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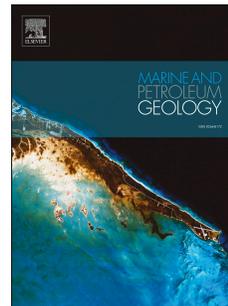
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1 **Sedimentary evolution and effects of structural controls on the development of the**
2 **Zambezi mixed turbidite-contourite system (Mozambique Channel, Southwest Indian**
3 **Ocean) since the Oligocene**

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15

16 **ABSTRACT**

17 High-resolution multichannel seismic reflection data that spans significant parts of the
18 Mozambique margin offshore the Zambezi River permits the study of the Oligocene to
19 present architectural evolution of the Zambezi turbidite system. In this time frame, five major
20 depositional units are recognized that evidence a widespread spatial and temporal
21 occurrence of both turbiditic and contouritic sedimentation. They indicate that the
22 sedimentary regime within the turbidite system changed from dominantly aggradational
23 during the Oligocene to mainly erosional during Miocene to an interplay of erosional and
24 depositional processes during the Plio-Quaternary. Different episodes of incision, linked with
25 the Serpa Pinto, Angoche and Zambezi valleys, are recognized in the upstream portion of

26 the Zambezi Fan and highlight a westward (anticlockwise) shift of feeding axes. The central
27 portion of the Zambezi Valley was affected by a progressive structural doming during the
28 Miocene. The dominance of long-lasting erosional processes generated by the continuous
29 rise of the seabed led to a deep entrenchment of the Zambezi Valley. This tectonically-
30 controlled over-incision is believed to be the cause of the absence of Miocene levees, and
31 has played an important role in the stabilization of the valley at its current position. Finally,
32 our study revealed a quasi-constant development of contourite accumulations since the Late
33 Miocene that occur most often synchronous with turbiditic sedimentation. The present study
34 offers unique insight into the controls and stages of development of one of the largest
35 turbidite systems in the world and demonstrates especially its susceptibility to structural
36 activity.

37 **Keywords:** Zambezi turbidite system, Mozambique Channel, multichannel seismic profiles,
38 turbidite, contourite, tectonic, Late Cenozoic

40 1. INTRODUCTION

41 Tectonic settings and sediment transfer are known to play an important role in the
42 development and characteristics of deep-marine turbidite systems (Stow et al., 1985; Mutti
43 and Normark, 1987, 1991). Besides possible regulation of upslope sediment flux and
44 sediment delivery configuration (e.g. Stow et al., 1985; Reading, 1991; Reading and
45 Richards, 1994), tectonics may deform basin floor topography and hence exert strong control
46 on the morphodynamic evolution of a sedimentary system (Alexander and Morris, 1994;
47 Bursik and Woods, 2000; Haughton, 2000; Morris and Alexander, 2003; Mayall et al., 2010;
48 Howlett et al., 2020). Pre-existing features forming positive relief and/or tectonic movements
49 (by faults, folds, salt or mud diapirs, salt walls, etc.) can disrupt the continuity of sediment
50 flows and cause unusual geometries and sediment distribution patterns as they can lead to:
51 (1) deflection, or the shifting of sediment routing due to an active structure (e.g., Tabernas-
52 Sorbas Basin: Hodgson and Haughton, 2004; Niger Delta: Morgan, 2004; Angolan margin:

53 Gee and Gawthorpe, 2006); (2) diversion, when the gravity-driven processes change course
54 because of a pre-existing structure (e.g., Makran margin: Kukowski et al., 2001; southern
55 Barbados prism: Huyghe et al., 2004; Brazilian slope: Smith, 2004; offshore Tanzania:
56 Maselli et al., 2020); (3) confinement, which indicates the restriction of turbidity currents by
57 adjacent structures (e.g., Lower Congo Basin: Oluboyo et al., 2014; Levant Basin: Clark and
58 Cartwright, 2009); or (4) blocking, where seafloor relief prevents sedimentation downstream
59 of a structure (e.g., Gulf of Mexico: Rowan and Weimer, 1998; Beaubouef and Friedmann,
60 2000; Annot System: Sinclair and Tomasso, 2002; Fangliao Fan: Hsiung et al., 2018) of
61 sediment pathways. Moreover, the crossing of a tectonic structure — which occurs if the
62 erosional downcutting of sediment transport systems keeps pace with the rate of structural
63 growth— can lead to a local or more extended topographic constriction of turbidity currents
64 impacting flow behavior and sedimentation patterns (e.g., Gee et al., 2001; Morgan, 2004;
65 Saller et al., 2004; Mayall et al., 2010). Although the principal anticipated response of deep-
66 water gravity flows to structural elements are known, it is still a challenge to elucidate the
67 depositional architectural evolution of extensive submarine turbidite systems to complex
68 seafloor deformations.

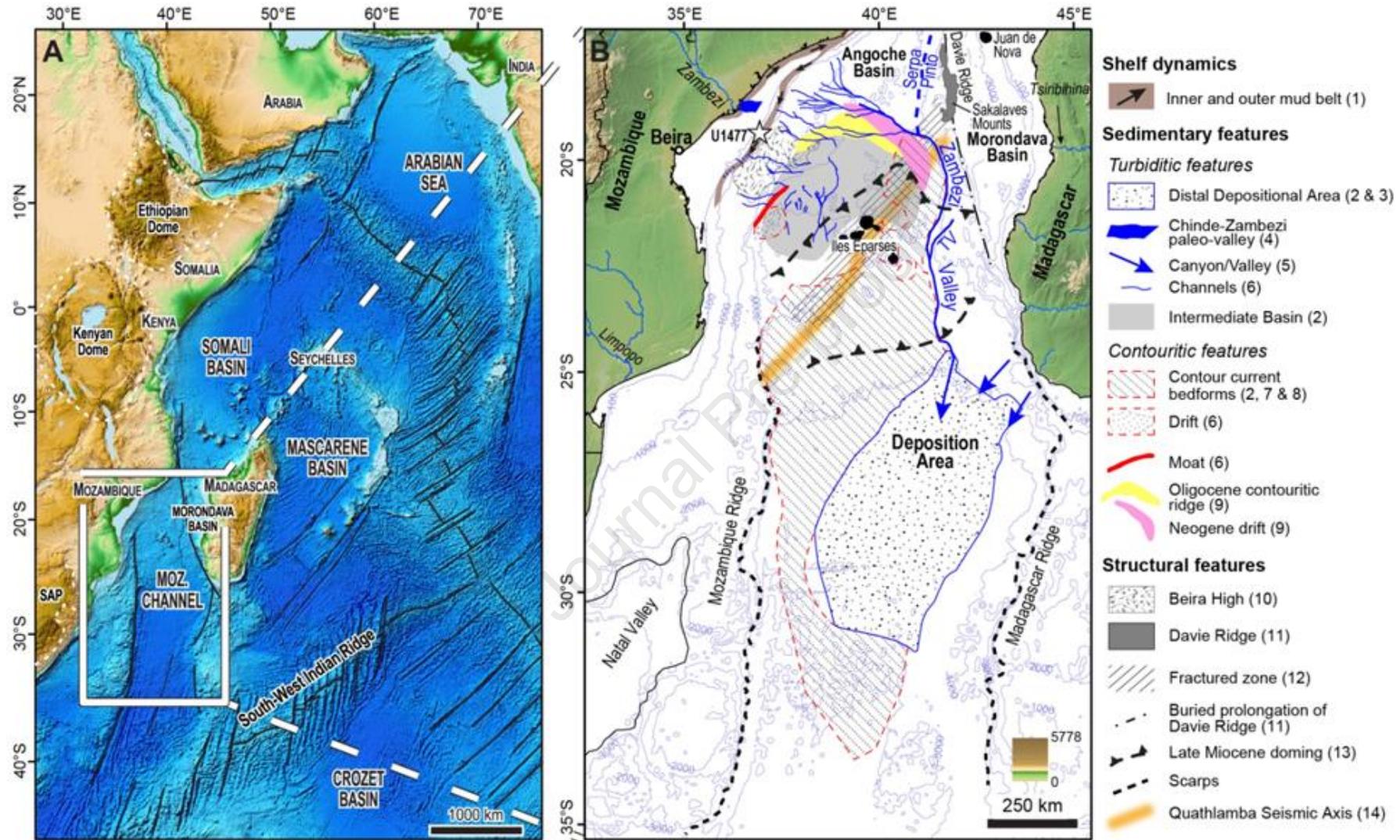
69 The Mozambique Channel, hosting the Zambezi turbidite system, that has arisen from the
70 break-up of Gondwana and the development of the East African rift system (e.g., Mougénot
71 et al., 1986; Salman and Abdula, 1995; Calais et al., 2006; Leinweber and Jokat, 2012; Saria
72 et al., 2014; Franke et al., 2015; Courgeon et al., 2018; Deville et al., 2018; Thompson et al.,
73 2019) is known to be a tectonically dynamic region and hence, provides an interesting
74 research area to explore the role of large-scale structural features and processes on the
75 growth and evolution of a deep-water turbidite depositional system. Based on seismic
76 reflection profiles, a number of previous studies on the Zambezi system have already hinted
77 at a significant impact of morpho-tectonic features (i.e., Davie Ridge and Iles Eparses and
78 seamounts) that caused the stable position of the Zambezi Valley and its resulting unusual
79 deep entrenchment (Lort et al., 1979; Droz and Mougénot, 1987; Castelino et al., 2017).
80 Unfortunately, the findings of these studies were hampered due to the low-resolution data

81 quality and/or insufficient seismic coverage. Other authors (e.g., Breitzke et al., 2017;
82 Fierens et al., 2019; Miramontes et al., 2019) have suggested the important influence of
83 oceanic bottom currents on the Zambezi Valley morphology. However, it seems unlikely to
84 attribute the total deep entrenchment of the Zambezi Valley (~700 m; Fierens et al., 2019)
85 merely to erosional activity of deep-water bottom currents (max. 500 m of incision; García et
86 al., 2009; Van Rooij et al., 2010; Bozzano et al., 2021; Miramontes et al., 2021) and so it has
87 not yet been possible to ascertain the precise cause of the deeply incised morphology of the
88 Zambezi Valley. This study based on a new and extensive high-resolution seismic reflection
89 dataset from the Zambezi depositional system seeks to improve our understanding of the
90 regional sedimentary evolution. The main seismic facies and incisions are examined in order
91 to explore and characterize the timing and extent of erosion and deposition in the Zambezi
92 turbidite system from Oligocene to present-day. This specifically allows us to decipher which
93 mechanisms are responsible for the exceptional deep entrenchment of the Zambezi Valley.

94

95 **2. REGIONAL SETTING OF THE MOZAMBIQUE CHANNEL AND ZAMBEZI TURBIDITE** 96 **SYSTEM**

97 The Mozambique Channel is located in the western Indian Ocean between Mozambique
98 (East Africa) and Madagascar (centered at 40°E and between 15°S and 42°S) (Fig. 1).



100 Figure 1: (A) Location of the Mozambique Channel in the southwest Indian Ocean, with
101 position of the main sedimentary basins, fracture zones (black lines) and continental
102 elevation highs (white dotted lines) (modified from Delaunay, 2018; map from Amante and
103 Eakins, 2009). SAP: South African Plateau. (B) Physiographic map of the Mozambique
104 Channel showing main sedimentary and structural features (modified from Fierens et al.,
105 2019). TV = Tsiribihina Valley. White star: core U1477 from IODP leg 361 (Hall et al., 2016).
106 Compiled from published literature: (1) Schulz et al., 2011; (2) Fierens et al., 2019; (3) Kolla
107 et al., 1980a; (4) Beiersdorf et al., 1980; (5) GEBCO, 2014; (6) Wiles et al., 2017; (7) Kolla et
108 al., 1980b; (8) Breitzke et al., 2017; (9) Raison et al., 2016; (10) Mahanjane, 2012; (11)
109 Mahanjane, 2014; (12) Schematized from Courgeon et al., 2017, 2018; Deville et al., 2018
110 and Wiles et al., 2020; (13) Ponte, 2018, partly based on Baby, 2017; (14) Stamps et al.,
111 2015.

112

113 **2.1. Structural evolution**

114 The formation of the Mozambique Channel was initiated in the Early Jurassic-Early
115 Cretaceous during the breakup of the Gondwana (Salman and Abdula, 1995; Leinweber and
116 Jokat, 2012; Thompson et al., 2019). Multiple rifting phases allowed the East Gondwana
117 (Madagascar, Antarctica, India and Australia) to separate from the African block at ca. 165
118 Ma and slide southward along the transform Davie Fracture Zone (Fig. 1B) until around 120
119 Ma (Segoufin and Patriat, 1981; Coffin and Rabinowitz, 1987; Cochran, 1988; Gaina et al.,
120 2015). During the Late Cretaceous (95 Ma) Madagascar separated from the Indian block
121 (Salman and Abdula, 1995) and acquired its current position at 88 Ma (Late Cretaceous)
122 (Reeves, 2014; Thompson, 2017). The East African continental margin underwent a period
123 of stabilization during the Paleocene and the Eocene, until rifting resumed when the East
124 African Rift System (EARS) developed (Salman and Abdula, 1995; Calais et al., 2006; Saria
125 et al., 2014; Franke et al., 2015). The eastern branch of EARS initiated in the Oligocene
126 (Dawson, 1992; Le Gall et al., 2008) and is prolonged offshore along the North Mozambique
127 coastline and northern part of the Mozambique Channel (Mougenot et al., 1986; Franke et

128 al., 2015). This offshore rift segment is characterized by Neogene extension superimposed
129 on earlier strike-slip structures of the Davie Fracture Zone (Rabinowitz et al., 1983; Reeves,
130 2014; Franke et al., 2015). A southwest prolongation of this offshore branch is argued by
131 Courgeon et al. (2018), Deville et al. (2018) and Wiles et al. (2020) on the basis of a NNE-
132 SSW densely distributed fault pattern, extending further south than the Sakalaves to the
133 Mozambique Ridge on the East African Margin. These faults deformed the oceanic
134 lithosphere of the Mozambique Channel in the same direction as the Agulhas-Falkland
135 transform fault zone from at least Miocene times and are spatially associated to the
136 Quathlamba active Seismic Axis (QSA) (Fig. 1B) (Stamps et al., 2015).

137

138 **2.2. Present-day morphology and main morpho-tectonic features**

139 The Mozambican shelf off the Zambezi River mouth gets connected to the deepest portions
140 of the Mozambique Basin by the long and curvilinear Zambezi Valley that constitutes the
141 main morphologic feature of the Zambezi Fan (Fierens et al., 2019) (Fig. 1). At present, no
142 direct connection is known between the Zambezi River outlet and the Zambezi Valley. This
143 submarine valley has a NW-SE orientation in its upper portion, transverse to the
144 Mozambique Margin. It deflects towards the south when it approaches the Davie Ridge and
145 passes through the Quathlamba Seismic Axis (Stamps et al., 2015) that is still active today
146 (Courgeon et al., 2018; Deville et al., 2018; Wiles et al., 2020). The valley runs thereon
147 between the Eparses carbonate platforms (Courgeon et al., 2016) to the west and the
148 Madagascar margin to the east (Delaunay, 2018). At around 22°S, the Zambezi Valley
149 coalesces with the Tsiribihina Valley (TV in Fig. 1B) that originates from the Western
150 Madagascar margin. Approximately at the latitude of the southern tip of Madagascar the
151 valley leads to a rather flat area constituting the Mozambique deep Basin. Between 22°S and
152 26°S, the valley crosses an elevated area that has undergone structural doming during the
153 Late Miocene (Ponte, 2018).

154 The Davie Ridge is a 1200 km-long prominent N-S trending bathymetric high crossing the
155 Mozambique Channel from the northeastern Mozambique to the southwestern Madagascar
156 margin. It served as a morphological barrier for sediments originating from Madagascar,
157 trapping the sediments in the Morondava Basin until the Miocene (23 Ma, Delaunay, 2018).
158 Subsequently, this basin was filled in and allowed the Madagascar river inputs to overspill
159 and contribute to the Zambezi Fan via the Tsiribihina Valley.

160 About 80 km off the Mozambican coast, the NE-SW Beira High (Fig. 1) forms a prominent
161 basement high parallel to the Mozambique margin (Mahanjane, 2012; Mueller et al., 2016).
162 This now buried structure is 300 km long and 100 km wide and served as a morphological
163 barrier for sediments originating from the Mozambique margin until the Middle Miocene.

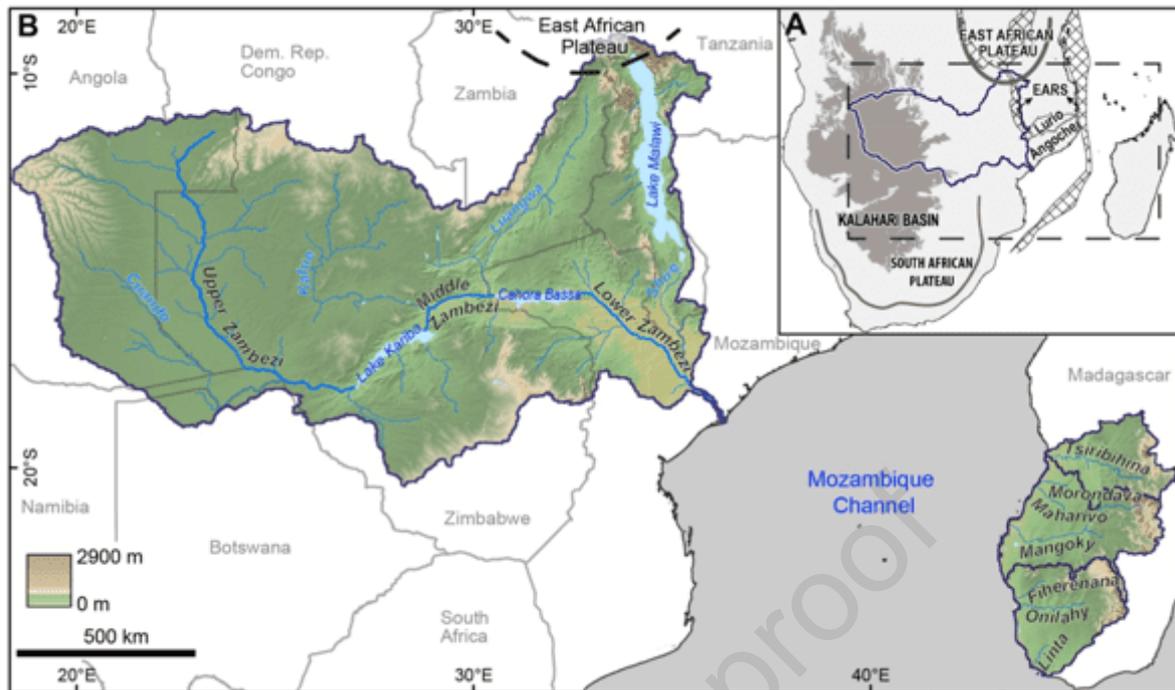
164 The central Iles Eparses are steep sloped carbonate platforms developed on top of volcanic
165 edifices relating to an Oligocene to Early Miocene volcanic episode (Courgeon et al., 2016;
166 Jorry et al., 2016). The Iles Eparses and the Beira High limit a small intraslope basin that has
167 been named the “Intermediate Basin” (Fierens et al., 2019). This basin constitutes the more
168 recent depositional system (Fierens et al., 2020).

169

170 **2.3. Sediment sources**

171 The Mozambique margin records a total sedimentary thickness of ca.6 stwt (~12 km) (Ponte,
172 2018; Ponte et al., 2019) and sediment deposition started at Early Cretaceous.

173 The main source of sediment filling the Mozambique Basin is the Zambezi River, which is
174 with a catchment area of 1.3×10^6 km² the fourth largest river on the African continent (Fig.
175 2) (Thomas and Shaw, 1988; Walford et al., 2005; Milliman and Farnsworth, 2011).



176

177 Figure 2: The Zambezi River and Madagascar Rivers catchments. (A) Position on the African
 178 continent (blue line) with indication of the major geomorphological and structural features
 179 (plateaus, basins, rift systems) (modified from Ponte, 2018; Courgeon et al., 2018; Deville et
 180 al., 2018). Cross design = rift systems and EARS = East African rift system. (B) Modern
 181 drainage system of the Zambezi, Tsiribihina, Mangoky and Onilahy rivers shown on
 182 topography (GEBCO, 2014). The Mongokyo catchment area includes the Mangokyo, Maharivo
 183 and Morondava rivers. The Onilahy catchment comprises the Onilahy, Linta and Fiherenana
 184 rivers.

185 The Zambezi River originates in central southern Africa and drains on its eastern portion
 186 major parts of the East African Rift System as well as the NE portion of the Kalahari Basin of
 187 the South African Plateau (Fig. 2A). It has had a polyphase evolution and has fed the
 188 Mozambican margin with fluctuating composition mixture of sediment (Garzanti et al., in
 189 press). The Zambezi River has a sediment load of 48×10^6 t/yr (Nugent, 1990; Milliman and
 190 Syvitski, 1992) and is 2,575 km long with a third of its length at an altitude higher than 850 m.
 191 From the African continent, two other important sources of sedimentary inputs have been
 192 observed: the Lurio (during Oligocene times) and Angoche (during Oligocene-Neogene
 193 period) watersheds (Fig. 2A). Western Madagascar rivers also contribute, but for a minor

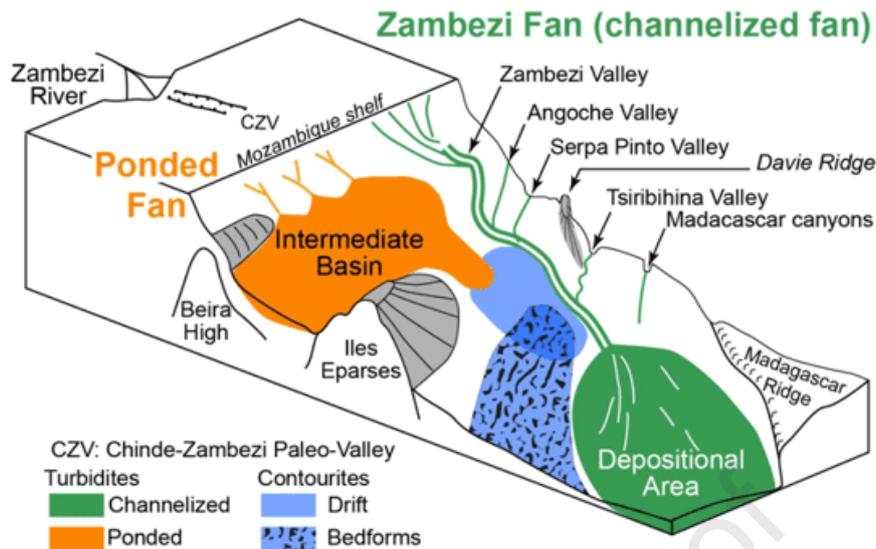
194 amount, to the deposition in the Zambezi turbidite system (Fig. 2B). Madagascar sediment
195 inputs are originating mainly from the Tsiribihina River (525 km long, catchment area of
196 49,800 km²) which is connected to the Zambezi Valley by the submarine Tsiribihina Valley.
197 The Mangoky River which drains the largest watershed in Madagascar (~55,750 km²) is
198 probably also connected to this Tsiribihina Valley. The complex of Onilahy and Fiherenana
199 rivers directly feed the distal turbidite system in the deep Mozambique Basin.

200

201 **2.4. The Zambezi turbidite system**

202 The vast amounts of sediments discharged onto the Mozambican continental shelf by the
203 Zambezi River is attested by the very high sedimentation rate registered for the last climate
204 cycle by IODP drilling U1477 (about 1 m/kyr as a mean sediment rate for the last 120 kyr;
205 Leg 361, Hall et al., 2016) and during the Late Glacial Maximum (LGM, 26.5–20 ka BP) as
206 attested by the MOZ4-CS17 core (reaching about 2-3 m/kyr, Zindorf et al., 2021) both cores
207 retrieved on the upper slope in extension of the Zambezi Delta (Fig. 1B).

208 Fierens et al. (2019) showed that the fluvial input of the Zambezi River is deposited into two
209 main depocenters (Fig. 3) that together compose the Zambezi turbidite system: the Zambezi
210 Fan, which is fed by the 1500 km long entrenched Zambezi Valley that transfers sediments
211 to the deep basin in a vast zone of distal deposition (“Depositional Area”, Fig. 3) and a
212 Poned Fan located in the Intermediate Basin, limited by the Mozambican slope and the Iles
213 Eparses.



214

215 Figure 3: Major elements composing the Zambezi turbidite system (modified from Fierens et
 216 al., 2019).

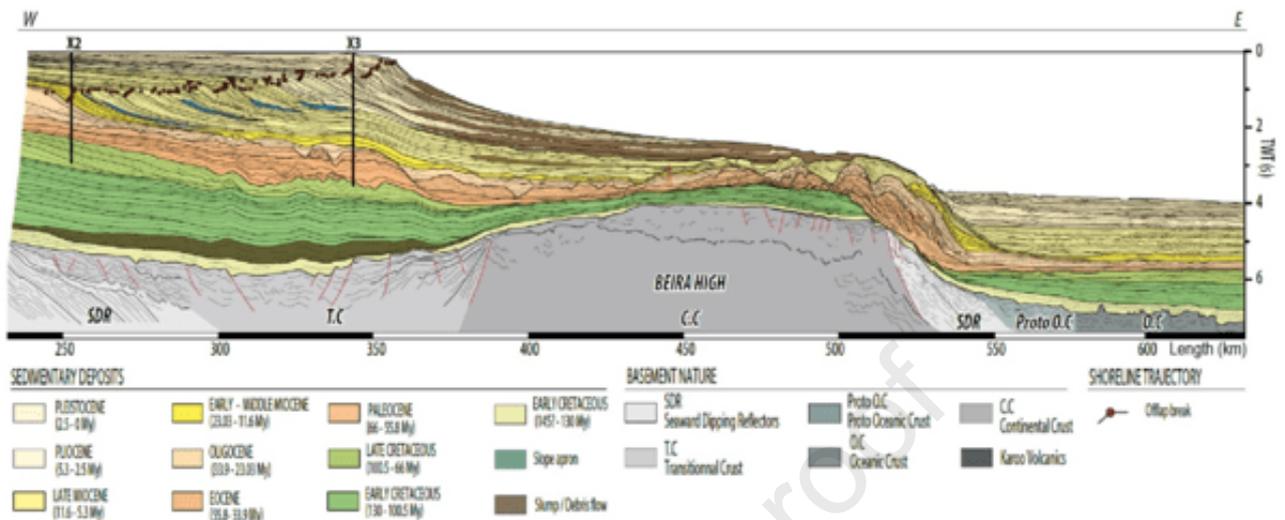
217

218 The Zambezi Fan has been studied previously by multiple studies (e.g., Simpson, 1974;
 219 Kolla et al., 1980a, 1980b; Droz and Mougenot, 1987; Breitzke et al., 2017; Wiles et al.,
 220 2017a; Miramontes et al., 2019; Fierens et al., 2019, 2020). From these we know that the
 221 Zambezi Valley and the distal Depositional Area are characterized by coarse-grained
 222 deposits (Simpson, 1974; Kolla et al., 1980b; Fierens et al., 2019). The presence of sediment
 223 waves (Breitzke et al., 2017; Fierens et al., 2019) and the flank erosion of the Zambezi Valley
 224 (Miramontes et al., 2019) reveal important sediment reworking by strong bottom currents. In
 225 contrast, the Ponged Fan has been more poorly studied (Wiles et al., 2017b; Fierens et al.,
 226 2019, 2020). Based on sub-bottom profiler data, Fierens et al. (2019) suggested that the
 227 Ponged Fan mainly consists of fine-grained turbidites with thin sheet-like, coarse-grained
 228 interbeds.

229

230 The current Zambezi Fan was established from Oligocene times when the Zambezi Delta
 231 progradation was initiated (Droz and Mougenot, 1987; Ponte, 2018). Since then, large
 232 quantities of sediment have been drained from the Zambezi watershed causing a substantial
 233 progradation of the Mozambique shelf (Walford et al., 2005; Ponte et al., 2019) (Fig. 4).

234 During Pleistocene times, the continental margin progradation was most important and mass
 235 transport activity was common (Ponte et al., 2019).



236

237 Figure 4: Stratigraphic architecture of the Mozambique margin (Ponte et al., 2019) (see
 238 location on Fig. 5).

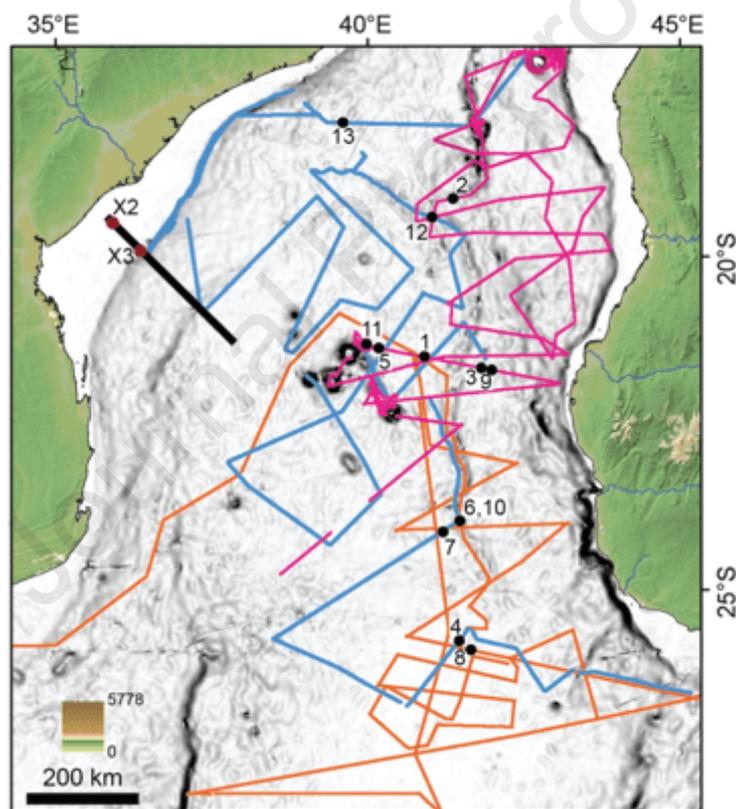
239 The architecture of the Zambezi Fan is poorly known, except for the feeding axes of the fan.
 240 Droz and Mougenot (1987) have shown that the initiation of the Zambezi Fan, during
 241 Oligocene times was related to the Serpa Pinto Valley, a N-S feeding axis close to the Davie
 242 Ridge (Figs. 1, 3). This valley received sedimentary inputs from the Lurio catchment
 243 (Roquette, 2016; Ponte, 2018) (Fig. 2A). The shift to the present-day NW-SE Zambezi Valley
 244 occurred in the Mid-Miocene possibly in response to tectonic activity induced by the
 245 development of the East African Rift System that affected the northern Mozambique margin.
 246 Ponte (2018) indicates that during Oligocene-Neogene times, sediments were supplied by
 247 the Angoche (Fig. 2A) and Zambezi watershed by several channeling systems that join the
 248 Serpa Pinto Valley (Oligocene) and later the Zambezi Valley (from Middle Miocene). Since
 249 the Middle Miocene, sediments from Madagascar contributed to the feeding of the Zambezi
 250 system (see section 2.2), funneled in the Tsiribihina Valley (Delaunay, 2018).

251

252 3. MATERIAL AND METHOD

253 This work is based mainly on high-resolution seismic data that were acquired during three
 254 cruises carried out as part of the PAMELA (PASSive Margin Exploration LABORATORIES) project

255 (Bourillet et al., 2013): PTOLEMEE (Jorry, 2014), PAMELA-MOZ2 (Robin and Droz, 2014)
 256 and PAMELA-MOZ4 (Jouet and Deville, 2015) (Fig. 5). The PAMELA data are unevenly
 257 distributed across the study area with a majority located around the Zambezi Valley (Fig. 5A).
 258 The seismic lines are more dispersed on the Mozambican continental slope (N to NE of Iles
 259 Eparses) and in the distal Mozambique Basin.
 260 On the Mozambican slope, the dataset was complemented with seismic data made available
 261 by Total. Additional seismic data from the MD163-MoBaMaSiS expedition (Reichert and
 262 Aslanian, 2007) were also used.
 263



264
 265 Figure 5: Data used in this study. PAMELA high-resolution multichannel seismic data set.
 266 Magenta lines: PTOLEMEE cruise (Jorry, 2014); orange lines: MOZ2 cruise (Robin and
 267 Droz, 2014); bleu lines: MOZ4 cruise (Jouet and Deville, 2015). Thick black line: position of
 268 the seismic line with industrial wells (X2, X3) presented in Fig. 4 (Ponte, 2018). 1 to 13:
 269 location of the seismic facies examples shown in Fig. 6.

270

271 3.1. PAMELA seismic data acquisitions

272 This study used approximately 23,000 km of multichannel seismic data (Fig. 5) that were
273 acquired aboard of the L'Atalante and Pourquoi Pas? research vessels. The key parameters
274 of the seismic acquisitions are given in Table 1. The multichannel seismic data image the
275 sediment cover up to ca. 2–3 seconds two-way time (stwt), depending on the nature of
276 deposits and the bathymetric conditions.

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Cruise	PTOLEMEE and MOZ2	MOZ4
Source	2 GI guns (105 and 45 ci)	2 GI guns (105 and 45 ci)
Receiving device	streamer 24 traces	streamer 48 traces
Acquisition speed	8-10 knots	8-10 knots
Inter shot	10 s (50 m at 10 knots)	10 s (50 m at 10 knots)
Vertical resolution	~15 m	~5 m

279

280 Table 1: Acquisition parameters of the high-resolution multichannel seismic systems used
281 during the PTOLEMEE, PAMELA-MOZ2 and PAMELA-MOZ4 cruises.

282

283 3.2. PAMELA data processing

284 The seismic data were processed using Ifremer in-house softwares Qc-SISPEED[®]
285 (PTOLEMEE, MOZ2) and SolidQC[®] (MOZ4). The processing sequence includes quality
286 controls of navigation and seismic data, binning, SEG2 to SEG-Y format conversion, pass-
287 band filtering (15-150 Hz), correction of source delay and stacking and migration at constant
288 velocity (1500 m/s).

289

290 3.3. Seismic data interpretation

291 Seismic interpretation was performed following the seismic stratigraphy principles (Mitchum
292 et al., 1977). This approach involves the recognition and correlation of seismic units
293 (definition according to Mitchum and Vail, 1977) complemented by an analysis of the seismic
294 facies. The limits of these units are recognized by reflection terminations (onlaps, downlaps,
295 erosional truncations, and toplaps). The geometry of reflections within an individual seismic
296 unit is described using seismic facies analysis. Seismic facies are defined by looking at the
297 internal and external configurations of the seismic units. Internal reflection characters are
298 described by the continuity, amplitude, frequency and geometry of the reflections. The upper
299 and lower boundaries of the seismic facies define its 2- or 3-dimensional external shape (e.g.

300 wedge, lens or sheet geometry). The stratigraphic framework established by Ponte (2018) on
301 the Mozambique margin (Fig. 4) served as a basis for our study.

302 The processed data (navigation and SEG-Y seismic files) were imported into the IHS
303 Kingdom Suite[®] software that was used to display and analyze the data. Isopach maps were
304 created with grid cell sizes of 200x200 m and produced in second two-way travel-time (stwt).
305 A time-depth conversion is provided using an approximate velocity of 2000 m/s (Ponte,
306 2018). With regard to the large size of the study area and the generally low density of the
307 seismic data, the interpolation of seismic interpretations has been locally difficult. We have
308 chosen to downgrade the isopach maps by showing a maximum of five classes of thickness
309 (0.015-0.25, 0.25-0.5, 0.5-0.75, 0.75-1.0 and 1.0-1.634 stwt). The lowest value (0.015 stwt)
310 corresponds to the vertical resolution of the seismic data with the lowest resolution
311 (PTOLEMEE and MOZ2 data, see Table 1). These isopach maps were displayed by using
312 ArcGIS[®] v10.3.1 (World Mercator map projection).

313

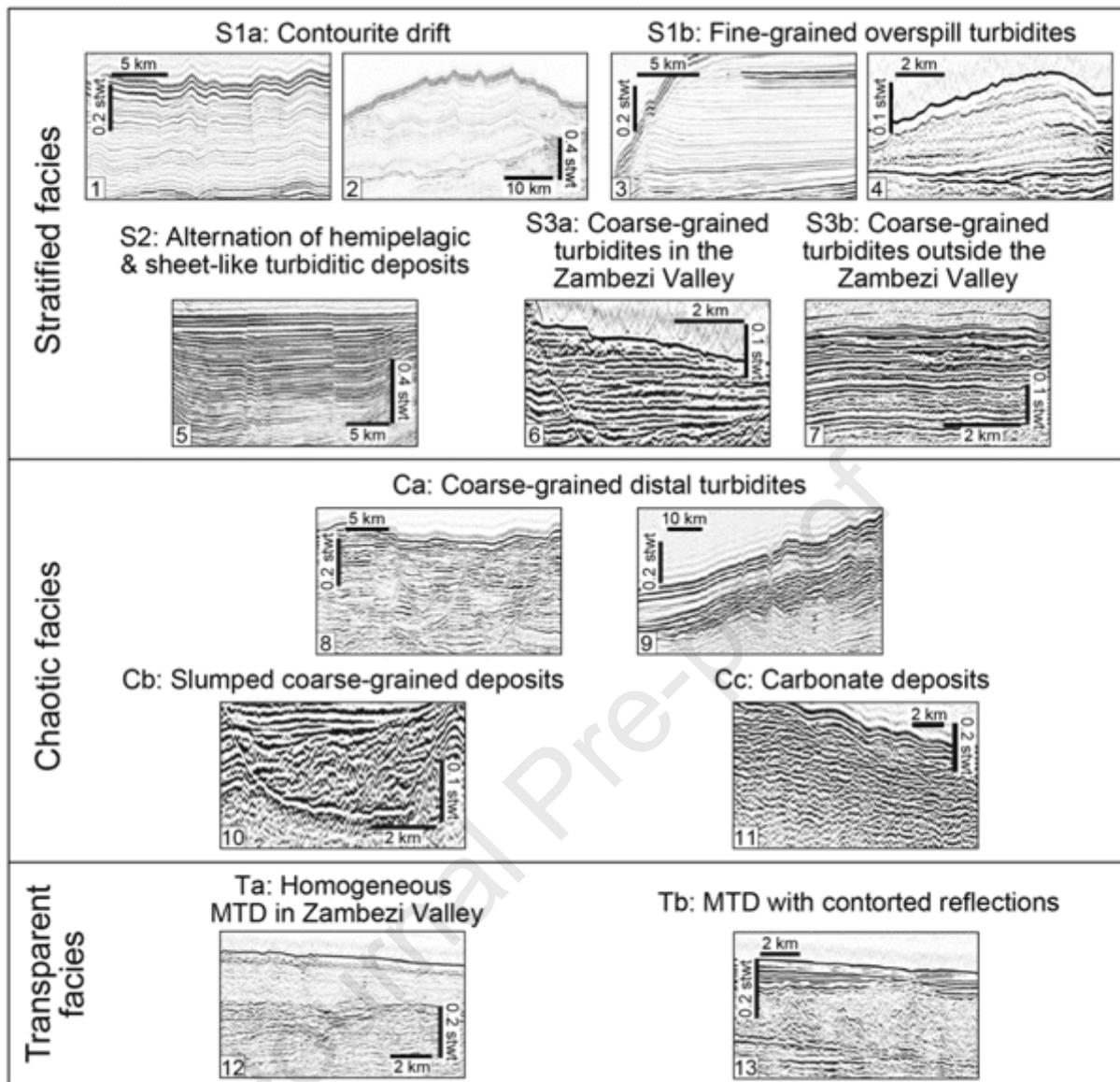
314 **4. RESULTS AND INTERPRETATION**

315 **4.1. Seismic facies and process-based interpretation**

316 The high-resolution multichannel (24- and 48-channels) seismic profiles of the Mozambique
317 Channel reveal three main types of seismic facies that are those typically encountered on
318 continental margins and in turbidite systems (e.g., Winker, 1996; Piper et al., 1999;
319 Babonneau et al., 2002; Adeogba et al., 2005): stratified (S), chaotic (C) and transparent (T)
320 facies. Main characteristics of the facies are summarized in Table 2 and examples are
321 provided in Fig. 6.

Facies class	Facies characters	Sub-class	Configuration	Location	Interpretation	
STRATIFIED	S1 High Co, Low to medium A, High F	S1a	Parallel, or bi-directionally convergent with undulations	Right hand-side of the Zambezi Valley	Contourite drift	
		S1b	Uni-directionally convergent away from a valley or channel axis	Left hand-side of the Zambezi Valley and levees of distal channel-levees	Fine-grained overspill turbidites alternating with very fine hemipelagic deposits	
	S2	High Co, High A, High F	S2	Parallel and onlapping (infilling)	Distal Intermediate Basin	Alternation of hemipelagic deposits and sheet-like turbiditic sediments
	S3 High Co, High A, Low F	S3a	Parallel (infilling valleys/depressions)	Zambezi Valley fill	Coarse-grained turbidites	
		S3b	Parallel, wide extension	Right hand-side of the Zambezi Valley	Coarse-grained turbidites	
	CHAOTIC	C Low Co, High A, Low F	Ca	Basal unconformity, flat topped lens shape	Madagascar margin and distal Depositional Area of the Zambezi Valley	Coarse-grained distal turbidites
Cb			Contorted and divergent from valley walls	Zambezi Valley fill	Slumped coarse-grained deposits	
Cc			Contorted	Eparses hills and sea-mounts	Carbonate deposits	
TRANSPARENT	T Very low A and F	Ta	Entirely transparent, isopach	Inside the Zambezi Valley	Mass-transport deposit	
		Tb	Some contorted reflections	Mozambique slope, Zambezi Valley, distal Depositional Area and Intermediate Basin	Mass-transport deposit	

322 Table 2: Description and interpretation of the seismic facies encountered in the Zambezi
323 turbidite system. Facies characters are described in term of the continuity (Co), amplitude (A)
324 and frequency (F) of the reflections.



325

326 Figure 6: Examples of the seismic facies encountered in the Zambezi turbidite system

327 (location of line portions is shown in Fig. 5 as black dots 1 to 13).

328

329 The stratified facies (S) are the most common and widespread facies identified in the

330 Mozambique Channel. Their main characteristic is a generally good continuity of the

331 reflectors that may be planar or undulated. Variations in amplitude, frequency and

332 configuration led to recognize contouritic deposits (S1a), fine-grained overspill turbidites

333 (S1b), alternating hemipelagic and sheet-like turbiditic deposits (S2) and coarse-grained

334 turbidites (S3a and S3b).

335 The chaotic facies (C) are characterized by contorted reflections with low continuity and by

336 frequent erosional features and local unconformities. The Ca facies are widely observed at

337 the distal end of the Zambezi Valley where coarse-grained sediments dominate (Kolla et al.,
338 1980a, b). In addition, local flat top lens-shaped seismic units are identified on the
339 Madagascar slope where it is thought to image coarse-grained turbidites. The chaotic facies
340 are also observed as contorted reflections that are tilted towards the valley axis (Cb), which
341 are interpreted as slumped deposits from the valley flanks in agreement with the
342 interpretation of other authors (e.g., Deptuck et al., 2003; Janocko et al., 2013). At the foot of
343 the seamounts of the Iles Eparses, the Cc chaotic facies is interpreted as carbonated
344 turbidites with hemipelagic muds (Counts et al., 2018).
345 The transparent facies (T) are observed as homogeneously transparent inside the Zambezi
346 Valley (Ta) or as mostly transparent with faint and contorted reflections at various sites of the
347 Mozambique margin and basin (Tb). These facies are usually interpreted as mass-transport
348 deposits (MTDs) (e.g., Imbo et al., 2003; Garziglia et al., 2008; Loncke et al., 2009;
349 Dennielou et al., 2019; Badhani et al., 2020).

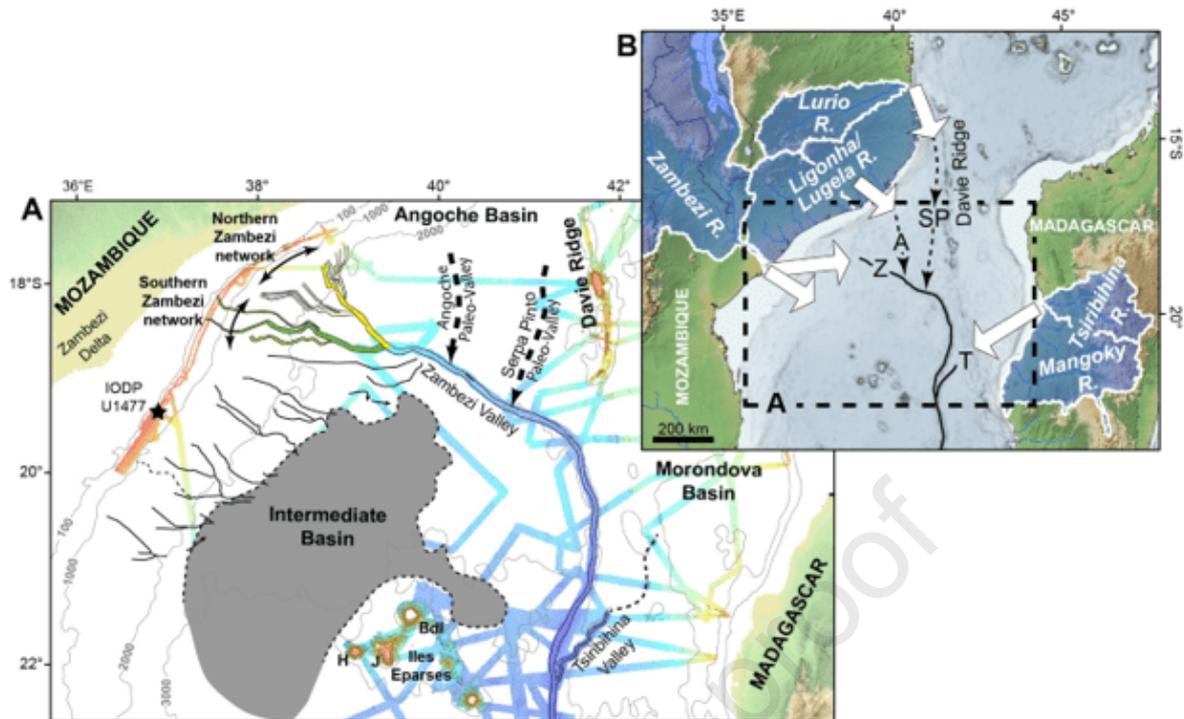
350

351 **4.2. Architecture and stratigraphy of the Zambezi turbidite system**

352

353 4.2.1 The Mozambique Basin feeding networks

354 The PAMELA data with a water depth up to 2500 m and data from Total between 2500 m
355 and 1000 m water depth show that the upper portion of the Zambezi Valley (i.e. most
356 northwestern part) has been fed by two main converging tributary networks (Fig. 7A), the
357 youngest Northern and the oldest Southern Zambezi network (Fierens et al., 2019).
358 Tributaries of these networks do not show clear connections to the upper slope and
359 disappear halfway up the slope. The absence of connection to the uppermost slope is not
360 due to a lack of data, but rather because of the absence of lasting incisions upstream of the
361 slope. The Intermediate Basin, in contrast, was fed by a loose network of parallel valleys
362 distributed homogeneously along the Mozambique slope (black lines in Fig. 7A).



363
 364 Figure 7: Marine feeding axes of the Zambezi turbidite system and continental sediment
 365 sources. (A): Various submarine networks of the Zambezi Fan (Northern and Southern
 366 Zambezi networks, Angoche and Serpa Pinto paleo-valleys and Tsiribihina Valley) and the
 367 ponded turbidites accumulated in the Intermediate Basin. Bdl: Bassas da India, H: Hall Bank,
 368 J: Jaguar Bank. (B): Main rivers feeding the Zambezi turbidite system (rivers watersheds
 369 from <http://www.fao.org/geonetwork>, 2019). Z: Zambezi Valley; T: Tsiribihina Valley; A:
 370 Angoche Paleo-Valley; SP: Serpa Pinto Paleo-Valley.

371
 372 Downstream, the Zambezi Valley receives three main tributaries on its left hand-side: the
 373 Angoche, Serpa Pinto and Tsiribihina valleys (Fig. 7A). The valley that originates northwards
 374 from the Angoche Basin is referred to as the Angoche Valley in this paper. The Serpa Pinto
 375 Valley (Droz and Mougenot, 1987) originates from the Lurio watershed and possible other
 376 northeastern African drainage basins (Ponte, 2018) and runs adjacent to the Davie Ridge.
 377 These two paleo-tributaries have a North-South orientation and provided sediments from the
 378 Northern Mozambique rivers to the Zambezi Fan (Fig. 7B). The Tsiribihina Valley originates
 379 from the Western Madagascar margin (Tsiribihina and Mangoky drainage basins) and is
 380 currently providing sediments to the lower portion of the Zambezi Fan.

381

382 4.2.2. Seismic units

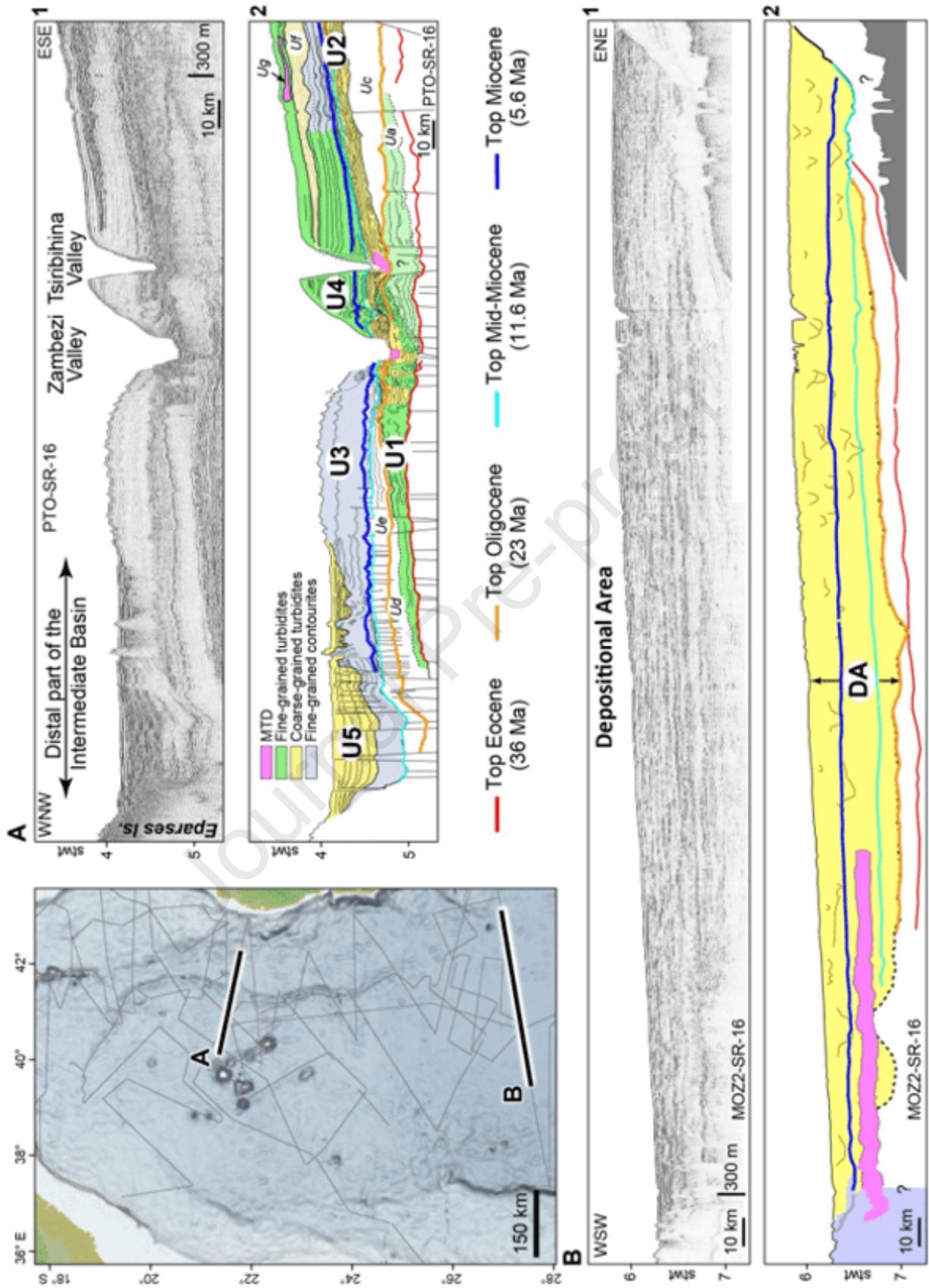
383 Based on the seismic facies analysis and interpretation (see Section 4.1) we identified four
384 main facies types: fined-grained overbank turbidites (lateral levees), coarse-grained
385 turbidites (mainly channel fills or lobe complexes), fine-grained contourites (drifts) and mass-
386 transport deposits (MTDs, restricted in valleys or more widespread in the distal depositional
387 area) (Fig. 8). These facies are organized into five main seismic units (U1 to U5) that are
388 regionally correlated (Fig. 8A, 9). U1 to U4 are stacked up in the Zambezi Fan, while U5
389 corresponds to the Poned Fan in the Intermediate Basin. Figure 10 shows the thickness
390 maps (in sec TWT) of the 5 units that could be correlated throughout the study area.

391 Additional units (Ua to Ug on Figs. 8A, 9) are observed locally in the Zambezi Fan, but the
392 low density of seismic data prevents their correlation and they are not considered in this
393 paper.

394 Towards the distal depositional area (Fig. 8B), we could not individualize U1 to U4, therefore,
395 a single 1000 m-thick seismic unit called Depositional Area (DA) has been considered in this
396 area.

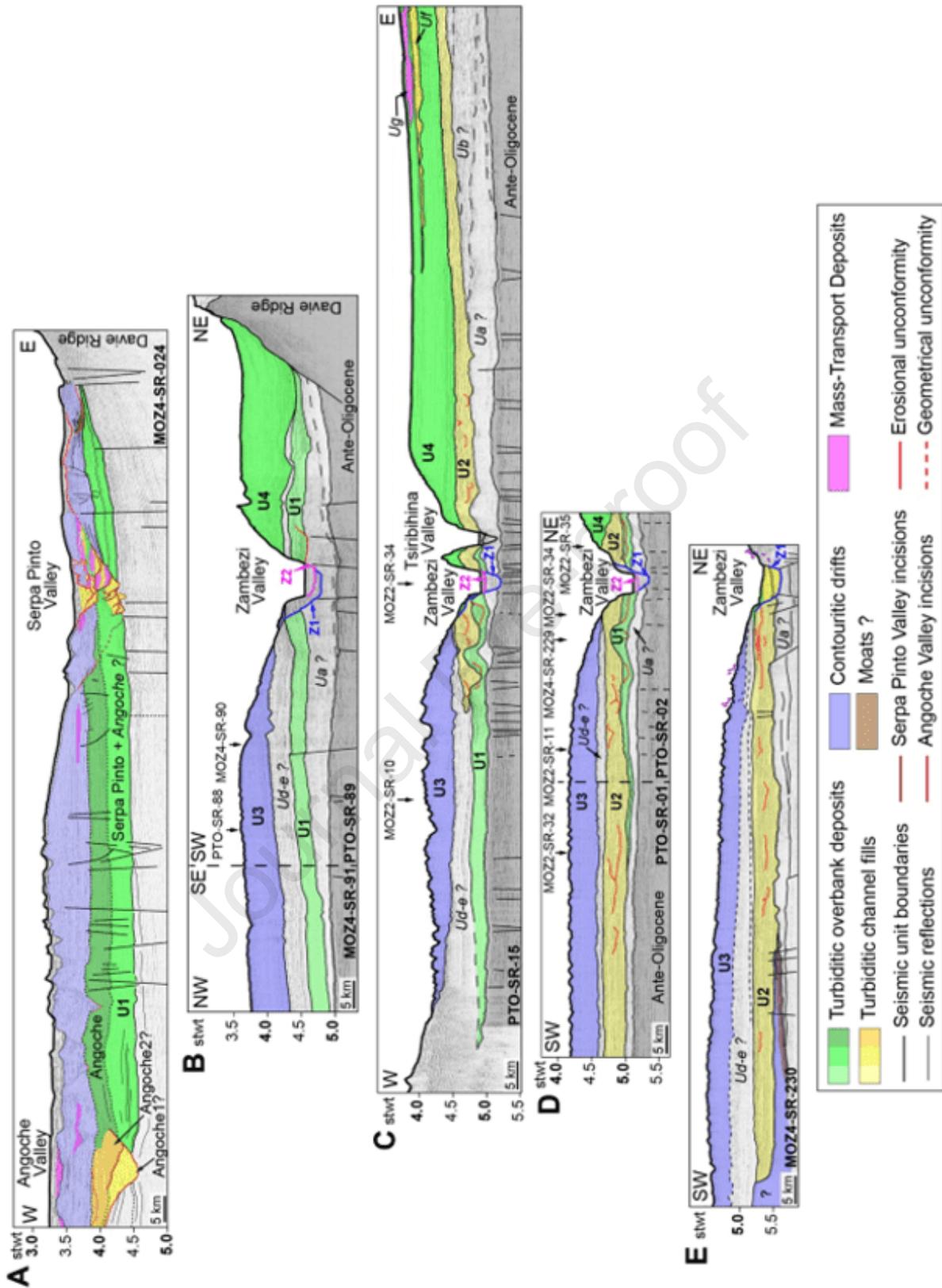
397

398



399

400 Figure 8: Seismic sections (with their location) illustrating the seismic facies, the regional
 401 seismic units and Ponte's (2018) stratigraphy found upstream (A) and downstream (B) of the
 402 Zambezi turbidite system.



403

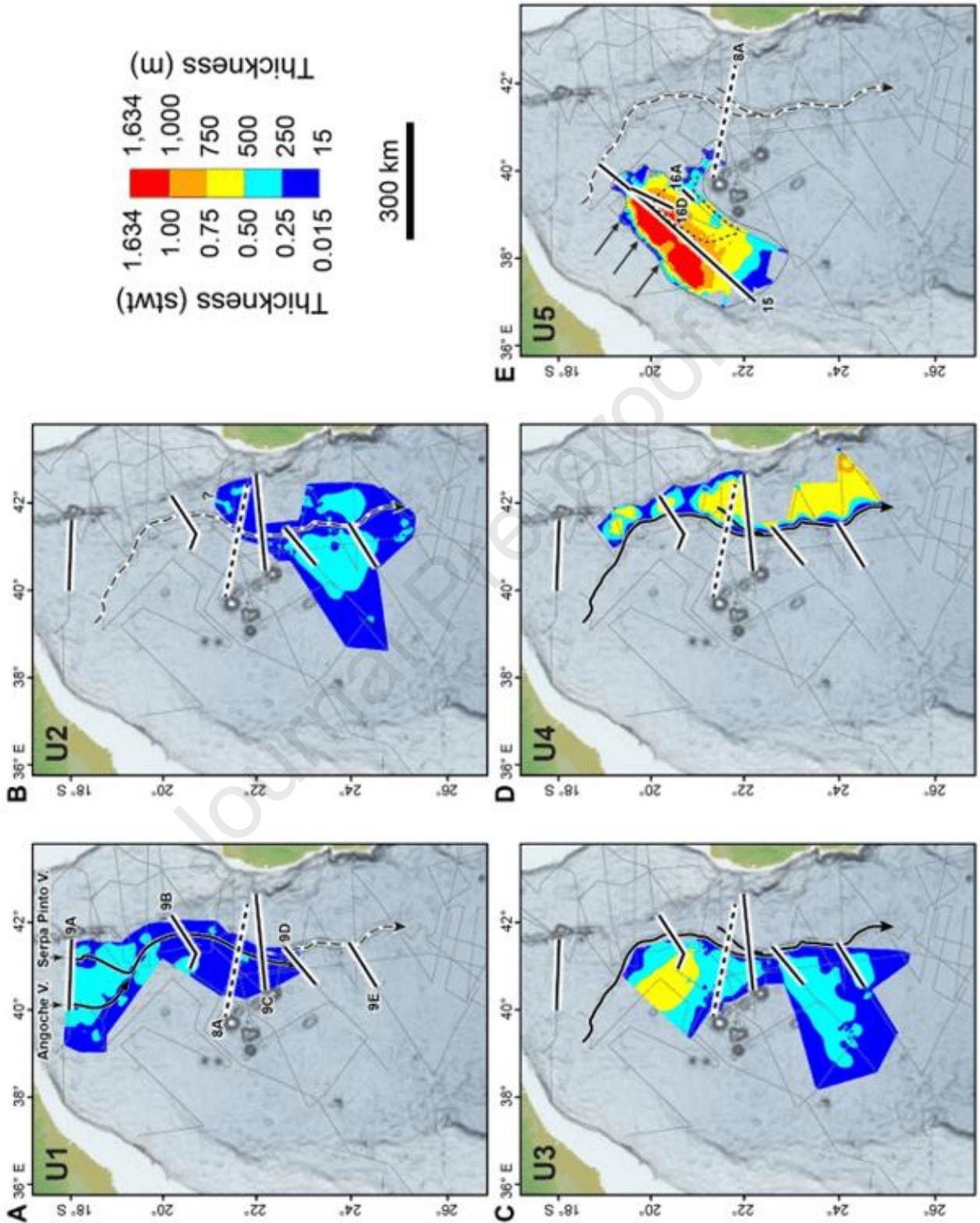
404 Figure 9: Interpreted seismic reflection profiles from north (A) to south (E) showing the major

405 sedimentary evolution of the Zambezi turbidite system (see supplementary material A for

406 uninterpreted profiles). Z1 and Z2 denote the main incisions of the Zambezi Valley. See Fig.

407 10A for location of the seismic profiles.

408



409

410 Figure 10: Distribution and thickness of the five seismic units of the Zambezi turbidite system
 411 (Zambezi Fan, U1 to U4, and Ponged Fan, U5). The position of the Zambezi Valley is
 412 indicated either as a dashed line when inactive (A, B, E) or as a continuous black line when

413 active (C, D). The possible course of the Angoche and Serpa Pinto Valleys is additionally
414 shown in A. Straight black and dashed lines are the location of seismic profiles of Figs. 8, 9,
415 15 and 16.

416

417 4.2.3. Sedimentary evolution of the Zambezi turbidite system

418 A general spatial overview (from north to south) of the architecture of the Zambezi Fan with
419 the distribution of the seismic units is provided in figure 9. The distribution and isochore maps
420 of the five main seismic units are provided in figure 10.

421

422 **Unit U1: Channel-Levee Complex**

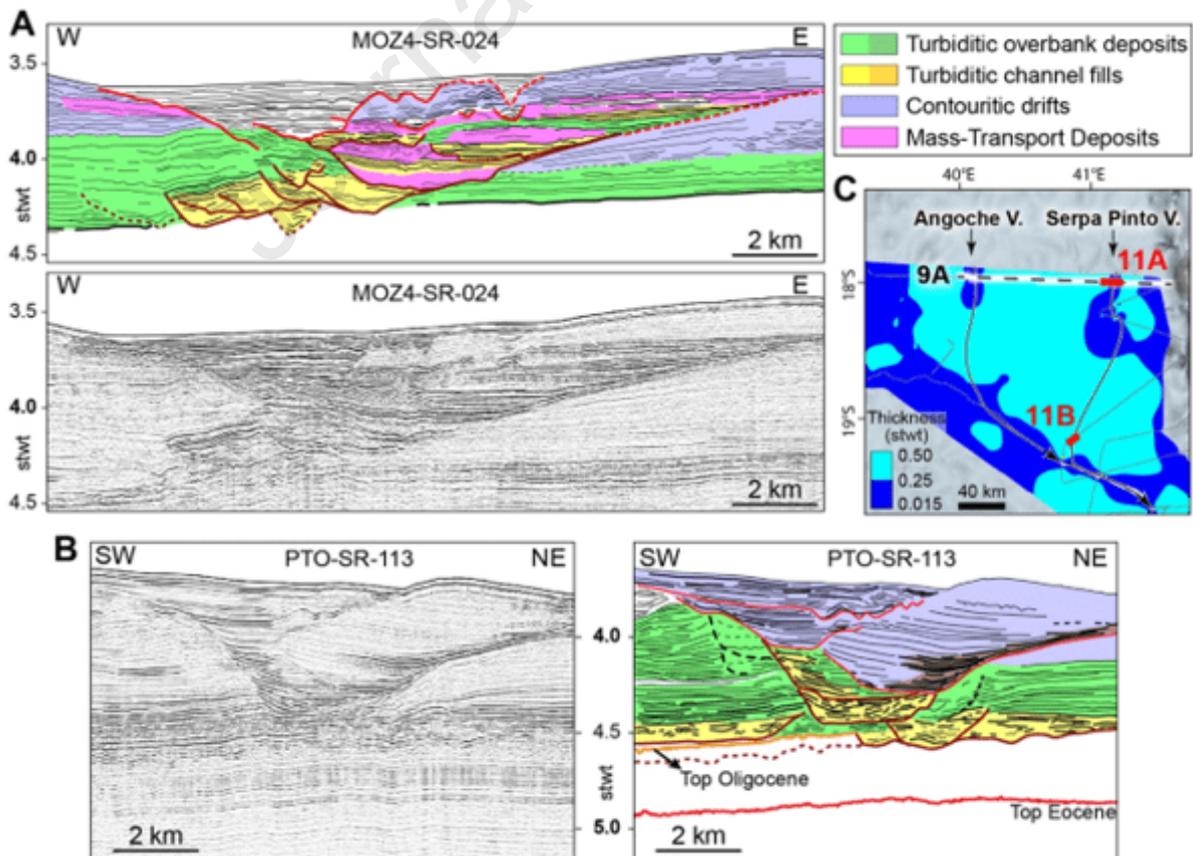
423 Unit U1 (Figs. 8A, 9) is wedge-shaped and composed of the association of high-amplitude
424 channel infilling facies (S3a) interpreted as coarse-grained turbidites and lateral low to
425 medium amplitude, high-frequency S1b facies interpreted as fine-grained turbidites (Fig. 6
426 and Table 2). The convergent configuration distally from the valley is typical of overbank
427 deposits (levees).

428 Unit U1 originates in the northern most part of the study area, in relation with the N-S
429 oriented Serpa Pinto and Angoche valleys (Fig. 10A). The depositional history of the Serpa
430 Pinto Valley appears especially complex with multiple episodes of cut-and-fill in link with
431 overbank deposition and intercalated with small mass-transport deposits inside the channels
432 (Fig. 11). Consequently, U1 is interpreted as a channel-levee complex comprising several
433 channel-levee systems. Available data are too limited to allow an extensive interpretation of
434 the activity of this valley, and therefore it has been considered as a thick single event in this
435 study. In addition, in this northern area, overbank deposition from both the Serpa Pinto Valley
436 to the east and the Angoche Valley to the west indicates that both valleys have been active
437 synchronously and served as feeding axes to the so called Serpa Pinto channel-levee
438 Complex (Fig. 9A, 10A).

439 U1, including the Angoche contribution, shows its maximal lateral extent (approximately 260
440 km) and thickness (0.5 stwt, i.e. ~500 m) in the upstream northern part (Fig. 10A). Close to

441 the Davie Ridge a significant contribution of contouritic sedimentation led to the deposition of
 442 thick contouritic drifts (S1a in Figs 6 and 9A).

443 The basal channels of the Serpa Pinto and Angoche Valley show limited erosion in the
 444 Eocene-Oligocene strata, and appear as a flat and wide erosional unconformity (Fig. 11).
 445 Downstream the confluence with the Zambezi Valley (Fig. 8A, 9B to 9D), the Serpa Pinto
 446 Valley is more deeply incised, and disappears downstream because of over-incision of the
 447 Zambezi Valley (see Section 4.2.4). Where the channels are still observed they are filled in
 448 with typical channel infilling facies, i.e. discontinuous, high-amplitude and low-frequency
 449 reflections (S3b in Fig. 6). The distribution of unit U1 (Fig. 10A) shows an approximate N-S
 450 direction. The channels appear relatively close to the present-day position of the Zambezi
 451 Valley except in the downstream extension of Unit U1 where they diverge toward the west
 452 (Fig. 10A). U1 is identified and correlated downstream to a latitude just a bit further south
 453 than the Tsiribihina confluence (Fig. 10A), however, the downstream extension of this unit
 454 remains uncertain.



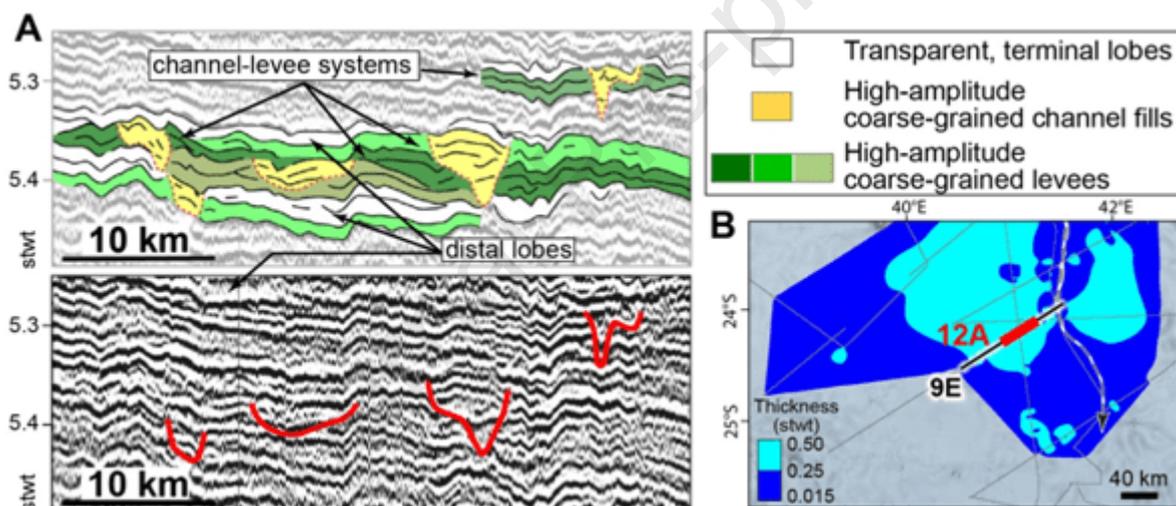
455

456 Figure 11: The Serpa Pinto Valley depositional succession. (A): Close up of seismic profile
 457 MOZ4-SR-24 (shown in Fig. 9A) illustrating the northern portion of the Serpa Pinto Valley.
 458 (B): Seismic profile PTO-SR-113 showing the southern portion of the Serpa Pinto Valley,
 459 close to the confluence with the Zambezi Valley. C: Close up of the distribution and isochore
 460 map of unit U1 (see Fig. 10A) showing the location of seismic lines A and B.

461

462 **Unit U2: Lobe Complex**

463 Unit U2 consists mainly of S3b facies (continuous, high-amplitude, low frequency reflections,
 464 with frequent local erosional unconformities) (Fig. 8 A, 9C-E) and is interpreted as coarse-
 465 grained turbidites.



466

467 Figure 12: (A): Close-up of unit 2 showing the possible stacking of small coarse-grained
 468 channel-levee systems (seismic profile MOZ4-SR-230, Fig. 9E). (B): Zoom of the distribution
 469 and isochore map of unit U2 (see Fig. 10B) showing the location of seismic profile A.

470

471 The detailed internal organization of this high-amplitude unit (Fig. 12) reveals ca. 0.03 stwt (~
 472 30 m) thick wedge-shaped seismic bodies lateral to channel-like erosional features, evoking
 473 small and coarse-grained channel-levee systems which are stacked up in the dominantly
 474 high-amplitude facies. More continuous high-amplitude reflections and transparent levels
 475 intercalated with the channel-levee systems evoke coarse-grained sheet-like turbidites and

476 terminal lobes, respectively. These seismic characteristics suggest that unit U2 is composed
477 of channel-mouth deposits, distinctive of distal depositional environments.

478 The distribution of unit U2 (Fig. 10B) shows a pear shape with an average NE-SW
479 orientation, i.e. oblique to the current Zambezi Valley (Fig. 10). This unit is up to 0.4 stwt
480 thick (~400 m, Fig 10) and is generally widespread (up to ~330 km of lateral extent in its
481 downstream portion, on Fig. 10B), more developed at the right hand-side of the Zambezi
482 Valley. At its northeastern limit, unit U2 is mainly recognized on the left hand-side of the
483 Zambezi Valley (Fig. 8A). Based on available data, it was not possible to extend this unit
484 more to the north, so that we may only hypothesize on its origin (see Section 5.1). The
485 southern limit of U2 extends more distally compared to unit U1. U2 is incised by the paleo-
486 incisions of both the Zambezi and Tsiribihina Valley (Figs. 8A, 9E), which might indicate that
487 unit U2 pre-existed the development of these valleys or that the incision of these valleys has
488 endured after the deposition of U2.

489

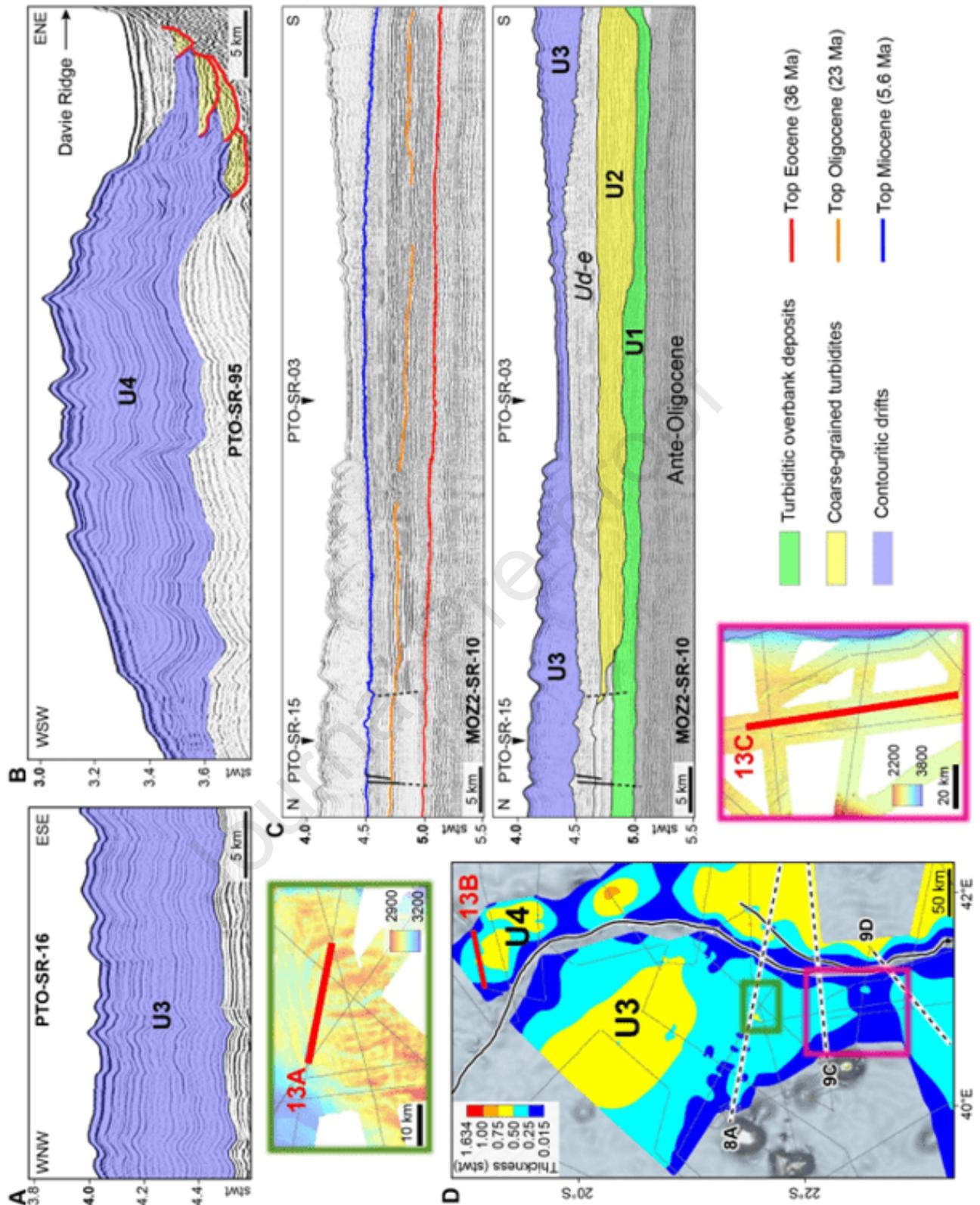
490 ***Unit U3: Contourite drift on the western side of the Zambezi Valley***

491 Unit U3 (Figs. 8A; 9) is composed of continuous low-amplitude, mostly high-frequency
492 reflections (facies S1a). This unit is up to 0.7 stwt (~ 700 m) thick and shows a slightly domed
493 wedged shape with bidirectional thinning. Close to the Zambezi Valley, the lateral thinning is
494 partly due to erosion on the Zambezi Valley flanks. Reflections are parallel under the thickest
495 part of the wedge and are affected by sediment bedforms that are observed in the whole
496 vertical extent of the unit (Figs. 9, 13A). These bedforms, observed on bathymetric and sub-
497 bottom profiler data (Fierens et al., 2019) are interpreted as bottom current controlled
498 sediment waves. Based on the shape, the internal configuration and the similarities with
499 other contourite drifts identified in the Mozambique Channel (Fig. 13B) or in literature
500 (Hernández-Molina et al., 2010; Miramontes, 2016), U3 is interpreted as a contourite drift.
501 Westward at the distal and basal limit of the Intermediate Basin, approaching the Iles
502 Eparses, unit U3 appears to be locally structured by high reliefs wherein reflections are lost
503 and the facies becomes mostly transparent (Fig. 8A). These reliefs are associated to a dense

504 network of faults (Deville et al., 2018), mainly observed in the underlying units (Ud and Ue)
505 and evoke structural domes (associated to volcanism?).

506 Closer to the Iles Eparses seamounts, high-amplitude reflections are intercalated in the
507 dominantly low-amplitude facies. They could represent detrital carbonate sediments
508 originating from the islands, synchronous with the contourite deposition (Counts et al., 2018).

509 Unit U3 is solely observed along the right (looking downstream) border of the Zambezi Valley
510 (Fig. 10C) and is locally less developed towards the SE of Iles Eparses (Fig. 13C). The width
511 of the contourite drift reaches up to ~300 km (Fig. 10C) and the unit is recognized along at
512 least 680 km from upstream to downstream. It is important to note that the northwestern and
513 southern limits of unit U3 remain uncertain due to the lack of data.



514

515 Figure 13: (A): Detail of unit U3 that is characterized by S1a facies affected by sediment

516 bedforms. (B): Example of contouritic sedimentation near the Davie Ridge as part of unit U4

517 that shows similar shape and internal configuration. (C): A second example of unit U3 more

518 to the south, where it is locally less developed. (D): Zoom of the distribution and isochore

519 map of unit U3 (right hand-side of the Zambezi Valley, see Fig. 10C) and unit U4 (left hand-
520 side of the Zambezi Valley, see Fig. 10D) showing the location of the seismic profiles.

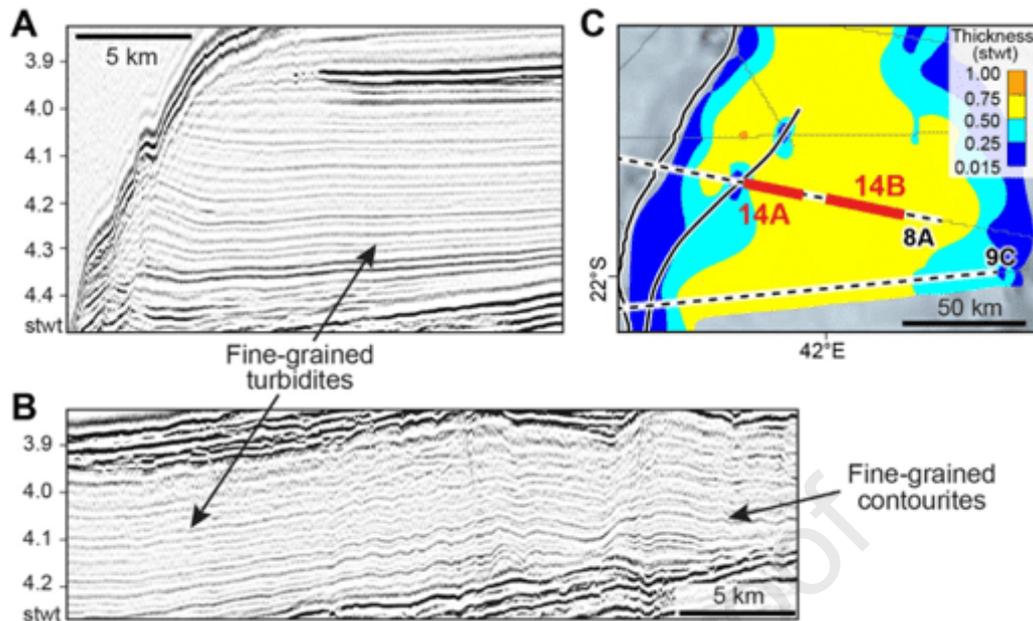
521 Enlarged bathymetric insets show the location of A and C.

522

523 ***Unit U4: Turbidite and contourite deposition on the eastern side of the Zambezi Valley***

524 The left bank (looking downstream) of the Zambezi Valley and both flanks of the Tsiribihina
525 Valley are mainly composed of stratified facies with very continuous medium-amplitude and
526 high-frequency reflections (Fig. 8A, 9). This facies shows truncated reflectors towards the
527 Zambezi Valley and a convergent internal configuration away from the valley axis (Fig 8A,
528 14A), similar to well-known levees of channel-levee systems (e.g. Congo, Amazon, Indus,
529 Mississippi). We therefore interpret this facies as fine-grained overbank turbidites (probably
530 alternating with very fine hemipelagic deposits). The stacking of these turbidites resulted in a
531 ca. 0.7 stwt (~700 m) thick seismic unit (up to 0.9 stwt, ~900 m, locally) (Fig. 10D). Smaller
532 units of inferred coarse-grained turbiditic (Uf, see Fig. 9 and section hereafter) and MTD (Ug,
533 see Fig. 9 and section hereafter) origin are intercalated locally within U4. In addition, towards
534 the east, lateral change in facies and external configuration to wavy parallel reflections (Figs.
535 8A, 14B) suggest a possible contemporaneous contouritic sedimentation on the Madagascar
536 slope and along the Davie Ridge (Fig. 13B). This transition is arbitrary since there is probably
537 a complete gradation between turbiditic and contouritic deposits.

538



539

540 Figure 14: Close up of unit U4 that characterizes the left (looking downstream) border of the
 541 Zambezi Valley. (A): Detail on fine-grained turbidites close to the Zambezi Valley, with
 542 truncated reflectors towards the valley and convergent internal configuration away from the
 543 valley axis. (B): More distally from the valley, a lateral change in facies to a wavy
 544 configuration suggests mixed turbidite-contourite deposits. (C): Zoom of the distribution and
 545 isochore map of unit U4 with the location of seismic profiles A and B.

546

547

548 ***Unit U5: Ponded turbidites confined in the Intermediate Basin***

549 Unit U5 is wedge-shaped (Fig. 15) and consists in two main depocenters up to 1.6 stwt
 550 (~1600 m) thick (Fig. 10E) along the Mozambique base of slope. It shows numerous small
 551 incisions inside it evoking erosional channels and is composed of seismic sub-units that
 552 migrate alternately to the NE and SW (Fig. 16D) indicating shifts of depocenters over time.
 553 The main core of unit U5, between the Mozambique slope and the Iles Eparses, is composed
 554 of an alternation of high-amplitude facies (probably coarse-grained turbidites) and more
 555 transparent or even chaotic levels (respectively small but recurrent MTDs and erosional
 556 channels) that suggest a cyclic sedimentation (Fig. 16). The base of U5 shows large irregular
 557 undulations (erosional structures?) (Figs. 15, 16A) where contourites (possibly related to the

558 Neogene drift proposed by Raisson et al., 2016) are suspected to be affected by structural
559 doming (Fig. 8).

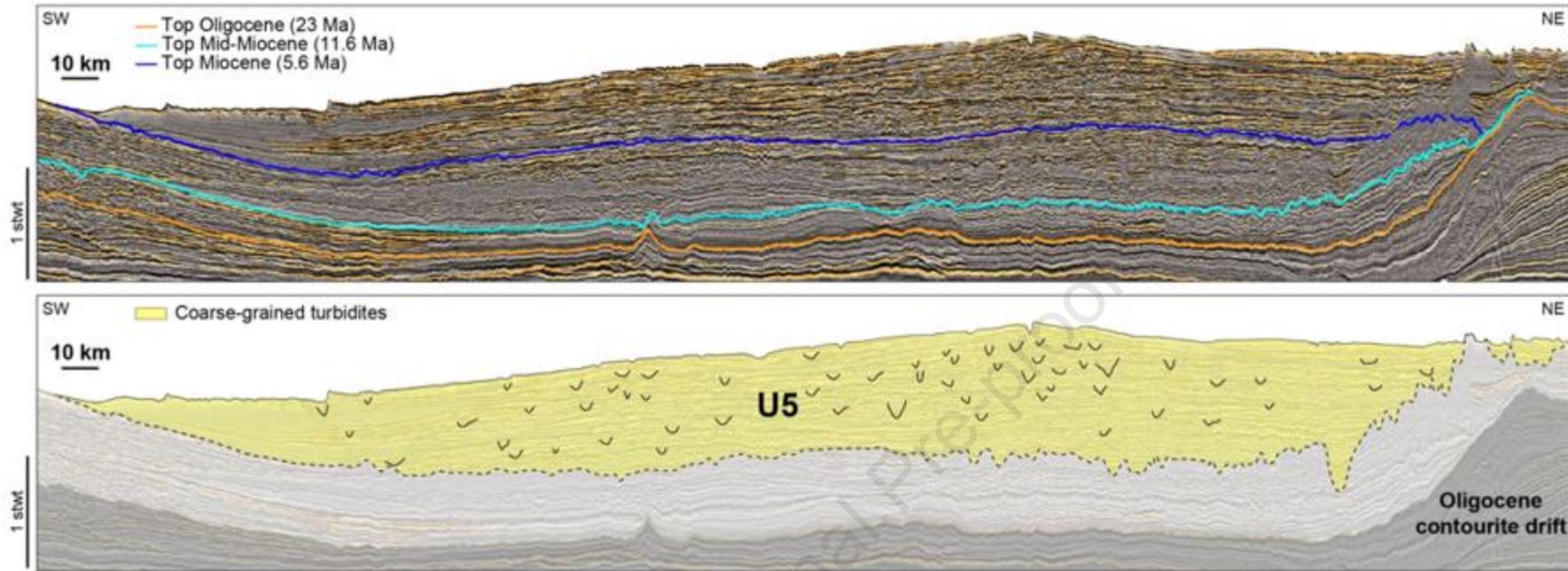
560 In its distal most part, between the Iles Eparses and the Zambezi Valley (Fig. 8A), unit U5
561 appears as an infilling unit composed of continuous, strong amplitude and low frequency
562 reflections with onlapping terminations (facies S2, Figs. 6, 8A) on the supposed contourite
563 drift (Fig. 17).

564

565 In the center part of the Intermediate Basin near the Iles Eparses, a transparent cover rests
566 unconformably on the turbiditic deposits (Figs. 16). On sub-bottom profiles, this cover reveals
567 continuous, high frequency reflections with increasing amplitude towards the top (Fig. 16C).

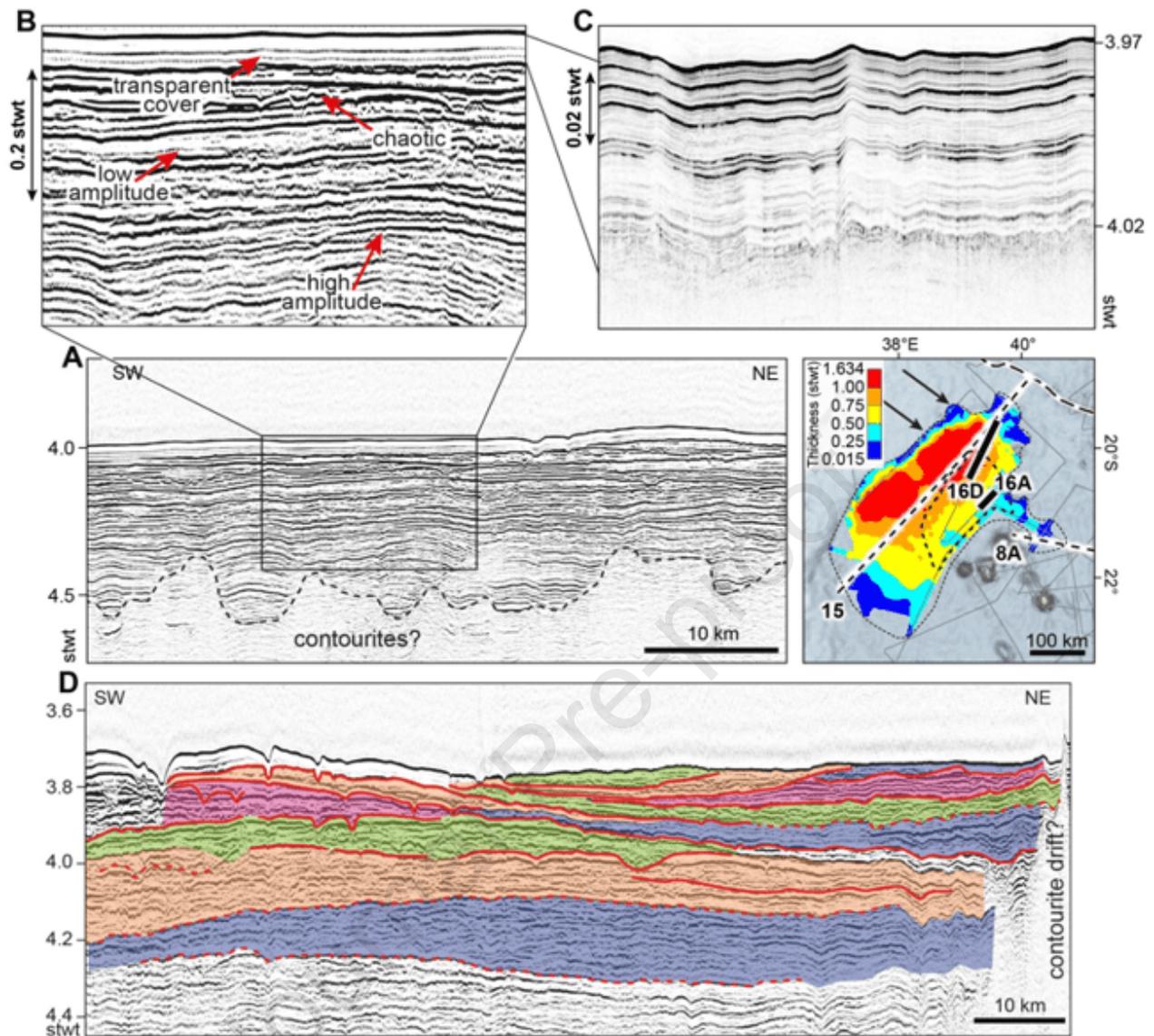
568 These characteristics at the top of the cover suggest an increase in coarse-grained material
569 in the youngest strata. This cover has a variable thickness (ca. 0-100 m) and a limited
570 distribution area. Owing to these characteristics, we suggest that this cover consists of an
571 alternation of contourites or fine-grained turbidites with hemipelagic sediments. Any firm
572 attribution of this superficial cover would need ground truthing by coring.

573



574

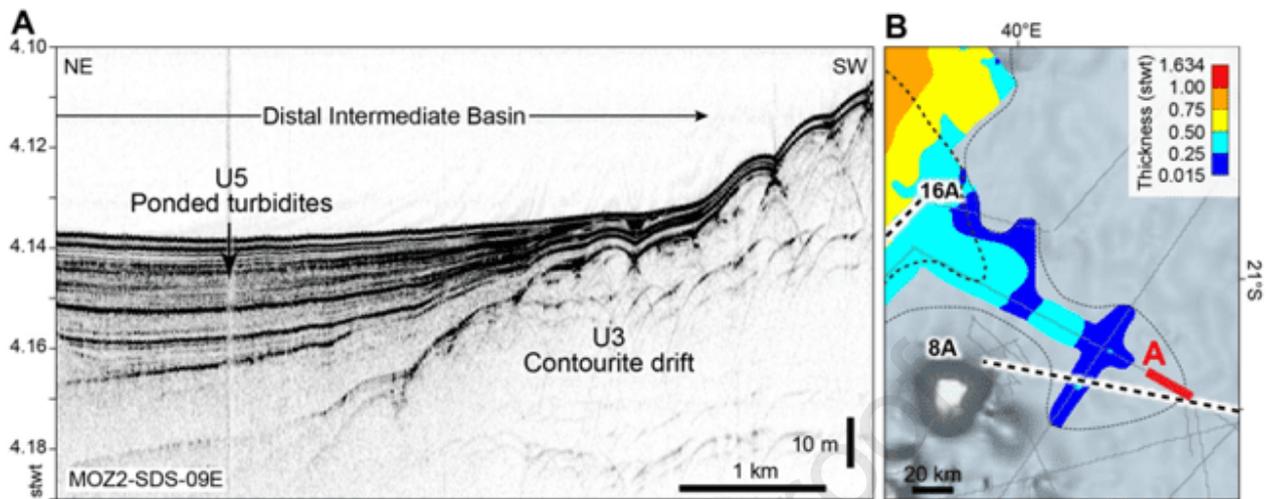
575 Figure 15: The architecture of the Pondered Fan. (A) NW-SE seismic section with stratigraphy established by Ponte (2018) and (B) corresponding line
 576 drawing with indication of facies, crossing the Intermediate Basin (modified from Thiéblemont et al., 2020, data image courtesy of INP and
 577 WesternGeco). The Pondered Fan (infilled by mainly coarse-grained turbidites) is cut by several small incisions (black V forms in B). The position of the
 578 profile is shown in Fig. 10E.



579

580 Figure 16: Detail of unit U5 that characterizes the infill of the Intermediate Basin. (A): High-
 581 resolution multichannel seismic profile (MOZ4-SR-173) showing the continuous, strong
 582 amplitude reflections with low frequency alternating with transparent and chaotic facies. The
 583 base of the U5 is delineated by a dashed line. (B): Zoom of A that shows more in detail the
 584 vertical variations in amplitude. (C): Transparent cover on a sub-bottom profile (MOZ4-SDS-
 585 173d and e with alternating highly stratified facies in uppermost section). (D): Migrations of
 586 the depocenters characterizing the filling of the Intermediate Basin (line MOZ4-SR-171a and
 587 b). Colors are only used to highlight shifts in seismic units (no particular lithological
 588 significance). Note also the decrease in the thickness of the transparent surface layer, until it
 589 disappears towards the NE. At its NE limit U5 is onlapping on a contourite drift (Raisson et

590 al., 2016). The location of the seismic profiles A and D is illustrated with a zoom of the
 591 distribution and isochore map of unit U5 (See Fig. 10).



592
 593 Figure 17: The distal end of unit U5 (Ponded Fan). (A): Sub-bottom profile illustrating the
 594 onlapping terminations on unit U3 (modified from Fierens et al., 2020). (B): Zoom of the
 595 distribution and isochore map of unit U5 (see Fig. 10E) showing the location of the sub-
 596 bottom profile A.

597

598 4.2.4 Stratigraphy of the seismic units

599 The regional stratigraphic framework of the Mozambique Channel and Zambezi turbidite
 600 system (Fig. 4) established by Ponte (2018) allowed us to assign ages for the deposition of
 601 seismic units (Fig. 8). Units U1 and U2 were deposited during the Oligocene (between Top
 602 Eocene and Top Oligocene horizons) and Early Miocene (between Top Oligocene and Top
 603 Mid-Miocene horizon) respectively. Units U3 to U5 are Plio-Quaternary in age (deposited
 604 above the Top Miocene horizon). Because of the lack of stratigraphic information on both
 605 sides of the valley and because units U3 and U4 are separated by the deeply incised
 606 Zambezi Valley, the precise timing of deposition of these units and the stratigraphic
 607 continuity of their sedimentary successions are unknown (synchronous or alternative,
 608 continuous or discontinuous deposition?). Unit 5 corresponds in profile A of Fig. 8 to the
 609 distal part of the Ponded Fan. The main depocenter of U5 is developed updip of the Iles
 610 Eparses. Downdip the islands, unit U5 onlaps on unit U3 and appears to have been

611 deposited late (Late Quaternary?). According to this stratigraphic framework, the Miocene
612 interval and especially the Late Miocene are very thin (only some hundreds of meters in Fig.
613 8A).

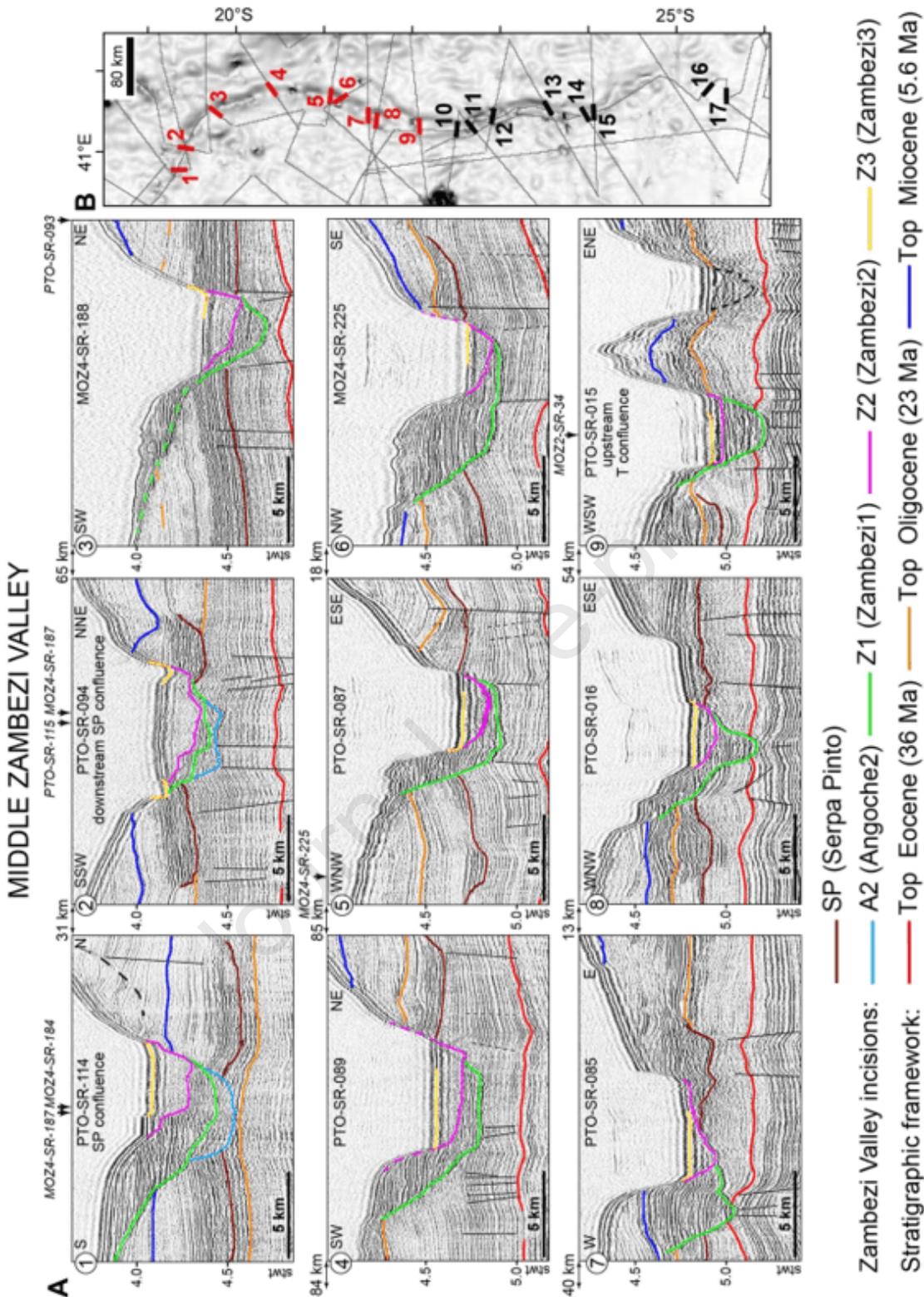
614 In the distal depositional area (DA), the timing of deposition is different from upstream:
615 turbidite facies are absent during the Oligocene and only began to deposit during the
616 Miocene. It must also be noticed also that contrarily to upstream, the Miocene deposits
617 (especially the Late Miocene) are much thicker.

618 4.2.4. The Zambezi Valley incisions

619 While the Oligocene, the Early Miocene and the Plio-Quaternary periods were dominantly
620 characterized by thick aggrading deposits, the Late Miocene period is distinguished by a
621 limited turbiditic deposition (Fig. 8A) and a deep entrenchment of the valley.

622 The Zambezi Valley is currently deeply incised with relief exceeding 700 m in the middle
623 portion of the valley (Fierens et al., 2019). It evolved during the Miocene through several
624 phases of incision and infilling (Figs. 18, 19), some of them observed continuously all along
625 the Zambezi Valley. Three main incisions, namely Angoche2 (A2), Zambezi1 (Z1) and
626 Zambezi2 (Z2) from the oldest to the youngest (Figs. 9, 18, 19) are identified. Additionally, a
627 fourth incision (Zambezi3, Z3) corresponds to very recent erosion, well expressed on
628 bathymetric data of the valley floor (Fierens et al., 2019). Besides some local shifts that may
629 be observed (e.g., profile 7, Fig. 18 and profile 13, Fig. 19), A2, Z1 and Z2 occur mostly
630 vertically under the current Zambezi Valley, indicating that this valley did not undergo major
631 migration since its formation. Multiple additional minor erosional unconformities inside the
632 valley and in the depositional area (purple unconformities in Fig. 19) are observed but cannot
633 be followed from upstream to downstream.

634



635

636 Figures 18: Upstream-downstream evolution of the incisions in the Zambezi Valley upstream
 637 of the confluence with the Tsiribihina Valley. Serie of seismic profiles (A): located as red lines
 638 on the Gebco slope map (B). Vertical black lines and black arrows in A are faults and profile
 639 crossings, respectively. The incision of the Tsiribihina Valley (not studied in this paper) is

645 as red lines on the Gebco slope map (B). Vertical black lines and black arrows in A are faults
646 and profile crossings, respectively. Uninterpreted seismic profiles are provided as
647 supplementary material B-2.

648

649 ***A2: Beginning of over-deepening of the Zambezi Valley***

650 Incision A2 is the deepest incision observed on available seismic data. It is recognized only
651 in the upstream portion of the Zambezi Valley, not far upstream from the Angoche Valley-
652 Zambezi Valley confluence (Fig. 18 profile 1). A2 is therefore thought to relate to the
653 Angoche Valley. This incision disappears rapidly downstream because of its erosion by the
654 following incision Z1 (Fig. 18).

655 As proposed above, the Angoche Valley may have contributed to the feeding of the fan
656 simultaneously with the Serpa Pinto Valley during an initial stage of activity (Angoche1, Fig.
657 9A). A2 is the trace of the latest incision by the Angoche Valley, when the Serpa Pinto Valley
658 was no longer active. It implies that the Angoche Valley probably deeply incised during its
659 second stage of activity, resulting in the total disappearance of the previous A1 erosional
660 course (Fig. 18, profile 1, 2).

661

662 ***Z1: Main incision resulting in the first occurrence of the upstream part of the Zambezi*** 663 ***Valley***

664 Incision Z1 is identified upstream from the Angoche Valley confluence. Consequently, it is
665 considered to indicate the first occurrence of the valley that funneled the inputs of the
666 Zambezi River. It marks the definitive installation of the valley at its present-day position on
667 the central Mozambique margin.

668 Z1 eroded down to the upper strata of the Eocene sequence (Fig. 18). It is identified all along
669 the Zambezi Valley (Figs. 18, 19). The depth below the current valley floor evolves irregularly
670 from up to ~0.4 stwt (profiles 1 and 8, Fig. 18) to down to ~0.2 stwt (profile 6, Fig. 18), and
671 the depth below sea level varies from 4.4 stwt (profile 1, Fig. 18) to 5.6 stwt on profile 15
672 (Fig. 19) where it is tentatively identified.

673 Its infill is very thick (more than 0.4 stwt, ~400 m, on profiles 4 to 6, Fig. 18) and is generally
674 made of high-amplitude stratified facies indicating coarse-grained material, with facies that
675 vary on profiles from chaotic to transparent to stratified (Fig. 18, 19).

676

677 ***Z2 and Z3: later incisions of the Zambezi Valley***

678 Incision Z2 is the last main incision of the Zambezi Valley. Its infill is characterized by a 0.2
679 stwt (~200 m) thick transparent body, identified continuously from the upper reaches of the
680 valley to about 100 km southwards of the Tsiribihina confluence. This transparent mass is
681 interpreted as a mass transport deposit (MTD). Above the MTD, a thin layer (at the seismic
682 scale) of sediments is observed, mostly in the upstream portion of the valley.

683 Erosion Z3 is observed all along the Zambezi Valley and represents the youngest erosional
684 events. Compared to previous incision events, this erosive period appears rather negligible.
685 It resulted in local over-deepening of the valley floor up to 0.063 stwt (~63 m) (profiles 1-2,
686 Fig. 18) and gave the valley its current morphology (see Fierens et al., 2019).

687

688 **5. DISCUSSION**

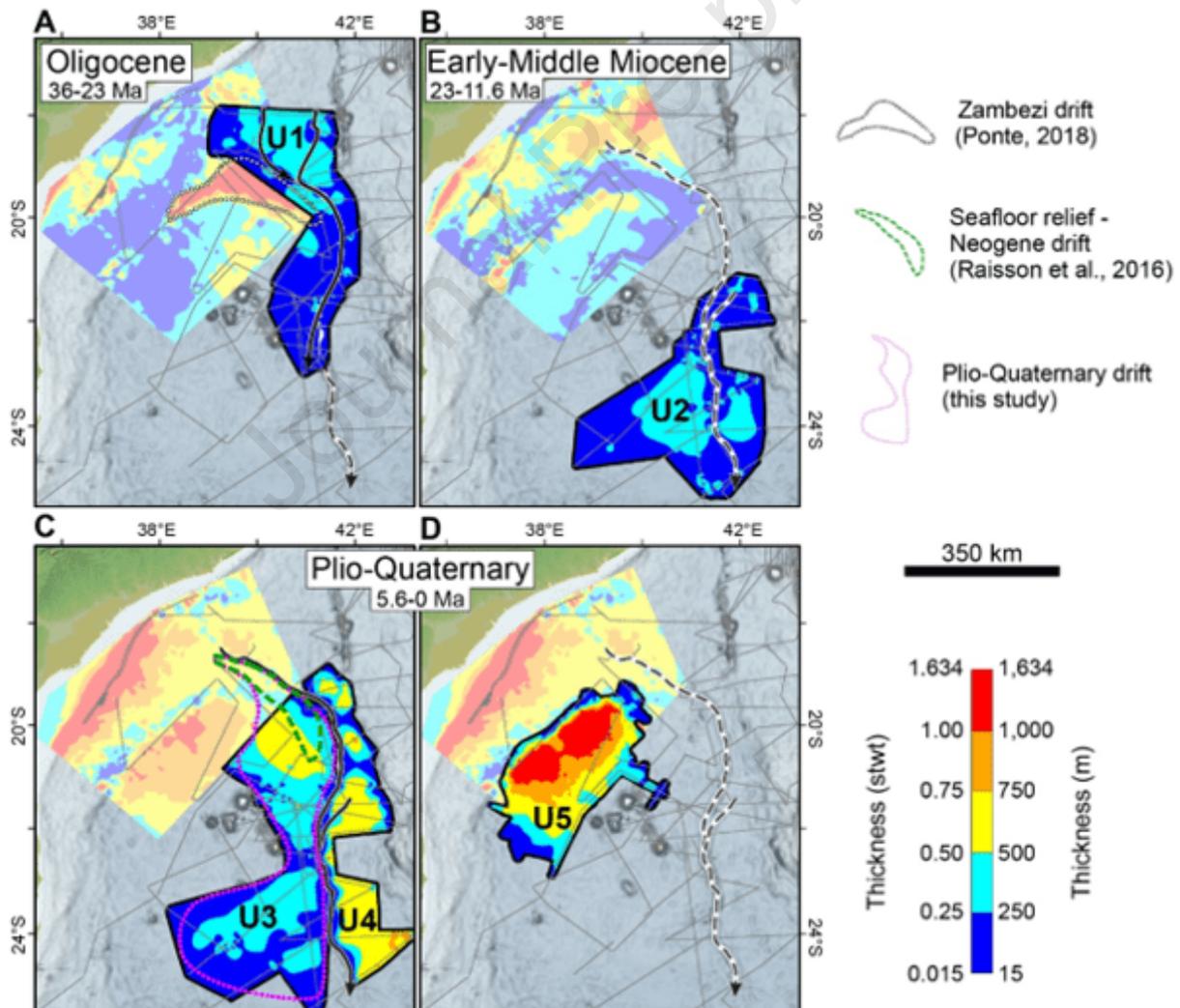
689 **5.1. Origin of depositional units**

690 ***U1: Serpa Pinto channel-levee complex with possible first stage of Angoche Valley***

691 As mentioned previously (Section 4.2.3) unit U1 deposits are related to the Serpa Pinto
692 Valley. The Serpa Pinto Valley received inputs from the northern part of Mozambique (Lurio
693 and probably other northeastern African drainage basins, Ponte, 2018), indicating a 1100 km
694 long transfer of sediments downstream to the most distal area where the channel-levee
695 complex is identified with certainty (Figs. 9E, 10A). Moreover, in the northernmost part of the
696 study area (Fig. 9A), overbank deposition is observed from both the Serpa Pinto and the
697 Angoche Valley. This indicates that there was possibly a contemporaneous first stage of
698 Angoche Valley (Angoche1, Fig. 9) that contributed to the channel-levee complex.

699 The U1 channel-levee complex, which was deposited during the Oligocene, is coeval to the
 700 building of the Zambezi giant 1.8 stwt-thick contourite drift on the southern bank of the upper
 701 Zambezi Valley (Fig 1B, 20A) (Raisson et al., 2016; Ponte, 2018; Thiéblemont et al., 2020).
 702 The juxtaposition of 2 major sedimentation mechanisms raises the question of their possible
 703 interaction. It is probable that the dramatic increase in terrigenous sedimentation brought into
 704 the basin by valleys (Ponte, 2018), associated with the major modification of global oceanic
 705 circulation (Ponte, 2018; Thiéblemont et al., 2020) controls the construction of the giant drift.
 706 It is noticeable that the giant drift builds approximately where the northeastward flowing deep
 707 waters were interpreted to turn back to the South (Thiéblemont et al., 2020).

708
 709



710

711 Figure 20: Composite thickness maps including the Zambezi turbidite system (this study)
712 (surrounded with a black line) and the upper Mozambique margin (Ponte, 2018). The
713 different contouritic drifts identified are indicated: (A): Oligocene sediment thickness (36-23
714 Ma); (B): Early-Middle Miocene sediment thickness (23-11.6 Ma); (C) and (D): Plio-
715 Quaternary sediment thickness (5.6 Ma-0 Ma). See Fig. 10 for key to understand of black
716 arrowed lines.

717 ***U2: Serpa Pinto (or Madagascar) Lobe complex***

718 With the available data, it was not possible to define the upstream extension of unit U2 and
719 therefore the origin of unit U2 could not be properly established. The NE-SW orientation of
720 U2 deposits suggests two possible origins: from the Madagascar margin (paleo-Tsiribihina
721 Valley) or from the Serpa Pinto Valley (with or without the Angoche Valley). However,
722 Delaunay (2018) stated that the overspill of Madagascar inputs to the Zambezi system
723 occurred only from Middle Miocene, when the Morondova Basin was infilled and detrital
724 sediments from Madagascar could overcome the Davie Ridge. The hypothesis of a
725 Madagascan origin of unit U2 appears therefore less convenient and thus a persistent
726 feeding by the Serpa Pinto Valley (or by the combined Serpa Pinto + Angoche valleys) is
727 favored.

728 ***U3-U4: Mixed contouritic-turbiditic sedimentation***

729 Units U3 and U4 have been described separately because we do not have any stratigraphic
730 information to give a relative chronology. However, owing to the top Miocene horizon of
731 Ponte (2018), they were both deposited during the Plio-Quaternary, and we think that they
732 were probably contemporaneous.

733 Unit U3, identified as a contourite drift at a water depth of ca. 2800 to 3500 m, may have
734 been generated by bottom currents associated to the northward flowing Mozambique
735 Undercurrent, which contain the North Atlantic Deep Water (NADW) at this particular depth
736 range (van Aken et al., 2004). This interpretation is consistent with the observation of
737 Miramontes et al. (2019) that the present-day NADW partly flows inside the Zambezi Valley

738 and contribute to the flank erosion and over-widening of the valley. This large contourite drift
739 which developed on the southern bank of the upper Zambezi Valley, just where it bends from
740 a NW-SE to N-S trend (pink dotted polygon in Fig. 20C), is shifted to the SE with regard to
741 the giant Oligocene drift (Fig 20A) and extends more to the SW. The Plio-Quaternary
742 contouritic drift is associated to a sea floor relief (green polygon in Fig 20C) that was formerly
743 called Neogene drift by Raison et al. (2016). Here again we can suppose that the drift
744 benefited from the terrigenous supply of turbidity current overflows (by possible sediment
745 pirating) whose origin is not clear (as it can come from turbidity currents from the Zambezi
746 Valley and/or distal sediment upwelling to the north).

747 On the left border of the Zambezi Valley and both sides of the Tsiribihina Valley fine-grained
748 levee turbidites dominate (Fig. 8A, 9B-C). The U4 deposit thus indicates that there is a
749 synchronicity of different terrigenous input sources coming from the Mozambique and
750 Madagascar margins. Moreover, the lenticular units Uf and Ug (present in the upper part of
751 unit U4) attest to recurrent inputs from Madagascar that are not funneled into the Tsiribihina
752 Valley. In addition, contourites appear to have been constantly deposited, either
753 synchronously or in alternation with levee deposition, especially in areas approaching high
754 reliefs, such as the Davie Ridge (Fig. 13B).

755 ***U5: Ponded turbidites from the Mozambique slope***

756 The mainly coarse-grained turbidites were fed to the Intermediate Basin through a network of
757 parallel valleys originating from the Mozambique slope off the Zambezi River mouth (Fig.
758 7A). Several channels have been identified, however the density of channels on the slope is
759 rather small (ca. 50 km between each main channel). These valleys disappear halfway up
760 the slope in agreement with the absence of canyons on the highest part of the slope (Jouet
761 and Deville, 2015), demonstrating that there is no current connection between the shelf and
762 the basin (as it was also observed for the Zambezi Valley). Wiles et al. (2017b) showed that
763 channels in the southwestern portion of the basin (see Fig. 1B) probably transfer some of the
764 Zambezi inputs towards the Bourcart-Hall Depression southeast of the Iles Eparses.

765 Based on the stratigraphy of Ponte (2018), the Intermediate Basin began to fill in during the
766 Upper Miocene, while deposition had mainly ceased in the Zambezi Fan that was mainly
767 subject to erosion inside the valley (see Section 5.2), except in the distal depositional area.
768 This is the only period of time during which data highlight a clear absence of synchronicity
769 between both turbidite accumulation sites of the Mozambique margin. Later on, during the
770 Plio-Quaternary, the Intermediate Basin was filled in and sediment deposition happened in
771 the Zambezi Fan.

772 The thickness map (Fig. 10E) is consistent with that of Thiéblemont et al. (2020) (Fig. 20D).

773

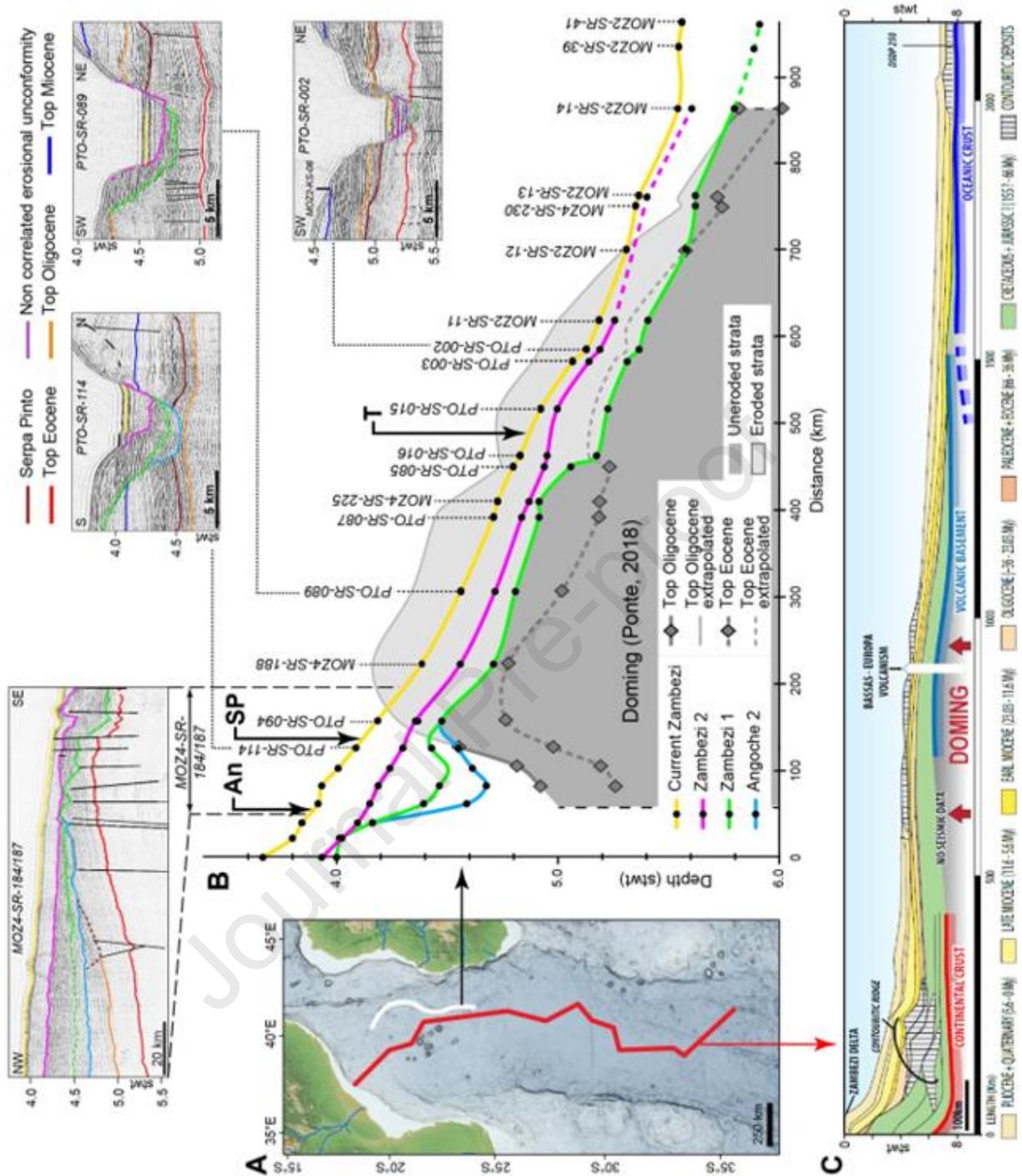
774 **5.2. Upstream-downstream evolution of the incisions and effects of the Miocene**

775 **doming**

776

777 The depth profiles of incisions A2 to Z2 (Fig. 21B) show that A2 and Z1 incisions suffered a
778 post-depositional deformation. This deformation is well expressed by the depth profiles of
779 Top Eocene and Top Oligocene horizons observed between km 100 and km 900. It was
780 described by Ponte (2018) as an episode of doming during the Miocene (Fig. 21C).

781



782

783 Figure 21: Effects of the Miocene doming in the central Mozambique Channel on the
 784 Zambezi Valley incisions. (A) Position of profiles shown in B (white line) and C (red line). (B)
 785 Depth profiles (in stwt) of the main incisions. An, SP and T: Angoche, Serpa Pinto and
 786 Tsiribihina confluences, respectively. The depth profiles of the Top Eocene and Top
 787 Oligocene horizons are reconstructed from Ponte (2018). (C) Synthetic dip profile of the
 788 Mozambique Channel showing the Miocene doming (Ponte, 2018).

789

790 The deformation of A2 and Z1 incision profiles (MOZ4-SR-184/187 in Fig. 21B from around
791 50 to 150 km) and of the Top Eocene and Top Oligocene horizons indicate that the
792 deformation began after the initial incision of A2 and Z1 axes and was prolonged during their
793 activity. This allows dating the A2 and Z1 incisions before the start of the doming deformation
794 in Middle Miocene (Ponte, 2018). On the other hand, we also observe locally the
795 preservation of the Top Oligocene reflector below the A2 incision (see profile PTO-SR-114
796 on Figs. 18 and 21), so A2 and Z1 are also post-Top Oligocene. The following Z2 and Z3
797 incisions are not affected by the deformation and have depth profiles close to an equilibrium
798 state. The incision of Z2 happened therefore after the end of doming deformation in Late
799 Miocene according to Ponte (2018).

800 The continuous deformation resulted in a constant adjustment of the Z1 incision depth profile
801 by entrenchment in order to compensate the uplift movement and to establish a new
802 equilibrium state. The deep entrenchment of Z1 incision resulted in the erosion and
803 disappearance of A2 (and probably also A1). The Z1 depth profile is not at an equilibrium
804 state, it is assumed that it was abandoned prematurely before it had time to reestablish a full
805 equilibrium profile.

806

807 The structural deformation on the Zambezi Valley during the Miocene had significant
808 influence on the capacity to transfer sediments downstream. The continuous erosion in link
809 with the elevation of the seafloor during the Miocene resulted in an over-incision of the Z1
810 incision, the production of important volumes of reworked sediments and the absence of
811 levee deposits related to over-deepening of the valley floor.

812 The lacking, eroded Oligocene strata are estimated to a minimum of 0.4 stwt thickness (~400
813 m) and occur at least along 700 km (from profile PTO-SR-094 to profile MOZ2-SR-13, Fig.
814 21B). If the shape of the Z1 incision is approximated by a half rectangular prism of ca. 700
815 km long, 400 m high and 4 km wide (mean wideness of Zambezi1 incision, see Fig.18), a
816 rough minimum volume of 560 km³ of eroded sediments is estimated. This reworked

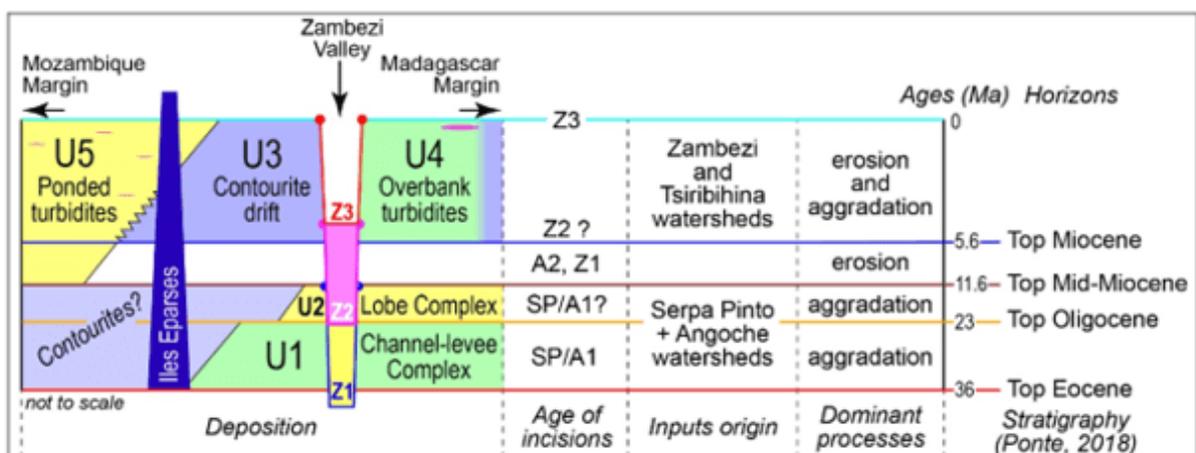
817 sedimentary volume is probably deposited downstream. At the time the incision occurred, it
 818 was unrelated to input by the Zambezi and other feeding rivers and therefore should be
 819 taken into consideration for the erosion-sedimentation balance calculations in source to sink
 820 studies. Conversely, the upstream portion of the Z1 incision (Fig. 21B, from km 50 to 150)
 821 shows a concave upward-shape suggesting that it could have served as a trap for the
 822 Zambezi River inputs. This would have decreased the sedimentary volume able to reach the
 823 deeper portions of the Zambezi Fan. However, it can be assumed that the volume of trapped
 824 sediments inside Z1 is negligible with regards to the eroded Oligocene strata volumes (from
 825 km 150 to km 850, Fig. 21B).

826

827 5.3. Distinct modifications in the Zambezi turbidite system development

828 The Zambezi turbidite system experienced drastic modifications of sediment deposition
 829 during its evolution. Since Oligocene, sediment feeding axes migrated westward for the
 830 upstream portion of the Zambezi Valley (from SP-A1 to A2 to Z1-Z3) and a general
 831 southward migration of deposits happened. This was partly accompanied by successive
 832 variations in sedimentological regimes alternating between mainly aggradational and
 833 erosional phases (Fig. 22).

834



835

836 Figure 22: West-east schematic illustration of the timing of seismic unit deposition and main
 837 incisions for the Zambezi turbidite system based on the stratigraphy established by Ponte

838 (2018). Green: fine-grained turbidites; Yellow: coarse-grained turbidites; Blue: contouritic
839 deposition; Pink: mass-transport deposit.

840

841 The Oligocene was dominated by mainly fine-grained deposits and aggradational processes
842 with the deposition of the Serpa Pinto channel-levee complex (U1). Limited erosional
843 processes were restricted to the basal surface of the channel and it was possibly combined
844 with a first stage of Angoche Valley activity (Fig. 9A). The deposition evolved during Early
845 Miocene into coarse-grained sediments that are interpreted as distal turbiditic channel-mouth
846 deposits of the Serpa Pinto system (U2). Their installation on previous more proximal
847 channel-levees could reflect the retrogradation of the system. The origin of the change in
848 depositional regime and possible retrogradation is unknown, but is probably related to the
849 offshore tectonic deformation in the eastern branch of the East African Rift (Courgeon et al.,
850 2018), which would provoke changes in sediment flux supplied from North Mozambique.
851 The thickness map of Miocene sediments (Fig. 20B) shows that deposition started in the
852 Intermediate Basin, while the Zambezi Fan is dominated by erosional processes during
853 Middle to Late Miocene. This with two successive incisions (A2 and Z1) that indicate a shift
854 of the position of the source, from the Angoche to the Zambezi drainage basin. In the Late
855 Miocene, the incisions were affected by a progressive structural doming in the central part of
856 the Mozambique Channel (Ponte, 2018). Oligocene strata were eroded and the Angoche2
857 incision was probably totally erased by the Z1 erosional phase in response to the long-lasting
858 elevation of the seafloor during Late Miocene. This incision period must have produced an
859 important volume of material (estimated to 560 km³, see section 5.2) that is probably
860 deposited downstream in the Depositional Area. It was however not possible to individualize
861 the seismic units associated to this episode of strong erosion.

862 Later on in the Late Miocene a new aggradational stage happened were the Z1 incision was
863 infilled with onlapping sediments probably in order to establish a new equilibrium profile and
864 deposition started in the Intermediate Basin.

865 The Plio-Pleistocene is characterized by a combination of aggradational and erosional
866 events that resulted in a diversification of deposits. Fine-grained turbidites are observed at
867 the left overbank of the Zambezi Fan, while mainly coarse-grained turbidites are present in
868 the Intermediate Basin and Depositional Area. Contourites occur on the right bank of the
869 Zambezi Valley as well as in the Angoche basin. Additionally, this period is characterized by
870 synchronicity of different terrigenous input sources (Zambezi and Madagascar margin). The
871 Zambezi Valley (incision Z2; Figs. 18, 19) is in a rather equilibrium state. It was lately infilled
872 by a MTD, observed 800 km along the Zambezi Valley more downstream than the Tsiribihina
873 confluence (Fig. 18, 19 profiles 1-11). Considering the maximum thickness of this MTD (0.2
874 stwt, ~200 m), the mean wideness of the Z2 incision (4 km), and a rectangular prism as an
875 approximation of the shape of the MTD, a rough estimation of the volume of transported
876 sediments can be calculated to 640 km³. Together with the MTDs in the distal Depositional
877 Area, the occurrence of these mass transport deposits attests to the recurrence of
878 instabilities in the Plio-Pleistocene period, also shown on the Mozambique slope by Ponte
879 (2018).

880 The Zambezi Fan has been shown to be dominantly erosional during very recent times
881 (Fierens et al., 2019; Miramontes et al., 2019). The erosional regime is attested by multiple
882 generations of incisions in the thalweg (corresponding to the Z3 incision), erosion of the
883 valley flanks possibly by bottom currents, and absence (or rarity) of fine-grained deposits
884 (pirating of the turbulent suspension cloud by contouritic currents?). Contrarily, in the Poned
885 Fan, the depositional regime is mainly aggradational.

886

887 **6. CONCLUSION**

888 Academic high-resolution seismic data complemented with industrial data allowed
889 deciphering the Oligocene to present architectural evolution of the Zambezi turbidite system
890 including the Zambezi channelized Fan and the Intermediate Poned Fan. Seismic
891 interpretation allowed distinguishing five major depositional units and four principal incisional

892 episodes. The respective depositional timing of these units is established based on the
893 regional stratigraphy from Ponte (2018).

894 The main results can be summarized as follows:

- 895 • The Zambezi turbidite system is shown to be composed of both turbidites and
896 contourites that were deposited mostly synchronously along the Mozambique and
897 Madagascar margins. The history of the turbidite system shows an alternation of
898 aggradational and erosional processes.
- 899 • Stratigraphic correlations place the Serpa Pinto (and Angoche1) deposition (unit U1)
900 during the Oligocene, the distal turbiditic deposition (unit U2) during Early Miocene, the
901 Angoche2 and Zambezi1 incisions during Middle - Late Miocene and the Zambezi2
902 incision at the beginning of the Pliocene. Units U3 and U4 were deposited during the
903 Plio-Quaternary.
- 904 • Succession of valleys that fed the sedimentary units evidences an anticlockwise shift of
905 feeding axes from the Serpa Pinto Valley to the Angoche Valley and finally towards the
906 Zambezi Valley. This goes together with a shift of the drainage basins that fed the fan,
907 from the northern most watersheds of the Mozambique (Lurio and possible other
908 northern rivers) to the Angoche watershed (more south), then to the Zambezi watershed
909 (central Mozambique).
- 910 • The main incision event occurred during the Late Miocene, when the valley suffered the
911 effects of a structural doming in the central part of the Mozambique Channel. The
912 continuous elevation of the seafloor forced the profound entrenchment of the Zambezi1
913 incision (~400 m of erosion), which supposedly is cause of the observed absence of
914 lateral levees proximal to the Zambezi Valley. Products of this strong erosional regime
915 (estimated to 560 km³ of reworked sediments) are supposed to be transported to the
916 distal Depositional Area.
- 917 • Most turbiditic deposits in the studied area are either fine-grained levee turbidites (units
918 U1 and U4) or coarse-grained channel-mouth turbidites (U2, U5 and Depositional Area).

- 919 • Mass-movement processes, recurrent on the Mozambique slope (Ponte, 2018) since the
920 Pliocene have been observed mainly in the Zambezi Valley, in the distal depositional
921 area, and on the Madagascar margin.
- 922 • Contouritic sedimentation is at least continuous since the Oligocene. The drift sediments
923 are supposed to be supplied by turbiditic processes (current overflow) and both (i.e.
924 turbiditic and contouritic) depositional processes occur most often synchronous (i.e. U3
925 during U4 levee deposition, possibly during northern Serpa Pinto deposition and close to
926 the Davie Ridge). Besides the two thickest Oligocene and Miocene drifts upstream on
927 the margin, a prominent Plio-Quaternary N-S contourite drift (U3) is identified on the right
928 flank of the Zambezi Valley where bottom current controlled bedforms are observed.
- 929 This study has important implications for the current understanding of deep-marine turbidite
930 systems. It demonstrates the sensitivity of large depositional systems to changing basin floor
931 topography created by progressive structural deformation in terms of the architectural
932 elements and the associated capacity to transfer sediments downstream.

933

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949

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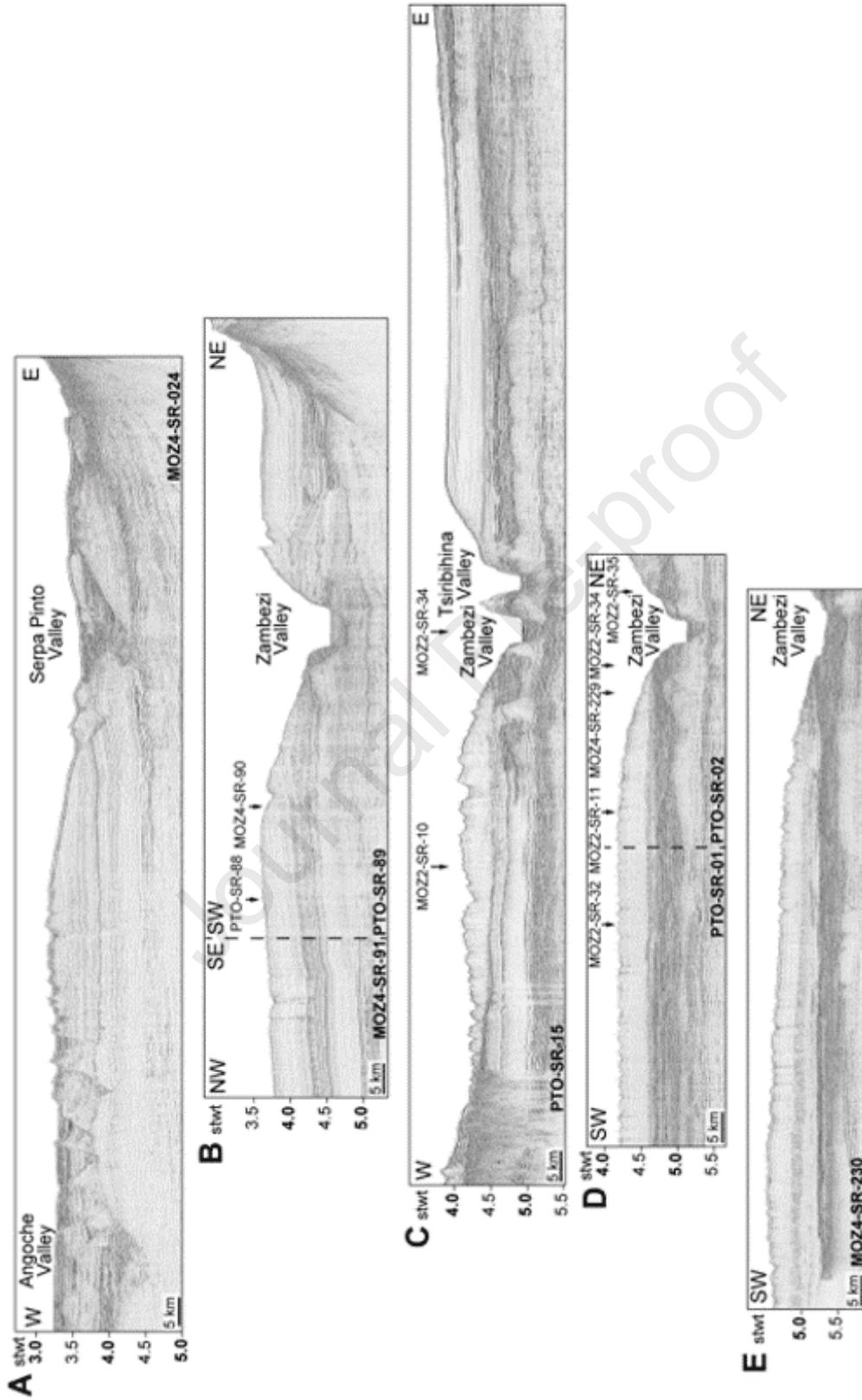
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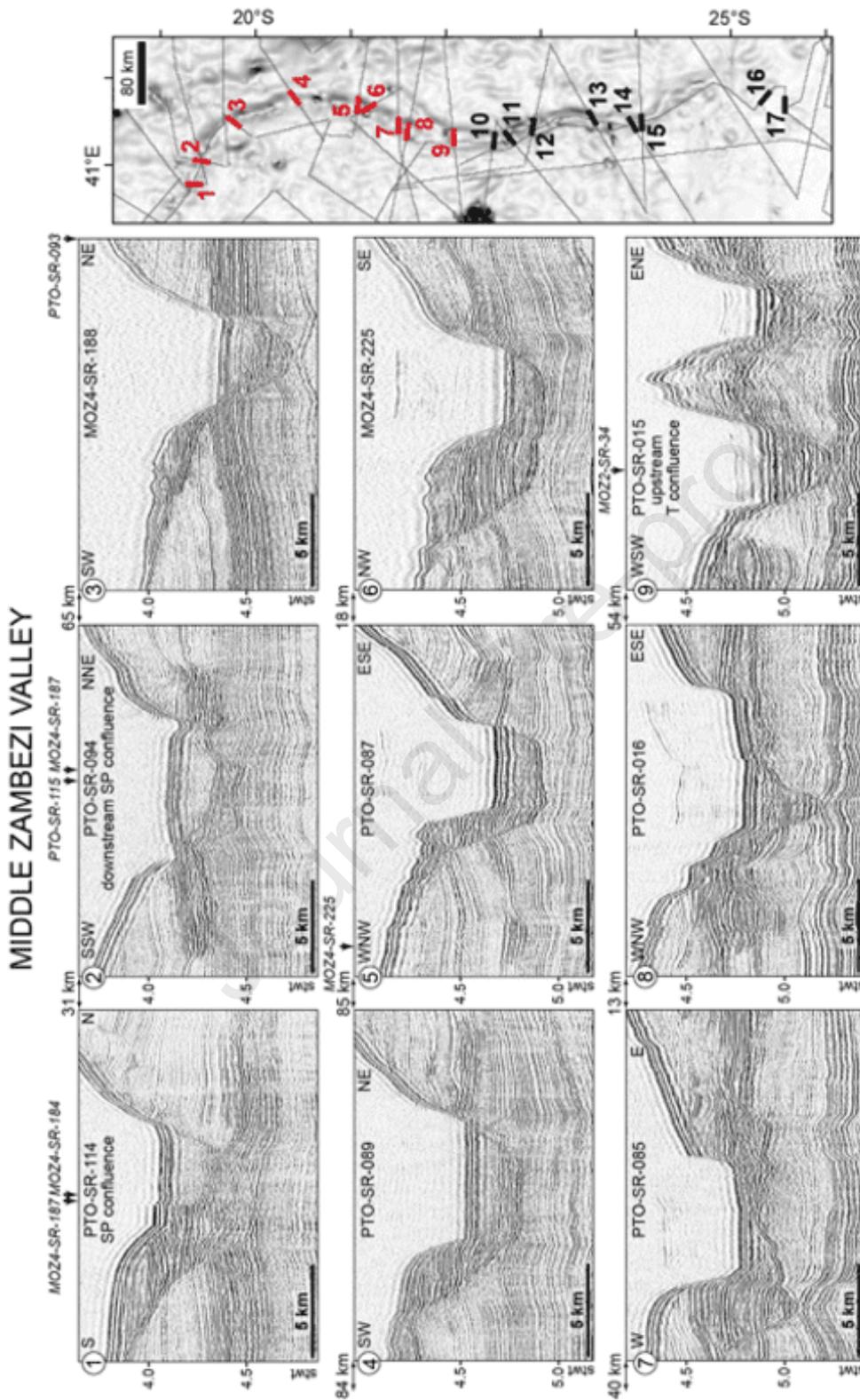
1308 **Supplementary material A**



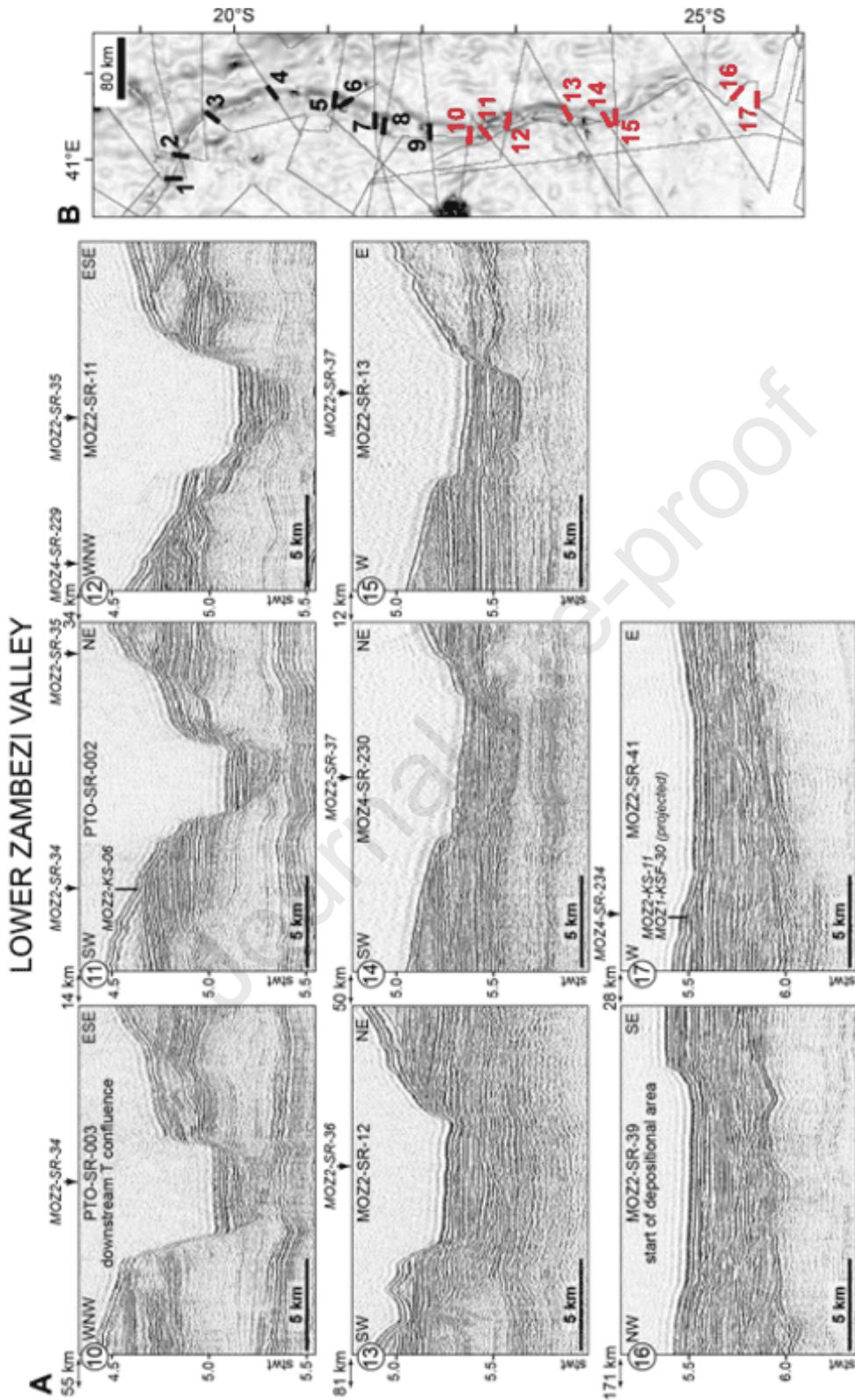
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1310 Supplementary material A: Uninterpreted profiles of figure 9.

1311 **Supplementary material B-1**



1314 Supplementary material B-2



1315

1316 Supplementary material B-2: Uninterpreted seismic profiles of figure 19.

Highlights

- High-resolution seismic reflection data is used to investigate the Oligocene to present architectural evolution of the Zambezi depositional system.
- Five major depositional units are identified and demonstrate both turbiditic and contouritic deposits that occur most often synchronously.
- The Zambezi Fan is characterized by various episodes of incision that evidence multiple shifts of feeding axes since Oligocene.
- Progressive structural doming during Late Miocene caused a deep entrenchment of the Zambezi Valley.

Declaration of interests

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

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

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