 (Figure 9; distance: 100-110 km), where multiple mounds are developed.

4.2.4 Seismic unit U4 (Palaeocene to Oligocene)

Seismic unit U4 is characterized by parallel to subparallel reflectors with moderate to low amplitudes from bottom to top. A prominent unconformity R5 coincides with the top of unit U4. The internal reflectors of unit U4 are truncated against the overlying unit. The top reflector of unit U4 cannot be traced in two complex areas of the channel-levee developing system (Figure 8, Distance: 30-60 km; Figure 9, Distance: 95-115 km), where this unit is heavily eroded and replaced by younger sediments. The thickness of this unit in the LC varies sharply after a strong incision, ranging from 0 to 1.2 s TWT.

4.2.5 Seismic unit U5 (Oligocene to present)

Seismic unit U5 varies enormously within the deepest part of the unit and overlies a prominent erosional unconformity R5 that delineates a series of U- and V-shaped channel incisions. The deposits of unit U5 exhibit a highly variable thickness ranging from 0 to 1.0 s TWT in the filled paleochannels. The unconformity R5 truncates the underlying strata, and the young overlying strata onlap the surface.

Multiple irregularly stacked channel-levee systems can be identified in this unit (Figure 8, distance: 30-60 km; Figure 9, distance: 95-115 km), indicating continuous mass transport and complex cut-and-fill processes, and these systems are heavily eroded and replaced by younger sediments. In the lower part of the unit, younger sediments have filled several smaller paleochannels, represented by incision filling with subparallel reflectors onlapping the incision channels. Discontinuous reflectors with high amplitudes are observed onlapping against the unconformity R5 at the base of the unit. However, the upper part of the unit is characterized by relatively transparent and chaotic seismic reflectors with generally low amplitudes. Incisions and associated fills can also be observed, but in contrast to the lower unit, the youngest upper unit, with low-amplitude and discontinuous reflectors, is truncated by the seafloor.

4.3 Basement interpretations of two other profiles cross-cutting the LC

Combined with the interpretation of the basement structure and sequence architecture along the seismic profile S01, we identified three similar basement domains (A, B, and C) along two seismic profiles (MZ05 and MZ01) (see Figure 1a for the location), roughly perpendicular to the LC.

Basement domain A with a prominent basement high is identified in the west section of the MZ05 and MZ01 seismic profiles. The depth of the top basement high in MZ05 increases from 2.8 s to approximately 4.8 s TWT (Figure 10a; distance: 50-90 km). An erosional unconformity R1 seals highly fractured VSS in the basement high. In seismic profile

MZ01, the top basement depth in domain A is found between 2.8 s and approximately 4.4 s TWT (Figure 10c; distance: 280-330 km). The deformed VSS in the basement high is characterized by dipping and low continuity with chaotic and high-amplitude reflectors that are cut by high-angle normal faults. The basement high, characterized by the dome-shaped geometries and a complex distribution of strong reflectors in this domain, represents an elongated asymmetrical anticline, extending from north to south along the western boundary of the LC.

Basement domain B in the MZ05 and MZ01 seismic sections represents a 40-50 km-wide area with a relatively flat reflector at the top of the basement, similar to that of S01. The basement depth is constantly observed at 4.8 s TWT from 90-125 km in MZ05 (Figure 10a) and 4.4 s TWT from 330-380 km in MZ01 (Figure 10c). In seismic section MZ05, the VSS architecture displays a flat geometric feature different from the eastward dipping reflectors in S01. Below the flat top of the acoustic basement, the VSS in the basement is characterized by generally discontinuous and parallel reflectors. In seismic section MZ01, VSS with relatively high reflectivity and low continuity are offset by low-offset normal faults and sealed by unconformity R1.

Similar to seismic profile S01, the top of the basement domain C is defined by a continuous, high-amplitude reflector. The top basement depth is observed from 4.6 s to approximately 4.8 s TWT in the MZ05 seismic section (Figure 10a; distance: 125-150 km). In seismic profile MZ01, the top basement depth varies from 5.0 s to approximately 5.5 s TWT (Figure 10c; distance: 380-420 km). The VSS underlying the top of the basement displays a different architecture than that of section S01 (Figure 10b). The VSS consists of a series of westward-dipping reflectors with continuous, high-amplitude, and low-frequency features, which clearly exhibit a divergent geometry typical of volcanic sequences.

4.4 Mozambique Fracture Zone

The N-S trending Mozambique Fracture Zone, characterized by a long prominent lineament, forms the transform boundary between the LC and Mozambique Basin. The MFZ represents the fossil of an active transform fault during the southward strike-slip movement of East Gondwana.

In seismic profile S01, the MFZ is represented by a prominent submarine escarpment where the water depth drops from 2000 m on the shelf to 4000 m across a 10kmwide zone. A group of faults in the MFZ with a high angle and local branching in a flower-like structure are observed (Figure 10b; distance: 130-140 km). The sediments seal the strike-slip structures at the end of the deformation sequence in the MFZ. The steep continental slope is eroded and devoid of sediments. The FAA varies considerably along the profile and rapidly decreases from positive to negative in the MFZ, corresponding to several steps on the top of the acoustic basement. (Figure 10b; distance: 130-140 km).

In MZ01, the MFZ is characterized by a prominent and highly chaotic topographic high and a strong reflector, representing a seamount associated with volcanic activity (Figure 10c; distance: 415-425 km). However, in MZ05, the MFZ is characterized by a highly uplifted upper acoustic basement with an internally dipping VSS (Figure 10a; distance: 145-155 km), given the interpretation of the small amount of magmatic additions. Similar to seismic profile S01, along the MZ01 and MZ05 profiles, we observe a sharp decrease in the FAA, which may coincide with the location of the MFZ.

5. Discussion

5.1 Basement architecture and early intracontinental deformation of the Limpopo Corridor

This study indicates that the acoustic basement of the LC consists of generally dipping and alternating strong and weak reflectors sealed by a prominent erosional unconformity (Figure 10). According to Moulin et al. (2020), 2 to 3 km of additional volcano-sedimentary layers overlie the crystalline basement, extending into the entire MCP and the NNV. We interpret these layers as VSS in the acoustic basement of LC.

The top of the acoustic basement, characterized by high-amplitude reflectors, is likely composed of lava extrusions related to the Karoo magmatic event (Salman and Abdula, 1995). From the distribution and age of Karoo magmatic rocks in SE-Africa, most of the Karoo basaltic magmatism was emplaced from 184 to 177 Ma (Jourdan et al. 2008), which resulted in the Karoo flood basalts in South Africa (Figure 11). Senkans et al. (2019) suggested that the Karoo continental flood basalts in the central Mozambique margin are linked to the early stage of rifting phase (~180 Ma). Mahanjane (2012) identified lava flows offshore Zambezi Depression (ZD); these flows were associated with thick volcanic dikes emplaced before the Mid-Jurassic. Several exploration wells have encountered the Stormberg volcanic series in the MCP (Figure 11) that were proposed to be of Mid-Jurassic age (Du Toit et al., 1997). However, the earliest marine sediments unconformably overlying the top basement are of Neocomian age (Salman and Abdula, 1995). The presence of Karoo basalts or VSS formed at Mid-Jurassic age of this underlying layer therefore implies a large sedimentary gap of approximately 30-25 Ma in the LC, NNV, and MCP, which can be explained by uplift and erosion Alternatively, the VSS must be an early pre-neocomian volcano-sedimentary deposit.

According to wide-angle data (Moulin et al., 2020), the continental ocean boundary is located at the limit between the NNV and the Southern Natal Valley (SNV), south of the Naude Ridge (NR) (Figure 11), in accordance with the results of geomagnetic sea surface vectors study (Hanyu et al., 2017). The final P-wave velocity model of the profile MZ7 (see Figure 1a for the location) an reveals an abrupt necking zone at the transitional zone between the NNV and the SNV, which shows that the continental ocean boundary is located south of Naude Ridge (Leprêtre et al., 2020, accepted), in accordance with the results of geomagnetic data (Hanyu et al., 2017). The onset of oceanic spreading in the SNV started at approximately 135 Ma, when the Patagonia plate moved to the west during the opening of the Austral segment of the South Atlantic Ocean (e.g., Goodlad et al., 1982; Baby et al., 2018; Thompson et al., 2019). The Outeniqua rift basins, located at the southern tip of the African continent and limited to the south by the AFFZ, consist of the Bredasdorp, Pletmos, Gamtoos, and Algoa basins (Figure 1) that are characterized by hemi-graben-style rifts are separated by fault-bounded basement arches composed of Cape Supergroup metasediments. The oldest dateable sediments drilled in the Outeniqua rift basins are from the Kimmeridgian/Oxfordian (155-160 Ma) and associated with terrestrial or proximal marine environments, and sediment deposition ceased in the Late Valanginian (134 Ma) around the period of the opening of the South Atlantic Ocean, in association with the movement of the Patagonian plate along the AFFZ (Dingle et al., 1983; Thomson, 1999; Paton and Underhill, 2004; Baby et al., 2018).

Regarding the LC, we proposed a similar process like in the Outeniqua rift basins (Figure. 1), with the formation of the VSS during the intracontinental rifting stage at the Oxfordian-Kimmeridgian time (Figure 12a). During the intracontinental stage, the LC was likely filled by lacustrine detrital or proximal marine sediments that were from landward areas and transported in the along-strike direction, as proposed along the Côte d'Ivoire-Ghana transform margin (Basile et al., 1998). During the Valanginian time, as a result of global kinematic reorganization (Thompson et al., 2019), the rifting stage ceased in the Natal Valley, similar to the Outeniqua Basins, and seafloor spreading started in the SNV and the South Atlantic Ocean.

5.2 Basement uplift and erosion

Along the western limit of the LC, a prominent basement high with fractured and dipping VSS is observed in basement domain A. (Figure 10). The prominent erosional unconformity R1 seals the VSS and vertical to sub-vertical faults on the top of the acoustic basement. The N-S-aligned basement high (Figure 11) corresponds to the boundary between the NNV and LC, representing the onset of the eastward continental crust thinning (Moulin et al., 2020).

At the active transform stage (Figure 12b,c), vertical movements in the basement domains (A, B and C) resulted in the different geometries of the basement. During the Tithonian-Neocomian, basement uplift and local subsidence deformed the VSS. In basement domain A, the VSS at the top of the acoustic basement had been highly eroded because of the continuous uplift event, resulting in top-lapping VSS that truncate against unconformity R1. A flat unconformity surface in basement domain B is truncated by the dipping and fractured VSS. In basement domain C, the depth of the unconformity R1 is deeper than that in domain B at the rugged top of the acoustic basement.

Associated with one-third of transform margins, a regional flat erosional surface on the accompanying marginal plateaus is common in the sedimentary boundaries that may be resulted from basement uplift prior to strike-slip movement (Mercier de Lépinay et al., 2016; Loncke et al., 2020). After the end of the intracontinental stage, the Côte d'Ivoire-Ghana transform margin was uplifted above sea level for several million years (Basile et al., 1998). Below the entire Demerara Plateau, subaerial erosion of older sediments led to the formation of a flat unconformity (Basile et al., 2013; Mercier de Lépinay et al., 2016). Thermal uplift and the associated subaerial erosion could have helped the formation of the flat surface in the LC. This flat unconformity surface is expected to have subsequently thermally subsided and become overlain by prograding sedimentary wedges (Loncke et al., 2020).

Few evidences of depth-dependent extension have been identified in the transform margin. In this study, horsts and grabens can't be observed in the basement domain B, suggesting that the LC was affected by N-S strike-slip rifting rather than W-E extension (Figure 10). Between the basement high and the MFZ, the fault system in the LC area is different from the characteristic conjugated systems of normal faults in the northern part of the Mozambique Basin. The faults in basement domains B and C, with high-angle dipping and vertical features, delimit the upper crust blocks rotated during the strike-slip rifting stage. This movement was accompanied by basement uplift, especially at the western limit of the LC (Figure 10). The uplift event may remain active until the Neocomian, represented by the tilting VSS truncated by the angular unconformity R1. The sub-vertical or vertical faults are associated with the strike-slip activities during the early development of the LC. Some border fault systems at the west boundary of the corridor are likely related to the right-lateral strike-slip transform fault. The continental breakup decoupling along the LC led to the differential vertical motion on each side of the fault with the uplift of the continental domain, and subsidence of the corridor. Oblique extension across strike-slip faults resulted in different levels of subsidence, such as that observed in the Salton Sea in southern California (Brothers et al., 2009).

During the active transform stage, the active transform fault was likely the boundary of the transform margin and Mozambique Basin. The LC is located at the edge of the transform margin, which may have been highly uplifted and eroded. The top-lapping VSS and high erosion on the top of the acoustic basement represent intense uplift during the active transform stage of the Tithonian (Figure 12b). Thermal heating effect on transform margins could have resulted in marginal uplift when the spreading centre was adjacent to the LC and migrated along the transform fault. Thermal uplift and associated subaerial erosion could have led to the formation of the flat unconformity surface. Another mechanism that may be responsible for uplift at transform margins is the transpression processes. During the active transformation stage, progressive change from the initial strike-slip regime to transpression has been documented along transform margins. However, the uplift zone in the basement domain A is far from the MFZ and the exhibition of the flat erosional surface in basement domain B, thus opposing the transpression hypotheses.

5.3 Evolution of sedimentary infillings in the active transformation stage

The onset of seafloor spreading at the central Mozambican margin is refined to chron M38n.2n (164.1 Ma) (Mueller and Jokat, 2017, 2019). The spreading direction in the Mozambique Basin changed from NW–SE-directed phase of rifting and oceanization to N–S-directed strike-slip movement at M26r (157Ma) (e.g., Eagles and König, 2008; Gaina et al., 2013; Reeves et al., 2016; Mueller and Jokat, 2019), which represents the onset of the active transformation stage. When the spreading centre migrated to the southern end of the LC, strike-slip displacement along the active transform fault was replaced by passive continental sedimentation in the LC. Subsequently, subsidence and sedimentation along the LC changed abruptly. During the right-lateral strike-slip motion between Antarctica and the MFZ, the LC experienced considerable sheared deformation adjacent to the transform fault.

Two types of prominent unconformities at transform margins have been proposed (Basile et al., 1998, 2015; Mercier de Lépinay et al., 2016): post deformation unconformity (PDU) and post transform unconformity (PTU), which delimit the three stages of transform evolution. The PDU that sealed deformed sedimentary basement units during the early intracontinental stage was proven to be diachronous but older than the PTU along the transform margin, especially at the outer corner of the transform margin (Basile et al., 1998, 2015; Mercier de Lépinay et al., 2016). The PTU marked the end of the active transformation stage when the oceanic spreading centre has passed by the end of the transform margin (Basile et al., 2015).

We propose that R1 and R2 correspond to PDU and PTU, respectively. The wedge-shaped seismic unit U1 between these two prominent unconformities documents the sedimentary deposit in the LC (Figure 10). Referring to the Mid-ocean ridge tholeiite basalts drilling at DSDP Site 249(Simpson et al., 1974), the erosional unconformity surface R1 represents the base of the Neocomian unit and can be dating to 145

Ma. We propose that the sedimentation of U1 was associated with rapid subsidence in basement domain B during the southward drifting movement between Africa and Antarctica along the LC (Figure 12b). Mahanjane (2012) proposed the erosional unconformity onsets of the continental breakup in the central Mozambique margin. Franke et al. (2015) suggested that it records the transition from rifting to strike-slip movement phase during the southward migration of Madagascar along the DFZ.

The erosional unconformity surface R2 corresponds to the top of the Neocomian unit. This unconformity marks the end of the wrench faulting stage (Klimke et al., 2016), corresponding to the initial movement of the Patagonia plate and onset of the South Atlantic Ocean at Valanginian Phase (Figure 12c). The earliest unit U1 between R1 and R2 was deposited in shallow water during Neocomian time (Salman and Abdula, 1995; Mahanjane, 2012). The well-layered and earliest post-rift Neocomian sediments are found on the top of the acoustic basement not only in the LC but also in the NNV and MCP (Salman and Abdula, 1995; Mahanjane, 2012). The Necomian unit shows evidence of growth strata, which are characterized by the parallel to subparallel reflectors with onlapping or truncation reflection pattern (Figure 10). The wedge-shaped unit indicates that the LC was subjected to rapid subsidence after uplift and subaerial erosion on the top basement. Along the LC, most of the depocentres are observed at the eastern foot of the basement high, implying that the sediments were sourced from the Eastern African mainland.

5.4 Sedimentation during the passive transformation stage

After the oceanic spreading centre passed the southern end of the LC segment, the corridor adjacent to the Mozambique Basin was characterized by rapid thermal subsidence during the passive transformation stage. Subsequently, the depocentres in the LC sharply migrate downslope, resulting in black shale deposition in anoxic conditions during the Upper Cretaceous (Figure 12d).

The unit U2 (Figure 12d), dated from the Aptian to Albian, mostly occurs at downslope in the LC. This unit is dominated by slope clinoforms with continuous and parallel reflectors associated with the deposition of Lower Domo shales (Salman and Abdula, 1995). Moreover, De Buyl and Flores (1986) established the presence of black shales that were deposited under euxinic conditions from well data. The progressive infilling structures onlapping the continental slope imply a rapid subsidence of the LC. Combined with a simple back-of-the-envelope calculation in the Mozambique Basin, Castelino et al. (2015) proposed the subsidence of Mozambique Basin basement reached more than 4 km until the Late Cretaceous.

The R3 represents the Albian unconformity (100.5 Ma) and records significant oceanic circulation changes. Deposition under partly euxinic conditions at the MozR was affected by robust shallow circulation that onset approximately 100 Ma and subsequently exhibited a hiatus (Fischer and Uenzelmann-Neben, 2018). A widespread erosional unconformity, called the McDuff unconformity in the southern Mozambique margin, correlates to the sedimentary hiatus in the Jc-C1 borehole (Du Toit and Leith, 1974; Dingle et al., 1978; Martin et al., 1982; Hicks and Green, 2016). It is likely resulted from enhanced bottom current activities, resulting in the hiatus between the Campanian and Cenomanian at DSDP Site 249 on the MozR (Simpson et al., 1974).

The wedge-shaped unit U3 (Figure 12e) was deposited during the Late Cretaceous with a full coverage in the LC. Along the eastern corridor region slope, unit U3 exhibits sedimentary lobes in its lower section, and the upper section consists of a mixed drift deposit. The thick accumulation of sediments reflects an increased sediment flux due to the rapid denudation of the South African Plateau during the Late Cretaceous (Patridge and Maud, 1987; Walford et al., 2005; Baby et al., 2018). The mixed drift deposit indicates the influence of down-slope and along-slope processes associated with two deposition-controlling currents. In the downslope process, a strong turbidity current transported sediments into the corridor. With increasing distance from the continent, the turbidity current waned, and an N-S bottom current along the continental slope began to dominate the mixed-drift deposition.

The oldest Beira drift located at the northwestern edge of the Beira high suggests the onset of bottom currents around the Cenomanian to Turonian transition (Ponte et al., 2018; Thiéblemont et al., 2020). Uenzelmann-Neben et al. (2017) suggested the occurrence of oceanic circulation through the African-Southern Ocean gateway beginning in the Albian (~110 Ma). Castelino et al. (2015) identified an elongated submarine fan lobe with the sediment wave structure, suggesting the initiation of bottom currents in the northern Mozambique Basin during the Late Cretaceous.

Unit U4 (Figure 12f) above the R4 was deposited during the Palaeocene-Eocene with the partial cessation of density currents, which favor the development of the CDS. The large field of sediment waves indicates the intensification and expansion of intermediate currents in distal areas. The R4, corresponding to the top Cretaceous unconformity (66 Ma), is identified in the Zambezi-1 and Zambezi-3 wells as Tertiary basement (De Buyl and Flores, 1986; Salman and Abdula, 1995). Erosional features formed at the top of U4 and marked the onset of vigorous bottom-current scour after a long period of stability. The emergence of these currents may reflect the major palaeoceanographic changes in the Southern Ocean during the Oligocene (Zachos et al., 2001; Potter and Szatmari, 2009).

The large-scale channel incisions along the LC are correlated with erosion and sediment bypassing in the unit U5 (Figure 12g) and may have contributed to the formation of the erosional unconformity surface (Simpson et al., 1974; Mahanjane, 2012; Baby et al., 2018; Jean-Pierre et al., 2018. Thiéblemont et al., 2019). The erosional unconformity surface R5 is marked by numerous channel incisions with a truncated seismic reflection pattern, associated with the sedimentary hiatus during the Oligocene. Castelino et al. (2015) identified a prominent erosional mid-Oligocene unconformity in the northern Mozambique Basin, indicating a marine regression. The widespread buried submarine channel incision was subsequently filled by relatively transparent Eocene sediments (Franke et al., 2015; Castelino et al., 2015). The second uplift of the South African Plateau from the Oligocene to the early Miocene resulted in a basin-wide unconformity at the southern Mozambique margin(Belton and Raab, 2010; Emmel et al., 2014). Therefore, the deep current flows along the LC resulted in complex sedimentary deposition and CDS during the Neogene time.

6. Conclusion

This study introduces a regional stratigraphic framework and identifies several basement domains based on the interpretation of the seismic reflection data crossing the LC.

Along the western boundary of the LC, we identify a basement high in basement domain A extending from north to south. Eastward, the basement depth increases abruptly, and we propose that this uplifted basement high is the western limit of the LC, while the MFZ represents its eastern limit. The acoustic basement between these two limits consists of east-dipping and alternating strong and weak reflectors sealed by a prominent erosional unconformity. According to Moulin et al. (2020), we interpreted these reflectors as a VSS extending throughout the entire MCP and the NNV. The first marine sediments that overlay the VVS are of Neocomian age; therefore, we dated the VSS to pre-Neocomian. By comparison with the adjacent Outeniqua Basins offshore of South Africa, we propose the VSS was formed at the Oxfordian-Kimmeridgian age in the LC.

Between the uplifted basement high and the MFZ, the LC represents a shear zone associated with a strike-slip movement that promoted the southward motion of Eastern Gondwana. The VSS between the western limit and MFZ is highly fractured by vertical to sub-vertical faults and overlain by a prominent wedge-shaped unit that seals most of the faults and the basement sequence. The first deformation during the intracontinental stage (Oxfordian-Kimmeridgian) led to the formation of the VSS. Thermal uplift and the associated subaerial erosion occurred during the active transform stage of the Tithonian. During the active transform margin stage, the second phase of deformation was associated with wrench faulting during the southward drifting of East Gondwana, which deformed and penetrated the top basement and earliest Neocomian units. After the oceanic spreading centre in the Mozambique Basin migrated to the southern end of the LC, the corridor entered a passive transform margin stage. The discrepant subsidence and deformation generated topographic steps in the LC that resulted in a complex contourite deposition.

Based on the interpretation of the acoustic basement and stratigraphy, we present the evidence of a sheared/transformed margin and subsequently divided the continental breakup evolution and sedimentary deposition of the LC into three stages: (1) an intracontinental transform stage, (2) an active transform margin stage, and (3) a passive transform margin stage.

Data availability.

Seismic datasets related to this article can be founded at: https://doi.org/10.17600/16001600, an IFREMER SISMER database of the PAMELA-MOZ3 project (Moulin and Aslanian, 2016).

Seismic datasets from the SIO are private without an open-source online data repository. Please contact the corresponding author **(Yong Tang: tangyong@sio.org.cn)** for the detailed information.

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FIGURE CAPTIONS

Figure 1: Bathymetric map (a) and Free-air gravity anomaly map (b) of the southern Mozambique margin. (a) Red boxes indicate the study area at the eastern edge of the Northern Natal Valley (NNV). The grey shadowed areas indicate Limpopo Corridor (LC). Black and blue lines are seismic profiles that acquired by IFREMER and SIO. Seismic profiles MZ05, S01, and MZ01 extend from west to east, and the sections included in this study are highlighted with yellow lines. White circles correspond to the position of the OBSs. (b) Free-air-gravity anomaly map of Sandwell et al. (2009). Magnetic anomalies, marked with different colors, are picked from Mueller and Jokat (2019). Oceanic fracture zones and fossils of transform faults with dashed red lines are modified from König and Jokat (2010) and Mueller and Jokat (2017,2019). Outeniqua rift basins are consist of Algoa Basin (AB), Bredasdorp Basin (BB), Gamtoos Basin(GB), Pletmos Basin (PB) along the AFFZ. Abbreviations: AFFZ = Agulhas-Falkland Fracture Zone, AG = Ariel Graben, BH = Beira High, MCP = Mozambican Coastal Plain, DFZ = Davie Fracture Zone, MadR = Madagascar ridge, MozR = Mozambique Ridge, MFZ = Mozambique Fracture Zone, NR = Naude ridge, SNV = Southern Natal Valley

Figure 2: A chronostratigraphic chart outlining the stratigraphy from the northern to southern Mozambique margin. West Somalia Basin (Franke et al., 2015), North Mozambique Channel (Klimke et al., 2016), Angoche Basin (Mahanjane, 2014), Central Mozambique Basin (Castelino et al., 2015), Beira High (Mahanjane, 2012), Zambezi Delta (Jean-Pierre et al., 2019), South Mozambique Channel (Thiéblemont et al., 2020), Mozambique Ridge, DSDP site 249 (Simpson et al., 1974). The seismostratigraphic framework of the Limpopo Corridor in this study is indicated from oldest to youngest as follows: R1(blue), R2(green), R3(orange), R4(purple), R5(yellow) in this paper.

Figure 3: Regional section within the NW-SE oriented multichannel seismic profile S01 cross cutting the LC was selected to highlight the structures of the main geological setting and the seismic interpretation Upper panel: original seismic section (line location in Figure. 1a). Lower panel: geological interpretation showing the major unit boundaries and distribution of the basement domains. Five prominent unit boundaries from bottom to top are marked with different colours: R1 (blue), R2 (green), R3 (orange), R4 (purple), and R5 (yellow). Dotted lines with different colours show the distribution of different basement domains. The locations of the enlarged seismic sections are shown in Figures. 4, 5, 6, 7, and 8.

Figure 4: Enlarged original seismic section (upper) and interpretation (lower) of the seismic profile in basement Domain A. Colored lines are the sequence boundaries separating different sedimentary unit. A basement high with a mound shape, associated with several steps of the top of the acoustic basement, marks the western boundary of the LC. Fragmentary, but occasionally strong internal reflectors (solid black line) below this basement high can be identified.

Figure 5: Enlarged original seismic section (upper) and interpretation (lower) of the seismic profile in basement domain B. Several strong internal reflectors (solid black line) with discontinuous and dipping features are interpreted as VSSs developed in the top basement. The basement is fractured by high-angle normal faults (solid red line) and sealed by the unconformity R1.

Figure 6: Enlarged original seismic section (upper) and interpretation (lower) of the seismic profile in basement domain C. Eastward dipping strong reflectors represent the VSS that are fractured by vertical faults. The basement is rugged and overlain by earliest unit U1 with varying thickness.

Figure 7: Enlarged original seismic section (left) and interpretation (right) of the seismic section crossing the MFZ. The MFZ is represented by a prominent submarine escarpment in a transitional zone from continental shelf to Mozambique Basin. A group of faults in the MFZ with a high angle and local branching in a flower-like structure bound the eastern limitation of the LC.

Figure 8: Enlarged original seismic section (upper) and interpretation (lower) of the seismic profile S01 showing different post-rift units. Colored lines are the sequence boundaries separating different sedimentary unit. Five distinct sedimentary units (U1, U2, U3, U4, and U5) from oldest to youngest overlying the acoustic basement along the S01 profile are presented

Figure 9: Enlarged original seismic section (upper) and interpretation (lower) within the LC. The contourite drifts in the different sedimentary units are bounded by colored sequence boundaries.

Figure 10: Seismic interpretations of MZ05, S01 and MZ01 profiles in W-E direction and along profile free air gravity (red thinned lines) are shown to delineate different basement domains (A, B, and C) across the LC and the MFZ. A huge basement high with peak close to the seafloor

can be observed in the domain A. Colored lines are the sequence boundaries separating different sedimentary unit. The wedge-shaped seismic unit U1 (green area), which is constrained between two prominent unconformities (R1 and R2), represents the earliest sediments overlying the acoustic basement. The VSS in the acoustic basement is highlighted in brown area. Mozambique Fracture Zone (MZF) (red dash line) represents the boundary between the LC and Mozambique Basin.

Figure 11: Structural sketch map of the study area showing that the N-S striking LC is bounded by the MFZ to the east and basement high to the west. The free-air anomaly gravity data of Sandwell et al. (2009) are shown in the offshore areas. The basement high area in transparent orange represents the location of the uplift zone and west boundary of the LC. Transparent blue area corresponds to the LC. The thick orange line with a grey shadow corresponds to the Beira High interpreted by Mahanjane (2012). The magnetic anomaly picks (thick colored lines) and locations of the oceanic fracture zones (red dashed line) in the Mozambique Basin are compiled from Konig and Jokat (2010), Leinweber and Jokat (2012), Davis et al. (2016) and Mueller and Jokat (2019). The distribution of the volcanic eruptions modified by the result of Mueller and Jokat (2017) are marked in red. Abbreviations: AG = Ariel Graben, DFZ = Davie Fracture Zone, ESFZ = Eric Simpson Fracture

Zone, MadR = Madagascar ridge, MozR = Mozambique Ridge, MFZ = Mozambique Fracture Zone, NR = Naude ridge, NNV = Northern Natal Valley, PEFZ = Prince Edward Fracture Zone, SNV = Southern Natal Valley, ZD = Zambezi Depression

Figure 12: Schematic model of the sedimentary evolution of the Limpopo Corridor defining three stages: (1) intra continental transform stage with VSS development (a), (2) active transform movement with strike rifting along the MFZ(b,c), and (3) passive transform margin development and sedimentary deposition (d-f).

Declaration of interests.

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

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Contributions.

The PAMELA MOZ35 project was led by M. Moulin, D. Aslanian & M. Evain from Ifremer in collaboration with Total. Processing of the seismic reflection data from PAMELA MOZ35 project was done by Angélique Leprêtre and Philippe Schurnle. He Li wrote the manuscript with valuable inputs from all co-authors. All authors contributed to the completed manuscript. He Li and Daniel Aslanian did the main analysis and interpretation of the seismic data.

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

Highlights

New multichannel seismic reflection data crossing the southern Mozambique margin delineate the crustal architecture and stratigraphy.

The Limpopo Corridor (LC), offshore southern Mozambique margin, evolved in a large area of shear zone associate with a transform fault during and after Gondwana breakup.

Basement of the LC is characterized by Volcano-Sedimentary Sequence, rather than the crystalline basement or oceanic crust.