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MASS-TRANSPORT DEPOSIT IN THE MOZAMBIQUE CHANNEL: AN ANALOGUE FOR EROSIONAL STRATIGRAPHIC TRAP AND IMPLICATIONS FOR PLEISTOCENE ZAMBEZI CANYON ACTIVITY

Alexandre ORTIZ [1], Massimo DALL'ASTA [2], Marina RABINEAU [3], Cécile ROBIN [4], Gwenaël JOUET [3], Ruth FIERENS [3], François RAISSON [2], Laurence DROZ [4]

[1] BRGM-French Geological Survey, F-45060 Orléans, France
[2] TotalEnergies, Avenue Jean Ferrer, Pau, France
[3] Geo-Ocean, Univ. Brest, CNRS, Ifremer, UMR6538, 29280 Plouzané, France
[4] Géosciences Rennes, Université de Rennes 1, INSU, UMR 6118, Rennes, France

Corresponding author: a.ortiz@brgm.fr

Abstract: Submarine mass-transport deposits (MTDs) in passive margin setting can drastically change the seafloor morphology. These events are instantaneous on a geological scale and can have consequences on the equilibrium between continental slope – canyon – abyssal plains. The study takes place in the Mozambican margin where sedimentation is fed by one of the largest rivers in southern Africa: the Zambezi River. During Pliocene-Pleistocene times, the increase in sediment flux triggered several MTDs in this margin. Thanks to 2D multichannel seismic data, we describe here the largest MTD in the northern Mozambican Margin, that we called the Zambezi MTD (dated between 780 and 440 Ka). It presents geometric and volumetric characteristics as follows: 2829 km^3, 20 391 km^2, 480 m (maximal thickness), and 790 km (maximal length). This quantification clearly places it in the 10 biggest MTD on passive margin in the world. The Zambezi MTD partly filled the paleo-Zambezi valley and is interpreted to have provoked the disconnection between the proximal domain of the turbidite system (outer shelf deltas, canyon heads) and the distal turbidite fans (Mozambique basin). This is demonstrated in the distal gravity cores, by the sudden stop of detrital sediments input in the distal area between 644 Ka and 550 Ka. Such disconnection processing o,ccurring between upstream and downstream turbiditic deposits is a good analog for the creation of an erosional stratigraphic trap for fluids (e.g. hydrocarbons, stored CO2) within sandy turbidites, as documented by subsurface data.

1 INTRODUCTION

The Mozambique Channel and the Zambezi River form a coupled continental–marine system whose evolution reflects the long-term tectonic, geomorphological and sedimentary history of south-eastern Africa and the south-western Indian Ocean. The Mozambique Channel formed during the Jurassic–Early Cretaceous breakup of Gondwana. Rifting and subsequent seafloor spreading caused Madagascar to separate from the African continent, establishing a deep marine basin. This basin is characterized by complex structural inheritance, including features such as the Mozambique Ridge, the Davie Ridge and the Beira High (Leinweber and Jokat, 2012; Mougenot et al., 1986; Mueller and Jokat, 2017).

Meanwhile, the Zambezi River is one of the oldest and most tectonically influenced fluvial systems in Africa (Deville et al., 2018; Ponte, 2018). Components of its drainage network predate the fragmentation of Gondwana and have undergone major reorganization in response to continental uplift, rifting and base-level changes throughout the Mesozoic and Cenozoic eras (Moore and Larkin, 2001). Since the Oligocene, sediment delivered by the Zambezi has fed one of the largest deep-marine turbidite systems in the Indian Ocean (Droz and Mougenot, 1987; Fierens et al., 2020; Ponte et al., 2019; Roddaz et al., 2020; Salman and Abdula, 1995). It constructed extensive submarine fans within the Mozambique Channel basin, made of channel–levee systems, terminal lobes and contourite complexes, which record variations in sediment supply, tectonic activity and oceanographic circulation (Aslanian et al., 2023; Babonneau et al., 2023; Dennielou et al., 2022; Droz and Mougenot, 1987; Fierens, 2019; Fierens et al., 2022; Le Hir et al., 2025; Miramontes et al., 2021; Ponte et al., 2019; Thiéblemont et al., 2020).

Continental margins are the transitional area of sediment routing between continental sediment sources and the distal basin, acting as a sink, they can be affected by numerous processes (slope failure, MTD's, contourite, turbidity current) that drastically change their equilibrium, morphology and stratigraphy. These processes can generate very fast erosion and large sediment mass transfers (Amy, 2019; Bull et al., 2020, 2009) compared to the long-term (*100 Myr) stratigraphic evolution of these margins. Mass transport deposits (MTD's) play a major role in deep-marine sedimentary systems, exerting a significant influence on stratigraphic architecture and reservoir distribution by remobilising slope sediments on a large scale (Bull et al., 2009; Masson et al., 2006; Posamentier and Martinsen, 2011). From a stratigraphic perspective, MTDs commonly form extensive, time-transgressive regional units that generate significant stratigraphic discontinuities. These units can locally erode or bury underlying depositional elements, strongly influencing the stacking patterns of turbidite systems (Moscardelli and Wood, 2008; Posamentier and Martinsen, 2011). In terms of reservoir characterisation, MTDs are usually made up of highly deformed and internally heterogeneous lithologies with low, spatially variable porosity and permeability. They commonly act as flow baffles or seals that compartmentalise adjacent turbidite reservoirs (Bull et al., 2009; Counts et al., 2021; Stagna et al., 2023; Talling et al., 2014). Consequently, accurately identifying and placing MTD's in the stratigraphic framework is critical for predicting the distribution and the connectivity and performance of reservoirs in deep-water hydrocarbon systems, as well as the probability of occurrence of stratigraphic trapping.

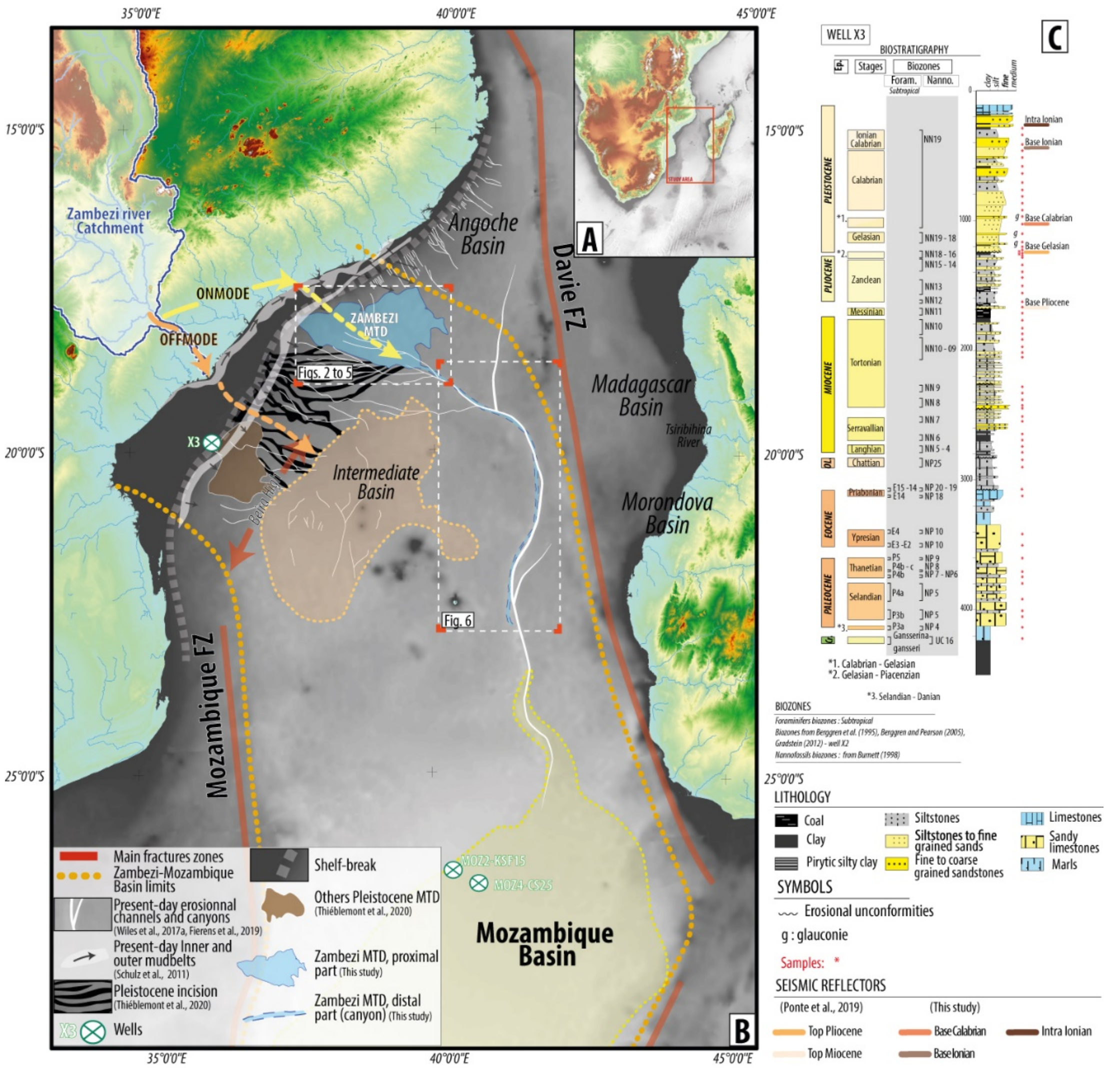

Figure 1. Study location, A: South-western Indian Ocean location, B: illustration of the different elements presents in the study area, present-day erosional channels, canyons and valleys (Fierens et al., 2019; Thiéblemont et al., 2020; Wiles et al., 2017a), present-day inner and outer mudbelts (Schulz et al., 2011), the Zambezi MTD at the core of this study is highlighted in blue. Outlines of the figures that will follow later in the text are also shown as white boxes C: Sedimentological description biostratigraphic framework of the well X3 From Ponte et al., (2019)

2 MATERIALS AND METHODS

This study was performed thanks to seismic data provided by (1) SLB Multiclient and INP and (2) PAMELA seismic acquisition (PTOLEME, PAMELA-MOZ02 and PAMELA-MOZ04), (Jorry, 2014; Jouet and Deville, 2015; Robin and Droz, 2014). It consists of well mesh 2D multi-resolution multichannel seismic data which enabled us to propose: (1) a cartography of the different structural areas in the MTD, (2) built isobath and isopach maps of the MTD from proximal to distal. Biostratigraphic calibration on the wells (well X3 location and synthetic interpretation shown on figure 1) for the late Neogene to Quaternary sediments was obtained from Ponte (2018) and is the reference for the Zambezi margin. Interpretation in the Zambezi canyon from intermediate to distal part benefited from Fierens et al., (2019, 2020, 2022). Time to depth conversion of the different maps was performed using the velocity model elaborated in Ponte (2018), velocity is 2100 m/s for the studied interval.

3 RESULTS AND DISCUSSION

Seismic interpretation and related maps are presented in this section to characterize the stratigraphic architecture of Zambezi MTD from its proximal to distal part along the continental slope and inside deep basinal Zambezi valley.

3.1 Proximal part

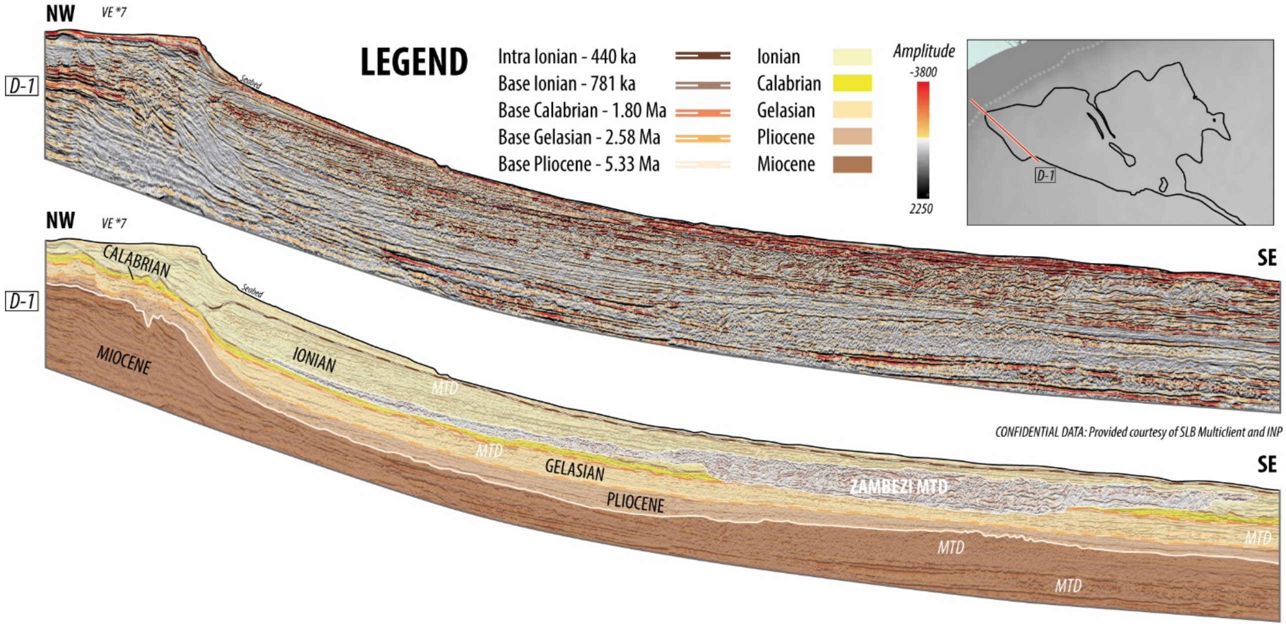

Figure 2. Seismic interpretation in the northeastern part of the Zambezi margin and delimitation of the southern tip of the Zambezi MTD, location on Figure 1. Seismic profile highlights the prevalence of MTD's in the stratigraphic organisation of the Mozambique margin.

The upper part of the Zambezi MTD is presented in Figures 2, 3, 4 and 5 and is illustrated thanks to (i) along dip seismic profiles (Figures 2 and 3) and (ii) serial strike sections (figures 4 and 5) with a semi 3D vision.

Dip seismics profiles located in the northern part of the Zambezi shelf edge and upper slope show steep margin. Ages are reported from Miocene up to Intra-Ionian. Seismic interpretation shows Zambezi MTD and highlighted the recurrence of MTD deposits since Miocene times. The Zambezi MTD occurred between 781 and 440 Ka as shown in Figure 2.

The Zambezi MTD is then illustrated through 7 dip seismic sections from west to east (Figure 3). The tear scar is situated updip and is not visible on the seismic data (Dennielou et al., 2022). Seismic facies shown in Figure 3 are composed of chaotic and disorganized features, but also deformed blocks with convex-up geometries found in D-1, D-2 and D-4-A. These features are typical of MTD deposits, particularly those resulting from slides, slumps and debris flows (Bull et al., 2009; Gee et al., 2007; Ortiz-Karpf et al., 2018; Scarselli et al., 2013).

Thanks to the MTD classification by Bull et al. (2009), it was possible to determine, in the seismic profiles, the limits of the structural domains: extensional (Headwall-blue), translational (Shear-orange) and compressional domains (Toe-red) (Figure 3). The D-2 in the figure 3 is an example of the entire MTD trilogy, whereas in other examples such as D-5-A, D-5-B, D-4-B and D-3 only the compressional domain is present. The D-2 section exhibits the upper part of the Zambezi MTD with "Staircase-like Basal Shear Surface" following downward by slide blocks with internal deformation in the headwall and translational domains. The translational domain is then dominated by chaotic facies up to the end of the MTD. The thrust belt is difficult to identify in this area, and no frontal ramps were identified (Figure 3).

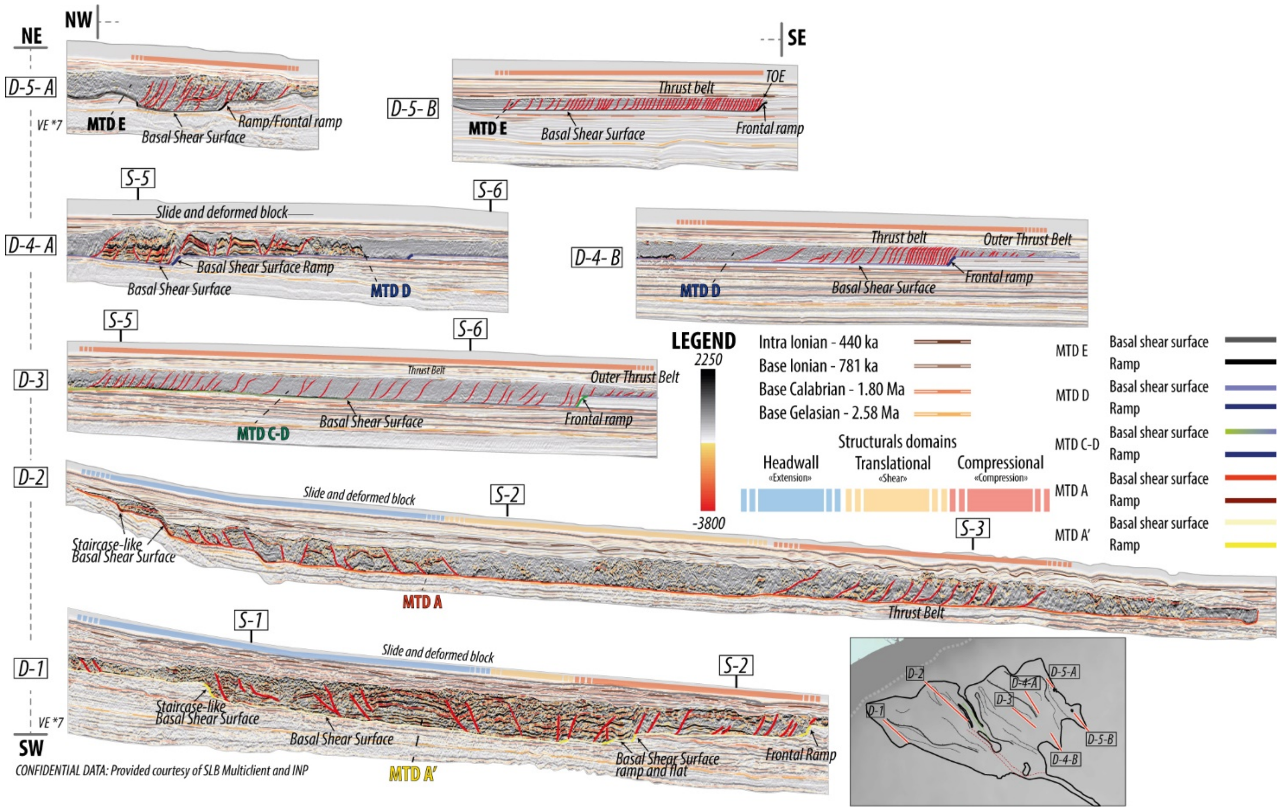

Figure 3. Dip Seismic profiles interpreted on the Zambezi MTD, location on Figure 1. Seismic sections highlighted the multiple MTD's occurrences from MTD-A to MTD-E with different internal organization.

Furthermore, other elements typical of MTDs are visible in seismic data. D-4-B, D-3 and D-1 sections show well developed frontal ramp which correspond to the distal limit of a frontally confined MTD (Bull et al., 2009; Frey Martinez et al., 2005). It should be noted that the only seismic section where the frontal ramp is absent is on D-2 (Figure 3) and corresponds to the area where the MTD continued its path in the paleo-valley, clearly showing that here the MTD was not frontally confined.

The Zambezi MTD is a coalescence of 6 different MTDs (A, A', B, C, D, and E), which are presented through transversal seismic profiles in figures 4 and 5. All these MTDs are connected and seem to correspond at unique event at the geological time scale.

MTD A is the main mass-transport deposit in the southern tip of the study area (Figure 4). Its eastern part in the proximal domain (S-1 and S-2, Figure 4) thins toward the east whereas in the western part its coalescence with MTD A'. This coalescence becomes more pronounced towards the lower part of the system, reaching a point (in section S-5) where the two are almost indistinguishable and mixed in section S-5. On the contrary, in the upper part (section S-1), the two MTD show their own well-individualized side ramps (Figure 4).

The profiles S-3 to S-5 (Figure 4) also highlight the coalescence between MTD A and MTD B. The evolution from individualized to coalescent MTD happens rapidly and the two MTDs appear to be converging in the Zambezi paleo-valley marked in blue in Figure 4.

The strike seismic sections of northeastern part of Zambezi MTD (Figure 5) show the upper part of the MTD B describe (Figure 4). As MTD A and A' the MTD B is bounded by well-individualized side ramps.

MTD C and MTD D are coalescent, their proximal parts are well defined with multiple side ramps (section S-3 in Figure 5). However, in the middle part, it becomes impossible to distinguish these two features and so the designation MTD C-D is therefore used (section S-5, S-6).

MTD E is the easternmost and smallest MTD. Zambezi MTD is larger than the presented area, especially in the northern tip of the MTD. In its middle part, MTD E is coalescent with the MTD D (section S-6 in figure 5). Finally, MTD C, MTD D and MTD E seem to separate in the distal part (section S-7 in Figure 5) to become three distinct laterally confined MTD's.

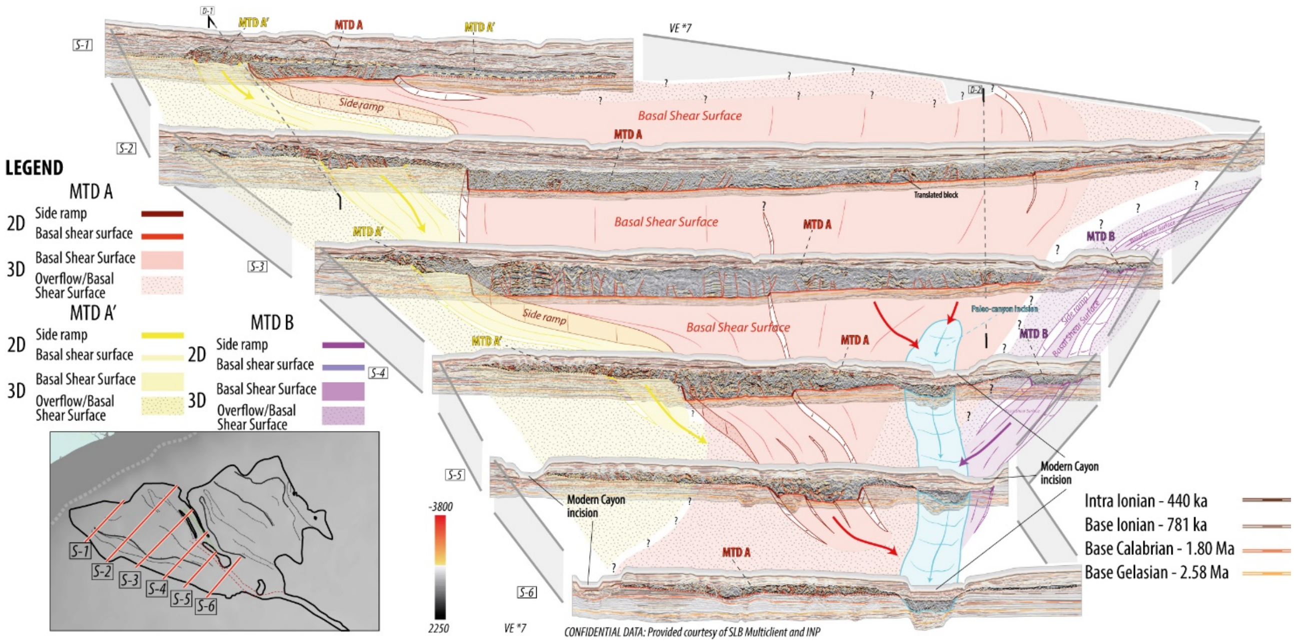

Figure 4. Strike seismic profiles from the western part of the Zambezi MTD, illustration of the multiple MTD's object (MTDs A, A' and B), location on Figure 1. MTD morphology classification pointed thanks to Bull et al., (2009) classification, Side Ramp, Basal Shear Surface.

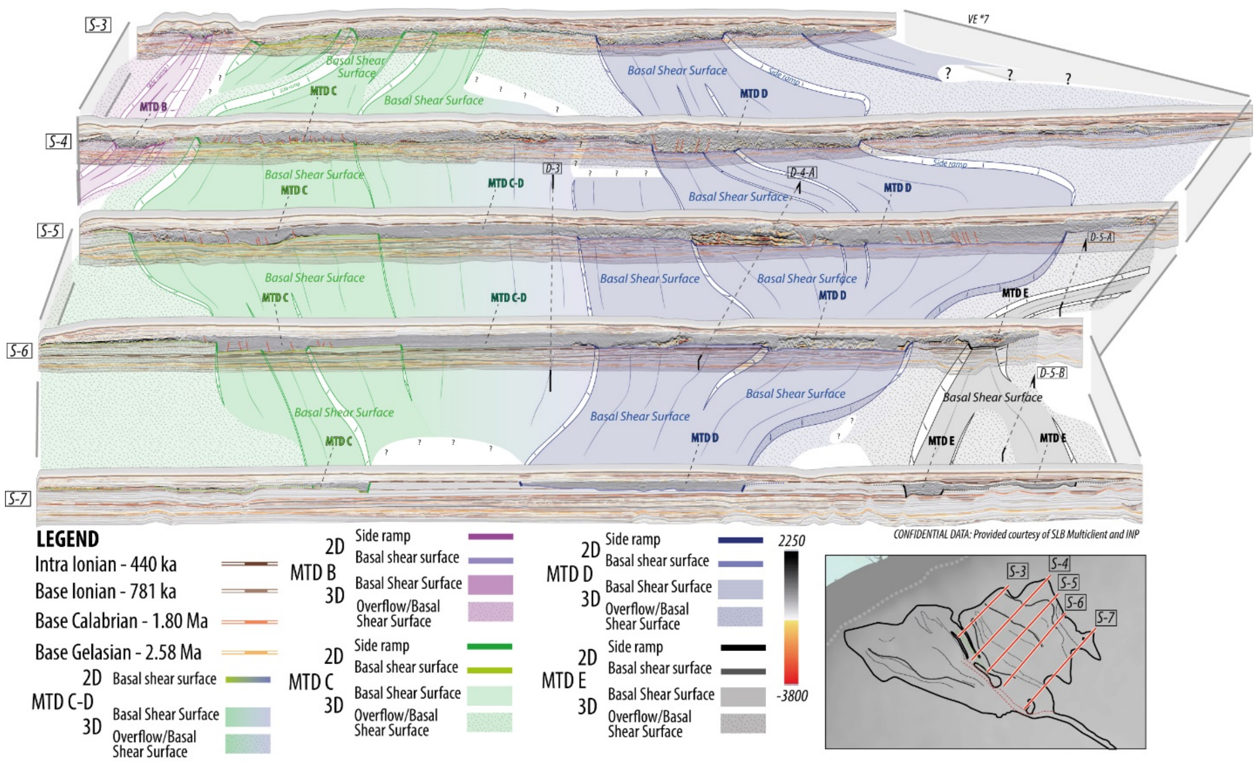

Figure 5. Strike seismic profiles from the eastern part of the Zambezi MTD, illustration of the multiple MTD objects (MTDs B, C, D and E), location on Figure 1. The western part of S-5 corresponds to the eastern part of S-3 in Figure 4. MTD morphology classification pointed thanks to Bull et al., (2009) classification, Side Ramp, Basal Shear Surface.

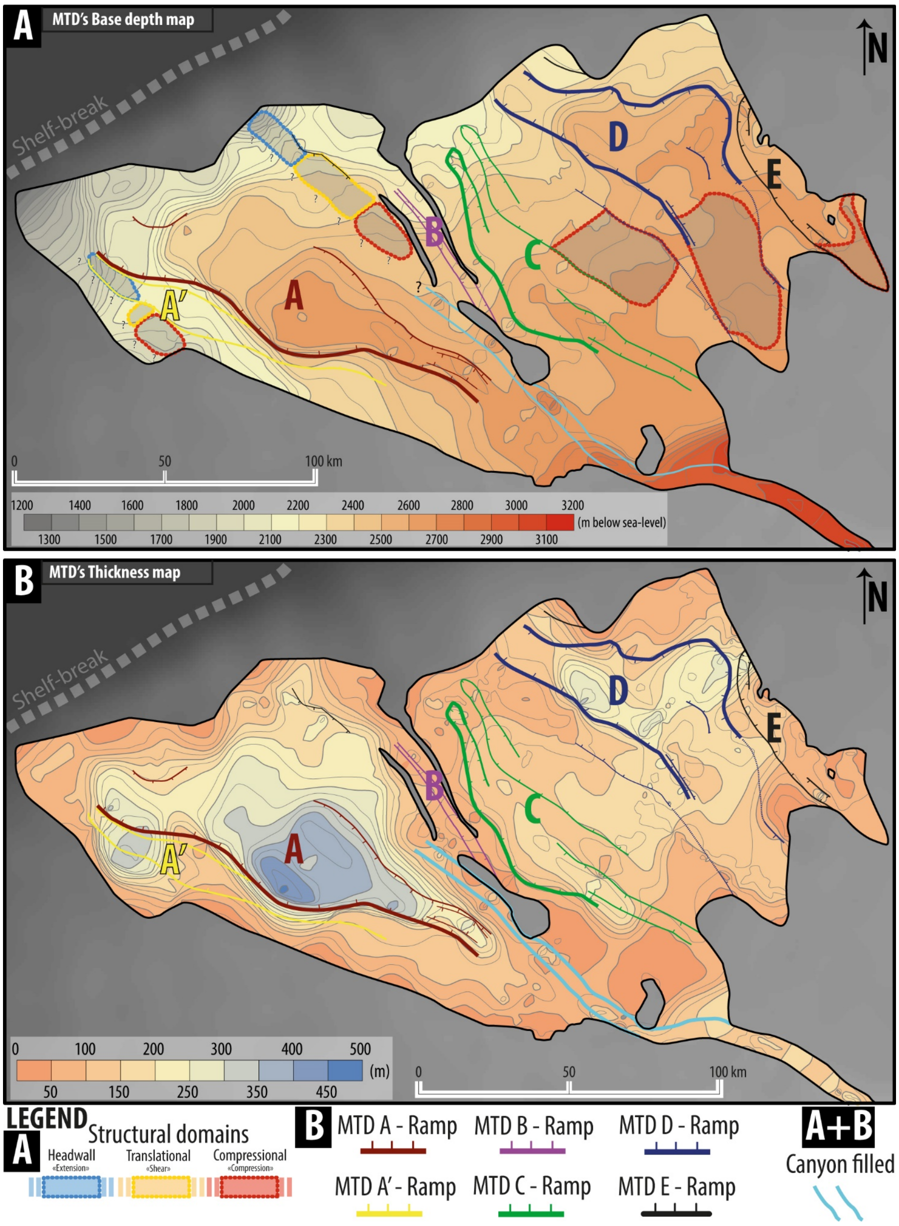

Figure 6. A: MTD's base depth map, B: MTD's thickness map, location on Figure 1.

Two maps are presented in Figure 6: the MTDs base depth (A) and the MTDs thickness (B). These two maps are converted to meters thanks to time-depth conversion.

That basal MTD surface is comprised between 1200 and 3200 mbsl (Figure 6A). The side ramps mentioned in the strike sections (Figures 4 and 5) have also been mapped, enabling us to identify the location of the various MTD's. Thanks to dip sections the different domains (extensional, translational and compressional) have been reported on the map. On the eastern part the MTD D and E show clear confined configuration with the two compressional domains ending rapidly (Figure 6A). Whereas the MTD A and the western part of the MTD C do not show any clear typical ending part from the isopach map interpretation. This fact is related to the presence of the paleo-valley (blue line) and the potential for the MTD to converge and be transported inside the valley. These two MTD's will be laterally confined further downstream in the paleo-valley.

The thickness of the Zambezi MTD is reaching up to 480 meters (Figure 6B). This map highlights two distinct parts separated by a central trend characterized by thinner deposit. The western part presents the major accumulation domain compared to the eastern one. The coalescence of MTD's, and mainly MTD A and C, is observed in the downstream part where the two MTD's reach the paleo-valley.

3.2 Distal part

The distal part of the Zambezi MTD is illustrated on Figure 7 with 5 seismic strike sections and the related MTD thickness map in the Zambezi valley. Former valley incisions (from the Miocene) have been reported from Fierens, (2019). The Zambezi MTD in the valley is characterized by a low amplitude chaotic seismic facies corresponding to debris flow deposits (Figure 7). These deposits take place between Pliocene and present-day incision which is consistent with the age given in the proximal part (781 and 440 ka).

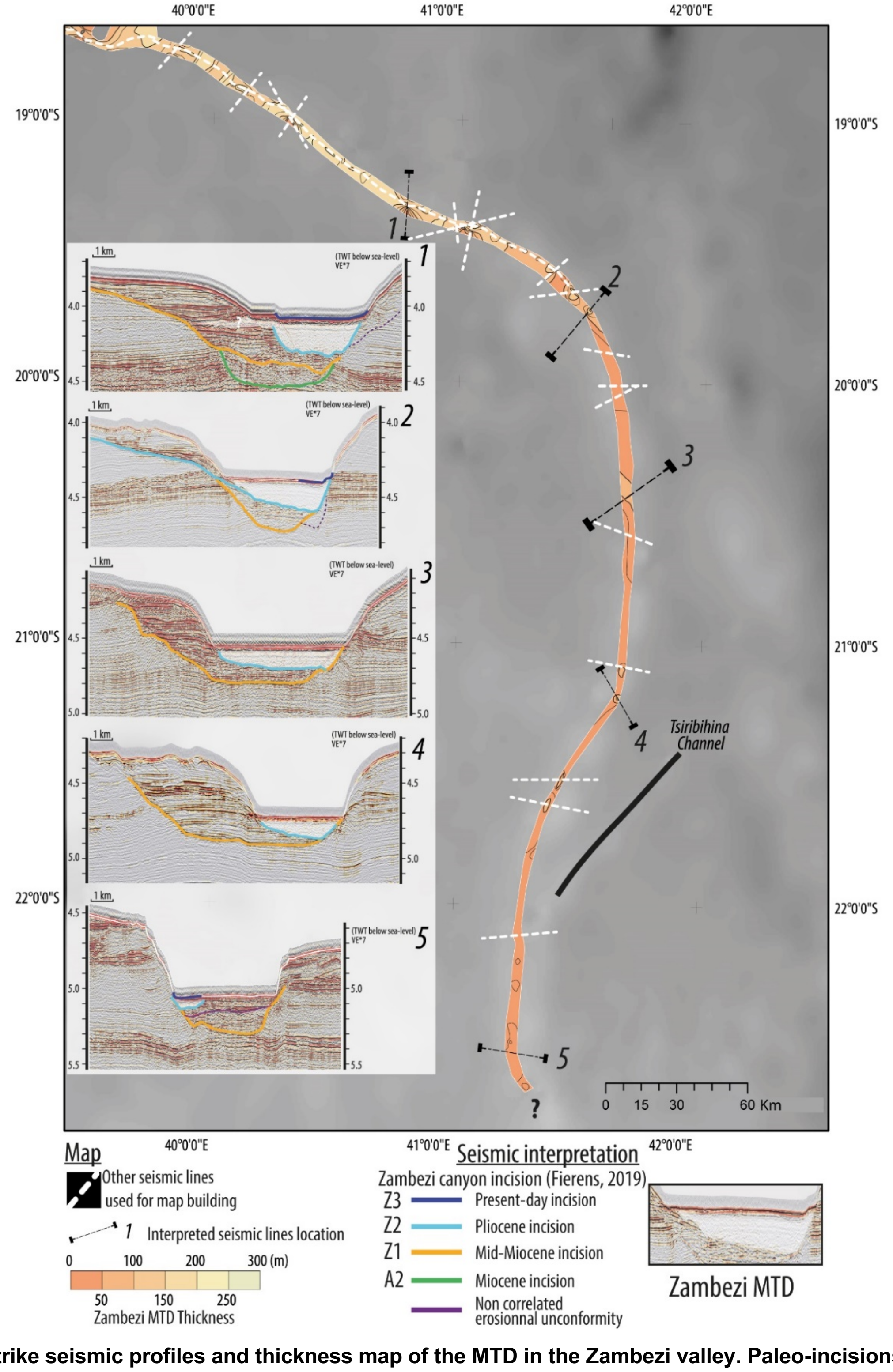

Figure 7. Strike seismic profiles and thickness map of the MTD in the Zambezi valley. Paleo-incisions are from Fierens (2019) and are reported in all the seismic sections. Zambezi MTD is pointed with white color. Thickness scale is the same as in Figure 6B.

The five seismic strike sections revealed a progressive decrease in thickness of the Zambezi MTD within the paleo-valley. This is confirmed by the thickness map, which shows that the upper part is 300 meters thick, while the lower part is less than 50 meters thick. It also appears that the Zambezi MTD completely fills the blue incision in each section (Pliocene incision), which has inevitably consequences on the post-Pliocene morphological balance of the canyon and on sediment exports.

Finally, from proximal to distal domain the Zambezi MTD is formed by several MTDs which composed geometric and volumetric characteristics as follows: 2829 km^3, 20 391 km^2, 480 m (maximal thickness), and 790 km (maximal length).

4 DISCUSSION

The Mozambican margin presents several Mass Transport deposits as mentioned in previous studies. Abu et al., (2022) mentioned large MTD in the Angoche Basin (location in Figure 1) occurring during Neogene time thanks to seismic data. Ortiz et al., (2016) and Thiéblemont et al., (2020) mentioned the recurrence of MTDs during Pleistocene on the continental slope (location in Figure 1). Finally, using bathymetric data, Dennielou et al., (2022) highlighted the occurrence of tear scars on the continental slope attesting once again the recurrence of the MTDs events. The Zambezi MTD located in the northern part of the margin take place in an area where the continental slope is steep which probably enhanced the formation of these features.

The Zambezi MTD results from the coalescence of 6 MTDs with 5 of them that are frontally confined. Only MTD A is unconfined and can be followed within the paleo-canyon. The Zambezi MTD is 790 km long and consists of a slide/slump in the proximal part and a debris flow in the distal part. Its maximum thickness is 480 meters, and its volume is 2829 km^3. Compared to the synthesis of Calvès et al., (2015) the Zambezi MTD can be placed in the top 10 MTDs in the world in term of volume and the first in term of runout length. The Zambezi MTD has volumetric and geometric characteristics equivalent to Storegga Slide which is found in the same morpho-sedimentary context (Bryn et al., 2005; Calvès et al., 2015; Canals et al., 2004).

The volume and length of this feature affected the global source to sink transfers of the Zambezi system. Several studies focus on the source to sink quantitative aspect of this sedimentary system (Ponte, 2018; Ponte et al., 2019; Roddaz et al., 2020) and also on the Pleistocene history of the deep submarine Zambezi system (Fierens, 2019; Fierens et al., 2022, 2020, 2019; Wiles et al., 2017a, 2017b).

Ponte (2018) through a source to sink synthesis highlights a change in term of sediment partitioning during Pleistocene time between proximal and distal parts. Indeed, the sediment rates in the Zambezi fan show a large diminution compared to Pliocene and upper Miocene times. At the same time the upper part of the system (i.e Zambezi delta) shows a large increase in the preserved sediments volume. The ratio between upstream and downstream preservation is clearly in favor of the proximal domain during Pleistocene.

Based on the study of Pleistocene sediment cores taken from the deep and intermediate basins (Figure 1), Fierens et al., (2020) demonstrate that sediment export from the Zambezi Delta is bimodal. The “on-mode” fed the intermediate basin and the deep-sea fan through the canyon whereas the “off-mode” only fed the intermediate basin with a clear disconnection with the distal turbiditic lobes. (Figure 1). Fierens et al., (2020) determined an “off-mode” period between 644 Ka and 550 Ka, characterized by a sedimentation hiatus which corresponds to the age of formation of the Zambezi MTD.

The interruption of sediment transfer from the delta to the distal domain is shown by these two studies during certain periods of the Pleistocene (Fierens et al., 2020; Ponte, 2018). The emplacement of the Zambezi MTD during this period undoubtedly led to a rapid morphological imbalance in the valley, causing its abandonment for several tens of thousands of years such as the example described by Stagna et al., (2023). Such disconnection processing occurring between upstream and downstream turbiditic deposits is a good analog for the creation of erosional stratigraphic traps for fluids (e.g. hydrocarbons, stored CO2).

5 CONCLUSIONS

The Zambezi mass-transport deposit (MTD) on the northern Mozambican continental shelf is one of the largest documented in a passive continental margin, with a volume of ~2,829 km^3, a maximum thickness of 480 meters, and a runout length of 790 kilometers. Seismic interpretation reveals a composite structure comprising six coalescent MTD’s that transition from proximal slump–slide deposits to distal debris flows laterally confined into the Zambezi valley. The emplacement of the MTD’s between ~780 and 440 ka caused significant disruption to sediment transfer from the Zambezi delta to the distal deep-sea fan. This is evidenced by a sedimentation hiatus between 644 and 550 ka. This emphasizes the major role of MTD’s in swiftly reorganizing source-to-sink systems, creating stratigraphic discontinuities and segmenting turbiditic deposits. Beyond its geomorphological significance, the Zambezi MTD is an important analogue for creation of deep-marine stratigraphic traps, with implications for hydrocarbon exploration and CO_2 storage in sandy turbidites.

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